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Review

Review of Power System Resilience Concept, Assessment, and Enhancement Measures

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Abstract: Power systems are generally designed to be reliable when faced with low-impact, high-probability, and expected power outages. By contrast, the probability of extreme event (extreme weather or natural disasters) occurrence is low, but may seriously affect the power system, from long outage times to damage to major equipment such as substations, transmission lines, and power plants. As, in the short term, it is extremely difficult to completely avoid the damage caused by extreme events, it is important to enhance the resilience of power systems. This study has provided a comprehensive review of power system resilience by discussing its concepts, assessment, and enhancement measures. This article summarized possible impacts and quantitative indicators of various types of disasters on power grids, presented the concept of power system resilience, and analyzed the main characteristics that a resilient system should possess. Moreover, this article further distinguished the differences between the resilience, flexibility, and survivability of a power system. More importantly, this paper has proposed a novel framework and the corresponding metric for assessing resilience, which makes the evaluation of system resilience more accurate. Finally, this paper discussed various measures to enhance power system resilience and outlined potential challenges for future research.

Keywords: extreme weather; natural disasters; power system resilience; resilience assessment; resilience metrics; resilience enhancement

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1. Introduction

Extreme events have an impact on the operation of distribution and transmission grids, thereby affecting a large number of customers [1]. As our society becomes increasingly reliant on electricity for various infrastructure and services, providing a continuous power supply is crucial. In order to make the power grid more flexible and intelligent and to better withstand natural disasters, the concept of resilience has recently been applied [2,3]. Extreme events have the potential to cause significant power outages, making it crucial and urgent to enhance the resilience of the power system [4]. The average number of billion-dollar disaster events in the United States from 2020 to 2023 exceeds twice the average from 1980 to 2023, as shown in Figure 1. As of 8 August 2023, a total of 15 weather/climate disaster events had occurred that year, including 13 severe storm events, which had a significant economic impact on the affected areas [5]. Kemabonta et al. [6] argue that storms have compromised the integrity of the power system in Minnesota. Compared to typical outages or failures, natural disasters often result in more extensive damage, requiring a longer recovery time for the system. Despite the implementation of disaster preparedness plans and the strengthening of grid infrastructure, power outages have become increasingly severe in recent years, with the majority caused by extreme events.

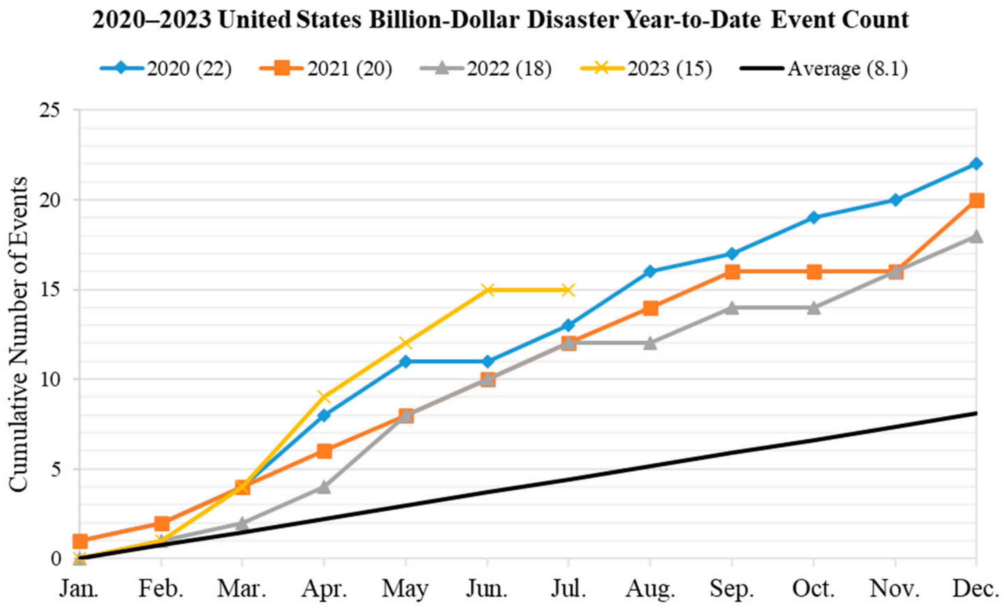

Figure 1. Disaster events in the U.S. exceeding one billion dollars from 1980 to 2023 [5].

Traditional power systems are generally designed based on reliability requirements, namely the "N-1" or "N-2" standard. Moreover, several reliability metrics such as SAIDI, SAIFI, and others have been widely used in different power systems. These metrics provide information on the duration or frequency of occurrences of power interruptions. However, extreme weather events have gradually increased; thus, these low-probability but high-impact extreme events should be of concern and urge the design of new metrics to evaluate power system resilience. A resilient system can help reduce the impacts of extreme events on it and recover the power system rapidly after these events. Therefore, the issue concerning the assessment and enhancement of power system resilience is crucial.

In recent years, the topic of power system resilience has emerged, and extensive research works have been conducted. In terms of resilience assessment and metrics, Yao et al. [7] categorized existing resilience assessment metrics into pre-event metrics, post-event metrics, and other commonly used metrics, and explained their characteristics and definitions. Huang et al. [8] discussed resilience assessment metrics from the perspectives of steady-state and transient operations. Umunnakwe et al. [9] proposed a classification scheme for quantitative power system resilience metrics. To enhance power system resilience, many works have proposed various methods; for instance, Mahzarnia et al. [2] discussed numerous methods, technologies, and future trends to improve power system resilience from the aspects of resilience-based planning, response, and restoration. Abdubannaev et al. [10] proposed a method to improve system resilience by connecting tie switches to recovery paths in a radial grid topology. Mohamed [11] explored various strategies for enhancing proactive resilience, including proactive strategies, machine learning, distributed energy resources, and renewable energy integration. In terms of the impacts of extreme events, Huang et al. [12] investigated the types of natural disasters that occurred in Taiwan and the factors causing power system outages or damages. Wang et al. [13] analyzed the impact of extreme events on the power system from the perspectives of generation, grid, and load. However, these articles provided less description of the meaning of resilience, which is due to the lack of a standard definition for resilience.

This paper reviewed the definitions of resilience by different organizations and summarized the main characteristics of power system resilience. After reviewing representative resilience curves and resilience metrics, it is observed that existing resilience metrics could not effectively reflect the actual system resilience. Thus, this paper developed a new framework and metrics to evaluate power system resilience, which can describe resilience characteristics accurately. Furthermore, this paper summarized various methods to enhance power systems. These methods can reduce electric failures and achieve rapid recovery during outages. Finally, this paper indicates potential challenges for power system resilience in the future.

This paper is organized as follows. Section 2 summarizes various quantitative indicators of the impacts caused by natural disasters, as well as the impacts and characteristics of extreme events on power systems. In Section 3, the concept of power system resilience is discussed, along with the main characteristics that a resilient system should possess, as well as some key features that distinguish resilience from reliability and robustness. In Section 4, the representative resilience curves and resilience metrics are reviewed, and a new framework and metrics for resilience assessment are presented. In Section 5, various measures and methods to enhance power system resilience are discussed. Finally, a summary of this article and the challenges for future research are presented in Section 6.

2. Impacts of Extreme Events on Power Systems

Natural disasters such as hurricanes, floods, earthquakes, snowstorms, and wildfires, as well as man-made threats such as physical attacks, human operator missteps, and cyberattacks, can cause significant damage to infrastructure, including permanent damage [14–17]. These events can lead to long-term power outages and the destruction of major equipment such as transmission and distribution lines, substations, and power plants, severely impacting the power system [18]. For instance, hurricanes, snowstorms, and wildfires can affect overhead transmission and distribution lines and towers. Earthquakes can impact both overhead and underground structures [19]. Floods may damage substations and power plants, leading to operational interruptions. Studies on the consequences of past power outages indicate that it is currently difficult to completely prevent power outages caused by natural disasters or man-made threats [10]. Therefore, resilience assessment is crucial to mitigate and respond to the impact of extreme events on power systems. Some resilience studies used fragility curves to assess the vulnerability of the system [20]. In [19], the annual occurrence probability of hurricanes was represented by a probability distribution function using a statistical approach. In [21], fragility functions were introduced to characterize the vulnerability of substations to high winds, representing the probability of damage based on terrain types and wind speeds. In [22], the failure probability of substations caused by floods was related to the flood depth, and the overall failure probability of the substation was obtained from the failure probability of each substation in a flood scenario. In [23], the failure function was characterized based on a logarithmic normal fragility curve, representing the probability of exceeding a damaged state under given earthquake parameters. In [24,25], the failure probability could be expressed as a function of weather intensity. When evaluating ice disasters, the weather intensity can be represented by ice thickness to obtain the failure probability. In [26], the rate of wildfire spread depends on wind speeds and the vegetation in the area. Thus, the rate can be calculated using a wind-dependent function. In [27], the variation of the conductor temperature was calculated using the non-steady heat balance equation when calculating the temperature of overhead lines. Table 1 presents the quantifications of the impact caused by natural disasters.

Table 1. Quantification of the impacts of natural disasters.

Events	Quantification	References
Hurricane	The annual probability of hurricanes can be expressed as follows. $P = \frac{exp(-\lambda)\times\lambda^h}{h!}$ where λ and h are the average number of hurricanes and number of hurricanes per year, respectively.	[19]
	The probability of damage for substations can be expressed as follows. $P = \Phi\left[\frac{\ln(\nu)-\mu}{\sigma}\right]$ where $\Phi[.]$ is the normal cumulative distribution function, ν is the wind speed, μ is the logarithmic mean, and σ is the standard deviation.	[21]
Flood	Failure probability of substation can be expressed as follows. $\pi_k = \sum \pi_{kj} \cdot \pi_{kj}^f$ where π_{kj} is the failure probability of substation k due to flood scenario j, and π_{kj}^f is the probability of flood scenario j at substation k.	[22]
Earthquake	The probability of damage can be expressed as follows. $P = \Phi\left[\frac{1}{\beta}\ln\left(\frac{S_d}{S_{d,s}}\right)\right]$ where $\Phi[.]$ is the standard cumulative normal distribution function, β is the parameter related to the earthquake, S_d is spectral displacement, and $S_{d,s}$ is the median value.	[23]
Ice	The failure probability of components can be expressed as ice thickness, as shown below. $R_{it} = \frac{H}{\rho_i \pi}\sqrt{(P\rho_\omega)^2 + (3.6VL)^2}$ where R_{it} is the ice thickness, H is the hours of freezing, ρ_i and ρ_ω are the density of ice and water, respectively. P is the precipitation rate, V is the wind speed, and L the liquid water content.	[24,25]
Wildfire	The rate of fire spread can be calculated as a wind-dependent function, as follows $\nu_f = \frac{k(1+\nu_w)}{\rho_b}$ where k is a factor, ν_w is the wind speed, and ρ_b is the fuel bulk density.	[26]
	The change in conductor temperature can be expressed as follows. $\Delta T = \frac{\Delta t}{mC_p}\left(q_l + q_s + q_f - q_c - q_r\right)$ where Δt is the duration of time intervals, mC_p is the total heat capacity of conductor, q_l is the resistive heat gain rate, q_s is the heat gain rate from sun, q_f is the heat gain rate from fire, q_c is the convection heat loss rate, and q_r is the radiated heat loss rate.	[27]

2.1. Hurricanes

Hurricanes may cause extreme wind speeds, rainstorms, and lightning. Extreme wind speeds can damage transmission lines, overhead transmission towers, or high-voltage substations. Rainstorms can result in the flooding of substations and cause serious short circuits. Lightning can also damage high-altitude towers or poles [12]. In October 2012, Hurricane Sandy caused severe damage to transmission and distribution systems across 21 states in the United States, with over 7000 transformers and 15,200 power poles being damaged and over 8 million customers experiencing power outages [28]. In September 2017, Hurricane Maria damaged numerous power infrastructures in Puerto Rico, resulting in power outages for 3.6 million residents [9]. In 2021, Hurricane Ida affected over 1.2 million load customers in Louisiana [29]. In 2022, Hurricane Ian struck Florida, resulting in $40 billion in property losses [30].

2.2. Heavy Precipitation and Floods

Heavy precipitation and floods can directly impact hydroelectric and thermal power stations. Heavy precipitation increases river flow, leading to higher water levels in reservoirs. Floods carry a large amount of sediment, causing the spillways of dams to become blocked. Low-lying areas where thermal power plants are located are also susceptible to direct flooding impacts [13,31]. In January 2013, severe flooding on the northern coast of Jakarta resulted in a 909 MW power plant being shut down for 12 days [32]. In the summer of 2010, Queensland, Australia, was affected by massive floods, resulting in severe damage to multiple infrastructure systems and approximately 150,000 users experiencing power outages [11]. In July 2021, Zhengzhou, China was hit by floods, causing multiple distribution lines to fail and leaving 1.2 million residents without electricity [33]. In May 2022, northeastern Bangladesh was affected by devastating floods, impacting more than 7 million people [34].

2.3. Earthquakes

Earthquakes are the underlying cause of landslides, soil liquefaction, ground subsidence, and lateral spreading, resulting in direct damage to infrastructure. Each of these threats has the potential to take power plants offline for months. Additionally, tsunamis are often triggered by submarine earthquakes and can destroy electrical system facilities when they propagate onto land [35–37]. In March 2011, the Great East Japan Earthquake and the ensuing tsunami caused immense destruction, resulting in 8.5 million customers experiencing power outages [38]. In February 2010, an earthquake with a magnitude of 8.8 MW and a subsequent tsunami struck south-central Chile, causing power outages for 4.5 million users [39]. In February 2023, a 7.8 magnitude earthquake struck southeast Turkey, causing significant damage to multiple infrastructure facilities. This imbalance in power generation led to voltage drops and spread throughout the interconnected transmission network, resulting in a severe power outage [40].

2.4. Snowstorms

Snowstorms and ice events have severe impacts on the power grid, especially on overhead transmission lines and conductors. Apart from the possibility of towers and conductors being damaged due to icing, these events can also result in icing flashovers and sleet jumping. Power outages caused by snowstorms can thus lead to long-term service disruptions and significant economic losses [41,42]. In 2020, a snowstorm hit the coastal areas of the Costa Brava in Spain, causing unexpected additional icing loads on transmission towers and resulting in damages to the power grid [13]. In February 2021, a heavy snowstorm caused power outages during a peak-demand period in Texas, affecting over 4.5 million customers and resulting in an estimated $130 billion in economic losses [43].

2.5. Wildfires

Wildfires can potentially impact any exposed components of the power grid. Transmission and distribution lines, transmission poles, and line conductors can be damaged due to fires. This can result in insulation breakdown and subsequent flashovers between the conductors, reduced safety clearance of the line, and loss of tensile strength in conductors, among other impacts [44–46]. Additionally, aerosols produced by the burning of fires can have significant effects on photovoltaic power generation [47]. In Bastrop County, Texas, two wildfires in 2011 caused by trees coming into contact with nearby power lines resulted in four fatalities and over $300 million in losses [48]. In 2018, a transmission line operated by the Pacific Gas and Electric Company in California sparked a wildfire, causing approximately $13.5 billion in property damage [45]. During 2020, over 4 million acres of land in California were burned by wildfires, affecting 466,000 electric customers [49].

2.6. Man-Made Threats

Incidents of power outages caused by man-made threats such as physical attacks, human operator missteps, and cyberattacks are on the rise. The power infrastructure is vulnerable to deliberate physical attacks. Power systems experience blackouts due to human operator missteps that disrupt normal operations [12,15]. Cyberattacks exploit vulnerabilities in the information domain to interfere with the proper functioning of monitoring systems or communication networks, and the potential impacts are significant, including data theft, electricity theft, denial of service, disruption of normal power system operations, and even equipment destruction [16,17]. On 23 December 2015, Ukraine suffered a severe cyberattack, resulting in approximately 225,000 customers losing power in various areas [50]. On 26 January 2015, Pakistan faced electricity supply issues affecting nearly

140 million people due to technical failures at power plants [51]. In 2019, a hydropower station and its control center in Venezuela were subjected to cyberattacks, resulting in a severe blackout affecting 18 states [52].

2.7. Characteristics of Extreme Event Impacts on Power Systems

These rare events have a catastrophic impact on the power system, resulting not only in significant performance degradation but also affecting other related infrastructure, greatly increasing the difficulty of system recovery. Resilient power systems are more capable of withstanding interruptions associated with extreme weather, natural disasters, man-made events, and combinations of these events compared to traditional systems. Such power system interruptions exhibit the following characteristics [10,53,54]:

- The prediction of the disaster and its progression are uncertain.
- Power system components and other critical infrastructure are severely damaged.
- Spatial and temporal impacts are associated with the power system performance.
- The process of repair and recovery is difficult, resulting in significant power outages.

The impacts of extreme events on the power grid differ from those caused by more commonplace failures and are related to their own peculiar characteristics. For example, floods primarily disrupt the equipment of substations and distribution stations rather than the distribution network. Restoring stations submerged due to floods also requires more time. This indicates that power systems designed for typical power outages will face more challenges in recovering from power outages caused by natural disasters [55]. Additionally, the various types of damage caused by extreme events severely affect the reliability of the system, and mitigating these damages requires adopting different, and sometimes conflicting, measures. When the infrastructure is designed to withstand one type of disruption, it becomes more vulnerable when faced with another type. Extreme robustness in fact leads to system brittleness, resulting in vulnerability to cascading events. Resilience also depends to a large extent on the type of damage, as improving resilience to one type of damage may reduce resilience to other types [17,56].

3. Understanding Power System Resilience

3.1. Definition of Resilience

With the occurrence of extreme events becoming more frequent, there has been an increase in large-scale power system disruptions, greatly impacting the integrity of the grid. In addition to possessing robustness and reliability, it is crucial for a power system to have resilience in order to minimize the effects of these extreme events [56]. The term "resilience" derives from the Latin word "resiliō", which literally means the ability of an object to return to its original state after being subjected to pressure [57]. In 1973, Holling introduced the concept of resilience in ecosystems, stating that it determines the persistence of relationships within a system and the ability of that system to absorb variables and still function properly [58]. To date, resilience still does not have a standardized definition. The concept is still evolving, expanding, and being applied to various fields. The definitions of resilience by different organizations or associations are as follows:

- United Kingdom Energy Research Center (UKERC) [59]: Resilience is the ability of an energy system to continue delivering affordable energy services to consumers even in the face of disruptions. When the external environment undergoes changes, a resilient energy system can quickly recover from impacts and provide alternative means to meet energy service needs.
- U.S. Department of Energy [60]: Resilience refers to the ability of an energy facility to quickly recover from damage to any of its components or external systems it relies on. Resilience measures do not prevent damage, but rather enable the energy system to continue operating, even in the event of damage or power outages, and quickly restore normal operations.
- The National Infrastructure Advisory Council (NIAC) [61]: Infrastructure resilience is the ability to mitigate the magnitude and/or duration of disruptive events. The

effectiveness of a resilient infrastructure or enterprise depends on its capability to anticipate, absorb, adapt to, and/or quickly recover from potential disruptive events.

- The Presidential Policy Directive (PPD-21) [62]: Resilience involves the capability to prepare for and adapt to changing circumstances, as well as the capability to withstand and recover rapidly from disruptions. Resilience encompasses the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or events.
- American Society for Industrial Security (ASIS) [63]: Resilience refers to an organization's ability to adapt to complex and ever-changing environments. It is the capability of an organization to resist the impact of events or to recover to an acceptable level within an acceptable timeframe after being affected by such events. Resilience is the ability of a system to maintain its functionality and structure in the face of internal and external changes, and gracefully degrade if necessary.
- The United Nations-International Strategy for Disaster Reduction (UN-ISDR) [64]: Resilience refers to the ability of a system, community, or society that may potentially face hazards to adapt and achieve and maintain an acceptable level of functioning and structure by resisting or changing. This depends on the inherent ability of social systems to enhance their capability to learn from past disasters, thus better protecting the future and improving risk reduction measures.

In contrast, Roege et al. [65] simply define resilience as "the ability of systems to recover from adversity". In reality, the specific definition of resilience is not as important as its fundamental concepts. Nearly all definitions share three common concepts: 1. The system is able to absorb potential disruptions. 2. The system is capable of adapting to these disruptions. 3. The ability to recover rapidly from disruptions [6,66]. In other words, the system must possess the abilities of absorption, adaptation, and recovery. Vugrin et al. [67] indicated that the ability of absorption refers to the extent to which a system is able to automatically absorb the impacts of system perturbations and minimize the consequences as much as possible. The ability of adaptation is the extent to which a system can self-organize to restore system performance levels. The ability of recovery, as mentioned earlier, is the ability of a system to easily repair itself, with these repairs being considered dynamic.

However, the power grid may be affected by extreme events, and although the probability of such accidents is low, the risks involved are high. Therefore, in the field of power systems, a new concept of resilience has been introduced to reflect the survivability of the power system when facing extreme events. The definition of resilience may vary depending on the organization or association. Table 2 summarizes the characteristics mentioned in each definition. The characteristics of a resilient system include anticipation, resistance, withstanding, absorption, adaptation, recovery, and learning. A brief description of each characteristic is given below [9,14,64,67,68]:

- Anticipation: Before the disruptions, predicting the occurrence of events, assessing their potential harm, and taking preventive measures to reduce the impact on power grid performance.
- Resistance: During the disruptions and before it expands, resisting and mitigating the harm of the events to ensure the continuity of the operations.
- Withstanding: Ensuring the system maintains basic functionality at an acceptable level under disruptions.
- Absorption: The system is capable of absorbing the impacts of disruptive events, avoiding potential cascading effects, and minimizing the system damage.
- Adaptation: Adjusting, reorganizing, or modifying system configurations in an attempt to overcome a disruption.
- Recovery: After the disruption, a system repairs or restores the damage from a disruption.
- Learning: Learning from past events and improving measures to reduce risks, enhancing the flexibility of the system against future disruptions.

Table 2. The characteristics in the definition of resilience by various organizations.

Organizations	Characteristics
UKERC [59]	Withstanding, Absorption, Adaptation, Recovery
DOE [60]	Withstanding, Recovery
NIAC [61]	Anticipation, Resistance, Absorption, Adaptation, Recovery
PPD-21 [62]	Withstanding, Adaptation, Recovery
ASIS [63]	Resistance, Withstanding, Adaptation, Recovery
UN/ISDR [64]	Resistance, Withstanding, Adaptation, Recovery, Learning

It should be noted that the capability to withstand is related to long-term exposure to disruption, while the capacity for absorption is demonstrated only in the short term. The main characteristics that a strong and resilient power system should possess are shown in Table 3. To better understand the concept of resilience, Figure 2 presents a whole picture of power system resilience, illustrates the characteristics of a resilient system before and after extreme events and the measures for enhancing resilience, and indicates the flexibility and survivability that a resilient system should possess.

Table 3. The main characteristics of power system resilience.

Duration	Characteristics	Intention
Before the disruption	Anticipation	Predicting the occurrence of events Assess the potential damage from events Pre-event planning
During the disruption	Resistance Withstanding Absorption Adaptation	Minimize the impact of the disruption Maintain basic functionality Absorb the impacts of the disruption Modify or reorganize system configurations
After the disruption	Recovery Learning	Restore system elements quickly The system returns to a steady state Learn experiences from events The system establishes a learning mechanism

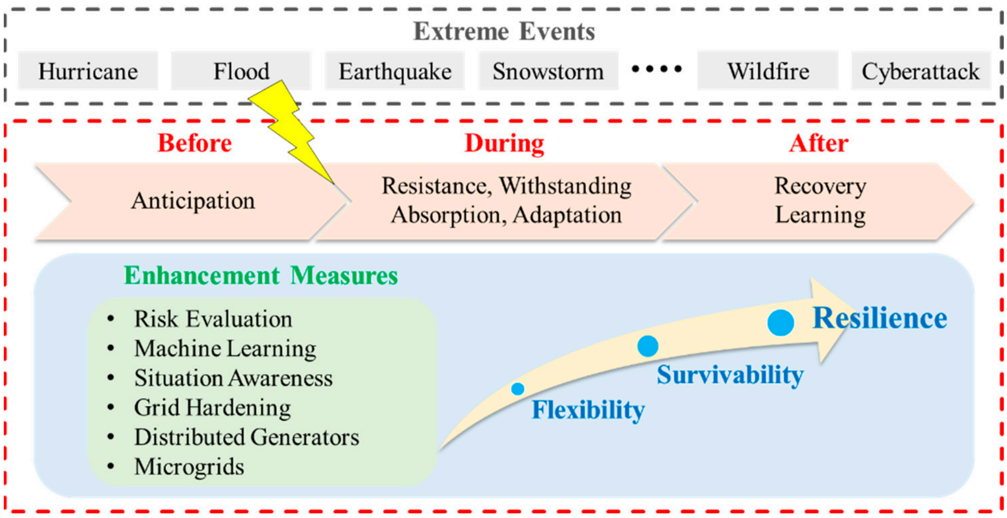

Figure 2. The conceptual construction of power system resilience.

3.2. Differentiate Resilience from Similar Concepts

The concepts of reliability and robustness are generally confused with resilience. Reliability refers to the ability of a power system to continuously deliver power to users with acceptable quality and the required quantity, even in the event of failures, thus maintaining the functionality of the grid [56]. For example, to prevent cascading failures, the power grid isolates certain circuits when a failure occurs, resulting in power outages for some customers. However, the power grid continues to operate reliably [6]. Compared to resilience, reliability is often seen as "keeping the lights on", while resilience is seen as "quick recovery when the lights go out" [61]. In other words, discussions on reliability focus on serving all loads, while discussions on resilience focus on the survivability of the system.

Robustness refers to the ability of a system to maintain its functionality in the presence of a set of disruptions [69]. Sometimes, systems are designed to be sufficiently robust to withstand anticipated shocks, while in other cases, alternative or redundant systems need to be designed so that the system can withstand interruptions in the event of accidents [61]. High levels of robustness can make a system brittle, leading to large-scale failures. For comparison, a grid with robustness, when subjected to impact, may break like an oak tree in a storm, while a resilient grid can bend like a reed in a storm. In other words, robustness means resistance to external changes, which is related to strength; whereas resilience refers to flexibility and survivability when faced with unexpected disruptions [56].

Typical power outages are usually quickly repaired or restored with a low impact on the power grid but a high probability of occurrence and are termed LIHP events. However, power outages caused by extreme events often result in significant damage to the power system, requiring more time for repairs and recovery. Although the probability of such events is low, their impact on the power grid is substantial, and they are termed HILP events. When comparing reliability, robustness, and resilience, reliability primarily focuses on handling LIHP events, while resilient systems possess the flexibility to withstand HILP events. Robustness, on the other hand, does not primarily focus on withstanding HILF events but can also be applied to LIHF events. Reliability is assessed for a system under unspecified threats, while robustness and resilience are associated with specific threats. Reliability often assumes that system components and their actions are independent of each other, while resilience places greater emphasis on the coupling between network components. Reliability relies on historical data for analysis, while robustness and resilience analysis do not depend on this. Reliability is based on the operation of the power system and is considered a static behavior. Robustness is a passive method based on system security, while resilience is an active method that responds in real time to changes in network topology and takes immediate action. It is considered a dynamic behavior. Reliability and robustness primarily consider expected failures during system design, while resilience focuses on the impact of events without considering their probability of occurrence. The differences between reliability, robustness, and resilience are compared in Table 4 [2,7,10,56].

Table 4. Comparison of the concepts of resilience, robustness, and reliability.

Criteria	Reliability	Robustness	Resilience
Objective disruptions	LIHP	LIHP, HILP	HILP
Specific threats	No	Yes	Yes
Network components	Independent	Independent	Interdependent
Reliance on historical data	Yes	No	No
Operation/Security method	Static	Passive	Dynamic/Active
Design for failures	Expected	Expected	Unexpected
Consider the probability of occurrence	Yes	Yes	No

4. Resilience Assessment and Metrics

4.1. Review of Resilience Curve

Rieger et al. [18,70] proposed the disturbance and impact resilience evaluation (DIRE) curve, which illustrates the relationship between time and performance levels for resilient and un-resilient systems, as shown in Figure 3. Additionally, several common terms have been presented, including robustness, agility, adaptive capacity, adaptive insufficiency, resiliency, and brittleness. In the DIRE curve, t_i represents the time when the disturbance starts; t_{Bi} indicates the duration during which the system performance is below the resilience threshold (i.e., minimum normal value); t_R is the time when the system reaches the minimum performance level; t_{Bf} signifies the time when the system performance returns to the resilience threshold; t_f represents the end time of the recovery process.

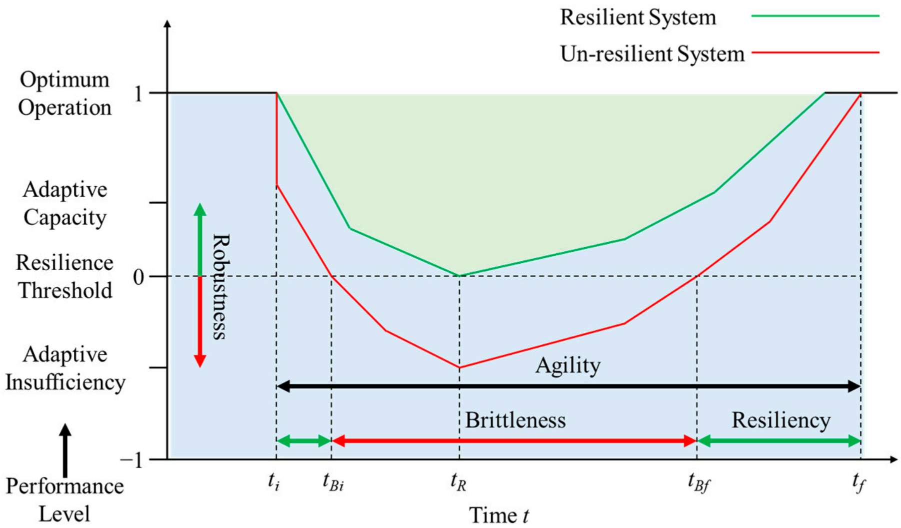

Figure 3. Disturbance and impact resilience evaluation (DIRE) curve [70].

Panteli et al. proposed the concept of a resilience trapezoid, illustrating the relationship between time and system states during and after disturbances, along with the available measures, as shown in Figure 4 [6,71]. Typical activities during each state are:

- Pre-disturbance resilient state: Evaluation of information about the disturbance and pre-arranging resources needed after the event.
- Phase I (disturbance progress): The capacity of absorption is demonstrated in this phase. Smart grid technologies and distributed energy systems play a role in providing operational flexibility to cope with the disturbance. The goal of this phase is to decrease the level of system performance degradation (i.e., R_o–R_{pd}).
- Phase II (post-disturbance degraded state): The ability to adapt is demonstrated in this phase. Evaluation of losses caused by the disturbance, formulation of recovery strategies, and initiation of recovery measures as soon as possible. The goal of this phase is to shorten its duration (i.e., t_r–t_{ee}).
- Phase III (restorative state): The ability to recover is demonstrated in this phase. In order to restore system performance and load, measures such as repairing damaged components, restarting units, and re-energizing lines are taken. The purpose of these measures is to restore the load within a short period of time (i.e., T–t_r).
- Post-restoration state: Analysis of impacts of disturbances on the system and subsequent improvements to the system to better handle similar events in the future.

Carrington et al. [72] decomposed the resilience curve $C(t)$ into outage and restore processes to track the accumulation and restoration of outages during the event, as shown in Figure 5. $O(t)$ and $R(t)$ represent the cumulative number of outages and restores, respectively. The total number of outages increases from zero to ten over time for $O(t)$ and $R(t)$. The cumulative number of outages at time t can be expressed as $O(t) - R(t)$. Therefore, the resilience curve $C(t)$ can be defined as the negative of the cumulative number of outages at time t, as shown in Equation (1).

$$C(t) = R(t) - O(t) \tag{1}$$

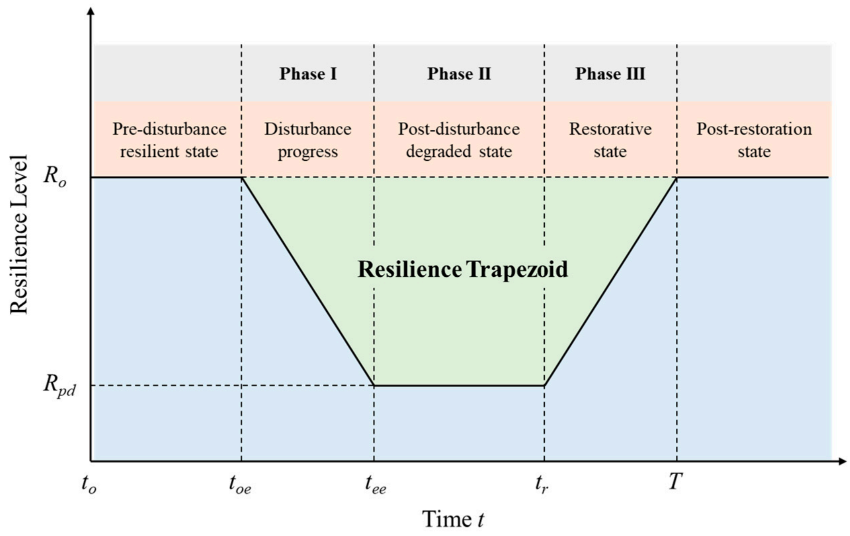

Figure 4. Conceptual resilience trapezoid curve [71].

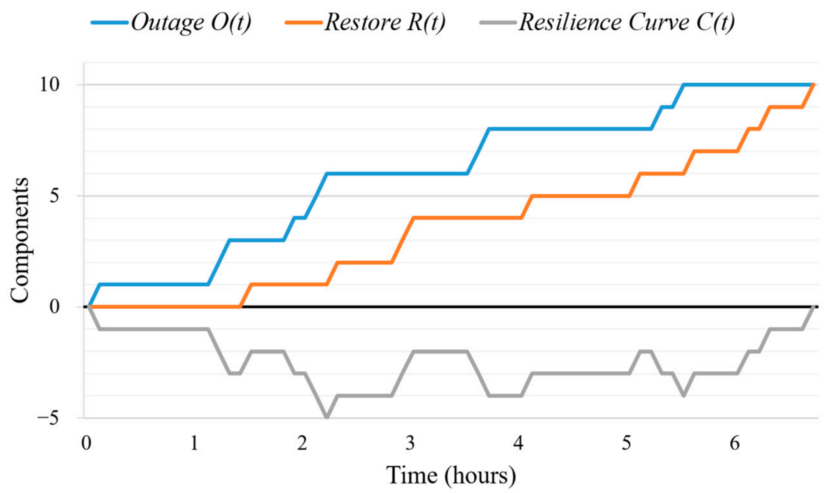

Figure 5. The resilience curve and its related outage and restore processes [72].

4.2. Relationship of Characteristics and States of Power System Resilience

The system state of resilient and traditional systems is described by the variation of system performance $Q_{(t)}$ over time t, as shown in Figure 6. The curve divides time into several sub-intervals to illustrate the system performance and corresponding characteristics at each time point, to capture the spatiotemporal correlations of the events on the power system [6,9–12,14,18].

- Pre-disruption (Anticipation): Before the occurrence of a disruptive event, the system performance remains in a normal state. By analyzing anticipation, the spatial and temporal impacts of events are identified. Certain response strategies are organized to prepare for disruptive events, in order to enhance the resilience of the system.
- Post-disruption (Resistance, Withstanding, Absorption, Adaptation, and Recovery): t_1 represents the start time of the disruptive event. In the case of a rapid decline in system performance, the system makes every effort to resist, withstand, and absorb the impacts caused by the event, in order to avoid potential cascading effects and ensure operational continuity. At this time, the robustness of the system comes into play, minimizing the impact of disruptive events on the power system and mitigating the degradation of system performance. At time t_2, the system performance reaches the lowest level Q_{min}. The adaptive measures begin to take effect, and the system operators need to develop recovery strategies to adjust and respond to the losses

caused by the disruptive event. At time t_3, the system enters the recovery state. The system takes immediate recovery measures to restore power and repair the damaged infrastructure, aiming to bring the system back to its normal state.

- Post-recovery (Learning): t_4 is the time when a resilient system recovers its performance to normal levels Q_0. Lessons are learned from past experience. The impact of the disruption on the system operations and performance is analyzed, and improvements are made based on them so as to better handle future events.

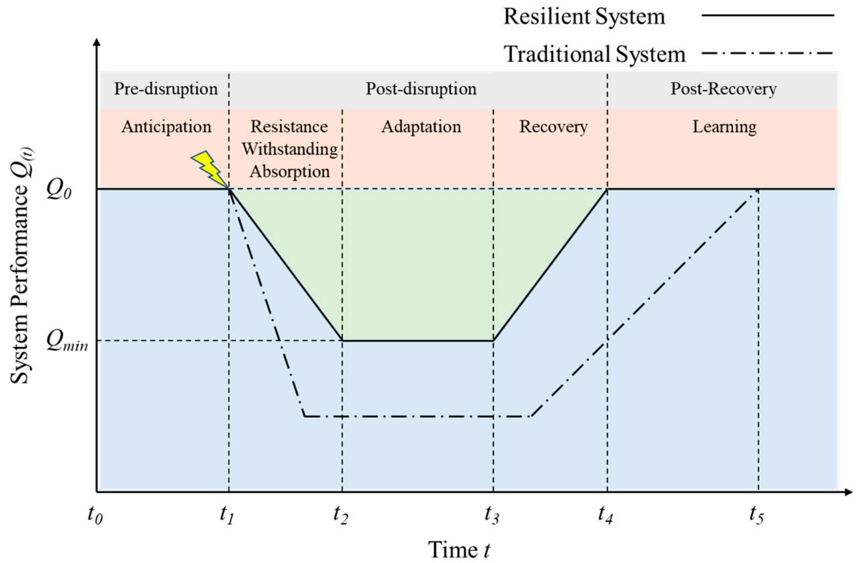

Figure 6. Resilience assessment curve with associated characteristics.

4.3. Metrics of Resilience Assessment

4.3.1. Pre-Event Evaluation

This paper suggests evaluating the resilience of a system from two standpoints: pre-event evaluation and post-event estimation. Before the event occurs, a general risk evaluation is conducted. D_{event} represents the extent of damage to the electrical power supply caused by the event. P_{event} represents the probability of the event occurring. $I_{RD\ event}$ is the outage risk index for a specific area associated with the event. $I_{Re\ event}$ is the resilience assessment metrics before the event, as shown in Equation (2). It is important to note that when calculating D_{event}, all possible emergency supply paths and potential remote-control methods should be taken into consideration to evaluate the number of customers without power [41]:

$$I_{Re\ event} = \frac{1}{I_{RD\ event}} = \frac{1}{P_{event} \cdot D_{event}} \tag{2}$$

Lakshita et al. [73] proposed a resilience risk assessment for the power grid based on Failure Mode and Effect Analysis (FMEA) to identify potential failures that may occur under different conditions. This FMEA-based risk assessment considers the probability of a failure occurring due to extreme weather events P, the severity of load losses caused by weather events S, and the detectability of the failure modes D to calculate the risk priority number (RPN) for different failure modes in the system. RPN is the matrix of $m \times n$, as shown in Equation (3).

$$RPN = [P \times S \times D]_{m \times n} \tag{3}$$

where m represents the number of failure modes in the power system caused by the extreme weather and n represents the number of zones in the selected region.

4.3.2. Post-Event Estimation

The variation in system performance is used to describe the load loss of resilient systems compared to traditional systems, as shown in Figure 6. The load loss of resilient systems is relatively smaller than that of traditional systems. The resilience metrics can be determined by a function of load loss, and reducing the area of load loss can improve the resilience of power systems. Therefore, the event-related system resilience can be quantified as a reciprocal of load loss, as expressed in Equation (4) [12,53].

$$Resilience = \frac{1}{Loss} \tag{4}$$

The load loss can be calculated by integrating the relative deviation over the duration of performance degradation (from time t_1 to time t_4), as shown in Equation (5).

$$Loss = \int_{t_1}^{t_4} \left[\frac{Q_0 - Q(t)}{Q(t)} \right] dt \tag{5}$$

Based on this calculation, reducing the performance degradation (Q_0–Q_{min}) or decreasing the duration of performance degradation implies a smaller area of load loss, indicating better system resilience. After a disruptive event occurs, the system performance begins to decline. By increasing the strength of the infrastructure, the damage caused by external factors can be reduced. In practice, we do not want the performance degradation time (from time t_1 to time t_2) to be too short. This indicates that the system has better reliability and robustness, enabling it to resist, withstand, and absorb the impacts caused by events. Moreover, it is crucial to have more time to take measures and mitigate the threats caused by events, thereby reducing the extent of the decline in system performance.

In contrast, when the system performance reaches its lowest level, implementing recovery strategies and measures can help the system adapt to the impact of the event and quickly restore it to a normal state. We would therefore wish to reduce the adaptation and recovery phase times (from time t_2 to time t_4), signifying a system that is more flexible and resilient. In other words, during the period when the system performance declines from a normal state to the lowest level, the rate of change in system performance can be relatively low. However, during the period when the system performance recovers from the lowest level to a normal state, the rate of change in system performance can be relatively high. For example, two systems with the same magnitude of load loss are depicted in Figure 7, but we consider the system in Figure 7b to have greater resilience potential compared to the system in Figure 7a. This is because the system in Figure 7b has better capabilities of absorption and recovery, allowing it to have more time to absorb the impact of events and recover quickly from disruptions. Therefore, we take into account both the rate of performance degradation and the rate of performance recovery (indicated by a red dashed lines) and introduce a coefficient γ to the original resilience metric equation, as follows:

$$\gamma = \left| \frac{t_2 - t_1}{t_4 - t_2} \right| \tag{6}$$

$$R' = \frac{\gamma}{Loss} \tag{7}$$

where γ is the resilience coefficient and R' is the optimized resilience assessment metric.

The article proposes a new framework and metrics for resilience assessment that is related to resilience characteristics, as shown in Table 3. It shows the main characteristics of power system resilience, which summarizes the required capabilities of a resilient power system before, during, and after extreme events. Additionally, this paper proposed resilience curves related to the main features, as shown in Figure 6. After a severe event occurs, the capability to supply power to load consumers begins to decline. By increasing the strength of the power system infrastructures, the potential damages can be reduced. Furthermore, appropriate recovery strategies and measures can help the system adapt to the impacts of the event and restore it rapidly to a normal state.

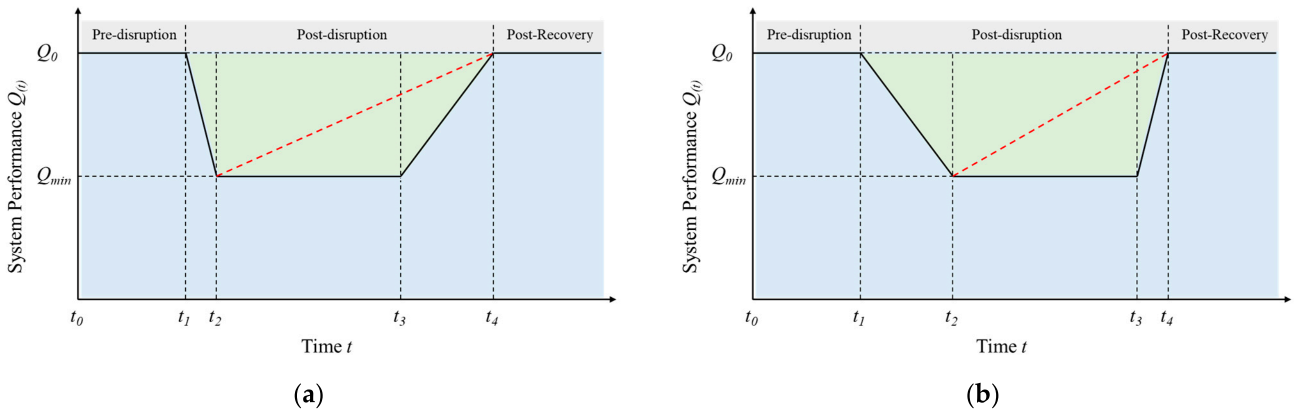

Figure 7. Comparison of two systems with the same load loss under different circumstances. (**a**) A system lacking capabilities of absorption and recovery. (**b**) A system with better capabilities of absorption and recovery.

Furthermore, it is suggested from this paper that the resilience of a power system can be evaluated from two perspectives: pre-event evaluation and post-event estimation (refer to Section 4.3). That is, resilience metrics can be designed before or after an event; the former evaluates potential risks before an event, but the latter represents a statistical result on load losses. Few papers have discussed resilience metrics in a complete way. In contrast, this paper provides a complete survey on resilience assessment and enhancement measures.

5. Enhancement Measures for Power System Resilience

Enhancing power system resilience means an improvement in the capabilities required at various operating stages of a power system. In other words, it can involve enhancing the system's anticipative capabilities before an event, as well as its capabilities to resist, withstand, absorb, adapt, and recover after an event. That is, this article discusses the measures to enhance power system resilience from two perspectives: before and after a severe event.

5.1. Measures before an Event

Some natural disasters such as hurricanes and tornadoes can be predicted [74]. Before the foreseeable occurrence of such disasters, conducting risk assessments on the system, determining appropriate topologies in advance, and formulating corresponding emergency response plans and disaster preparedness plans can help minimize losses and risks during system operations. Various machine learning approaches and advanced monitoring technologies can enhance the efficiency of the early decision-making process stage. For example, supervised or unsupervised learning approaches and Monte Carlo simulations can be applied to estimate the probability of system failures through statistical analysis. Particle swarm algorithms and mixed-integer linear algorithms can optimize response measures for power grid dispatch [11,12,75]. Advanced monitoring technologies such as situation awareness systems can facilitate the monitoring of constantly changing weather conditions, enabling the system to assess damages more efficiently and make timely decisions [71,76,77]. In addition, taking proactive control actions for distribution system reconfiguration and resource allocation before an event occurs can effectively enhance the resilience and economic efficiency of the power grid [78,79].

5.2. Measures after an Event

Traditional recovery strategies may not be able to cope with severe natural disasters because, after the disaster, the major equipment and interdependent infrastructure may be damaged [10,54]. Resilient systems, when dealing with disruptions, are designed to "bend" instead of "break", meaning they must possess flexibility and survivability. For instance, utilizing emergency power sources to provide temporary support or reconfiguring system configurations will enhance a system's flexibility [11]. To maximize the load capacity of the power system and minimize the duration of power outages, various hardening and operational measures are implemented to enhance the power system's resilience.

Based on the optimized resilience metrics, enhancing system resilience means slowing down the rate of system performance degradation, which involves improving the capabilities of resistance, withstanding, and absorption of the system. This can be realized through the implementation of hardening measures, such as grid hardening. On the other hand, improving the capabilities of adaptation and recovery of the system to reduce the duration of such a state can also enhance the system's resilience. This can be achieved through operational measures, such as distributed energy resources (DER), microgrids, and advanced smart grid technologies.

- Grid hardening

Increasing the strength of infrastructure enhances its durability and stability, making it more capable of withstanding the impacts of extreme events and reducing damage [60]. For example, overhead power lines are the most vulnerable components in a distribution system, as they are susceptible to damage from external factors such as weather, vegetation, animals, and human interference. Recommended measures include upgrading utility poles and towers with stronger materials can make them more robust and durable, and replacing overhead power lines or other transmission and distribution lines with underground cables can effectively reduce damage caused by external factors [57,80]. However, underground cables are challenging to locate in cases of faults and repair, and the cost of burying the entire electrical network underground is high. Therefore, a compromise solution is to identify the critical components in the system and prioritize their underground installation. It is crucial to consider the potential impact of extreme events and improve construction standards accordingly before constructing new distribution systems [81]. Additionally, relocating facilities to areas less prone to flooding or elevating substations can protect the electrical system from flood damage [15].

- Distributed energy resources

Even with the implementation of emergency response plans and disaster preparedness plans before and during extreme events, it is not possible to completely avoid power outages [13]. The availability of generator sets is crucial to ensure power supply to critical loads during extreme events [2]. Distributed energy resources such as distributed generators (DG), micro-turbines (MT), fuel cells (FC), mobile power sources (MPS), and renewable energy sources (RES) can generate, store, and control power locally, enabling more efficient response to emergencies and reducing the occurrence of power outages caused by events [10,57]. Additionally, energy storage can balance the supply and demand of power during disruptions. Integrating distributed energy resources and energy storage into the distribution network and rerouting resources can improve the availability of power generation. Therefore, accurately determining their location and size greatly contributes to enhancing power system resilience [82–84].

- Microgrids

A microgrid can be seen simply as a subset of the power grid, consisting of distributed loads, generation, storage, and protection devices that are synchronized with the main grid through a control system. The microgrid can operate in both grid-connected and island mode, allowing it to provide power during emergencies. For example, microgrids can be connected to the main grid to assist in restoring power to critical loads on distribution feeders. Alternatively, microgrids can be disconnected from the main grid and utilize DERs to provide power specifically for critical loads [57,81]. Furthermore, the coordinated operation of multiple microgrids can increase the flexibility of grid operations to help the system adapt to the impacts of extreme events [85]. Due to their ability to effectively supply power to loads, microgrids are an important measure to enhance the resilience of future power systems. They are also a significant focus of many research studies [86,87].

- Advanced smart grid technologies

One of the concepts of resilience is to restore more load as quickly as possible after a power outage, and this can be achieved through advanced smart grid technologies. For example, distribution automation (DA) enhances the reliability of the system through remote monitoring and automated switching operations, reducing the number of affected customers and the recovery duration for system performance [54,81]. Furthermore, network reconfiguration refers to the process of modifying the topology structure of the system. By utilizing remote-controlled tie switches and creating alternative paths with existing distribution lines, the power grid becomes less vulnerable to the impact of events [13]. This flexibility also facilitates the integration of microgrids with the distribution system.

6. Conclusions and Challenges for Future Research

Resilience in power systems has become increasingly important and has been widely used to reflect the systems' ability to respond to high-impact and low-probability events. This article reviews the concept of resilience in the power system and identifies the main characteristics that a resilient power system should possess, including anticipation, resistance, withstanding, absorption, adaptation, recovery, and learning. From the perspective of these main characteristics, a new framework for the resilience assessment of power systems is proposed in this study. Furthermore, considering the rate of performance degradation and recovery, we present an optimization of existing resilience metrics to make them more stringent and accurate, and strategies for enhancing power system resilience are introduced to minimize failures and achieve rapid recovery during the disruption. These strategies include hardening measures to mitigate performance degradation and operational measures to expedite performance recovery. This article can provide power system operators with the means to determine and develop appropriate metrics to assess power system resilience, facilitate the rapid recovery of power systems with corrective measures, and reduce the impacts of extreme events. Based on our study, the possible challenges for future research works include:

- Definition of resilience: In the context of power systems, there is no explicit standard definition of resilience. Resilience depends largely on the type of disaster, and research on classifying, defining, and evaluating power system resilience would benefit from having a standard definition of resilience.
- Energy infrastructure: The resistance of various types of energy infrastructure during natural disasters is largely unknown. Research focuses on the immediate and intermediate impacts of disasters on energy infrastructure, conducting detailed classification, and exploring the interdependence and flexibility among different types of energy infrastructure. This helps system operators make informed decisions and mitigate the cascading effects of such events.
- Renewable energy sources: Research indicates that when the penetration of renewable energy sources reaches a certain level, the power system is prone to instability. Investigating the involvement of renewable energy sources in the recovery process to enhance system resilience is a challenge and may involve studying energy storage technologies.
- Advanced smart grid technologies: Time is a critical factor in power system resilience, and researching advanced smart grid technologies can contribute to a more efficient recovery of loads.
- Developing innovative technologies and strategies: microgrids and energy storage systems can provide higher supply capacity and flexibility to enhance power system resilience, which improves survivability during outages. However, there are still many challenges to a resilient power system, including aspects of technologies, installed or operating costs, market designs, and so on. Developing relevant technologies or operational strategies based on microgrids or energy storage systems will be a fruitful area in the near future.

- Combination threats: Increasing system resilience to a certain type of threat may decrease resilience to other types of threat, as mentioned above. Therefore, research on resilience assessment and enhancement measures for multiple events is necessary.
- Anticipation: Studying the occurrence probability and intensity of natural disasters, as well as conducting geographical spatial analysis, is necessary. Preparedness in advance can effectively mitigate the impact of events.
- Economic factors: Hardening measures for infrastructure invoke higher costs. Research on developing strategies to enhance power system resilience, while considering economic factors, is important.
- Transient factors: At present, most research on power system resilience is conducted under stable conditions and assumes a sufficient duration and effective approaches to eliminate unstable factors. In reality, the transient stability in power systems should be taken into consideration.

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