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Review

A comprehensive review on power system resilience: Definition, assessment, and enhancement strategies

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ABSTRACT

The increasing frequency of extreme events in power systems has rendered traditional operation and control techniques ineffective during these events. This has led to the emergence of the concept of power system resilience as a key area of investigation. The literature presents a variety of definitions and metrics associated with this concept. However, misconceptions, misinterpretations, and confusion exist between resilience and other well-known concepts, including reliability and robustness. This paper provides a comprehensive review of the concept of resilience, emphasizing the need for new assessment metrics and techniques for evaluation, as well as enhancement strategies. The paper has drawn the research results and resilience works from a large number of studies to provide a holistic view of this subject. Significant efforts have been made to distinguish the concept of reliability from that of resilience. The paper has also provided a state-of-the-art review of current practices in the power and energy areas and shed light on potential directions of future studies.

1. Introduction

The escalating frequency of extreme events and the escalating complexity of power networks have dramatically shifted the risk landscape in power systems. These extreme events, driven by climate change and cybercrimes, have led to severe power outages, posing a significant challenge to the operation and control of power systems. The World Meteorological Organization reports a fivefold increase in extreme weather events like hurricanes, ice storms, and floods over the last five decades [1]. For instance, EWE in the United States increased by over 70 % from 2009 to 2019 compared to 2000–2009. Seven significant storms worldwide occurred in the last ten years [2]. Moreover, critical infrastructures, susceptible to human errors and cyber-attacks, are interconnected through computer networks, heightening cyber threats. Electrical power systems, a crucial infrastructure, have far-reaching consequences on agriculture, water, energy supplies, public healthcare, transportation, and telecommunication sectors. Extreme events can cause unprecedented consequences and extensive infrastructure damage, complicating recovery and extending power restoration times.

Conventional techniques and methods, such as reliability-centered design and analysis, can help assess system operation under frequent random hardware failures with specific probability distributions. However, their ability to analyze power system behavior under extreme events remains limited. Moreover, the rising expenses linked to enhancing reliability in complex systems require a closer evaluation of systems' performance, even during common events with known consequences. While many events are beyond human control, proper strategies can mitigate their negative impacts. Recognizing the inevitability of failures in any system, irrespective of its reliability and robustness levels, is a first step toward developing strategies to minimize adverse consequences. A fast recovery process to restore the affected system to its regular operation is crucial, necessitating changes and promising design philosophy in power system design, control, analysis, and implementation. *Resilience* refers to features such as reducing power blackouts and duration and providing essential services to more customers through unconventional means. The importance and necessity of rapid recovery strategies cannot be overstated, as they play a crucial role in minimizing the impact of extreme events on power systems. Although excellent progress has been made, consensus definitions and standard evaluation and design techniques for power system resilience are yet to be systematically established. These issues are becoming increasingly pressing as extreme events impacting power systems become more frequent and standards begin to mandate the integration of resilience into system design.

Numerous reviews in the literature explore this subject. Yet, a recurring trend in existing works is to present prior study findings

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without conducting thorough and systematic analyses of the underlying issues [3–10]. First, a clear and well-established distinction between resilience and established concepts like reliability is often lacking, hindering the development of standardized definitions and metrics for resilience and obscuring the rationale for introducing resilience as a distinct concept. Second, existing studies frequently fail to establish a logical connection between key resilience characteristics, their practical applications, and proposed definitions. Third, some fundamental gaps in existing resilience evaluation approaches have not been identified. For example, in [4], a case study clarifies resilience concepts using various metrics, including reliability-based and curve-based metrics, without evaluating their suitability and advantages under extreme conditions. In [5], the main gaps in resilience definition, metrics, and evaluation frameworks are addressed by referencing several published works. However, it still needs to outline future directions for overcoming these challenges in more detail. In [9], a review of energy system resilience, focusing on extreme events and cyberattacks, is presented. While the study explores the connections between energy resilience and related concepts, it equates resilience with energy security. Still, it is essential to recognize that these are distinct terms and cannot be used interchangeably. In [10], a summary of resilience metrics from previous studies is presented, yet it lacks a discussion of the gaps within these metrics and does not offer a comparative analysis. Hence, an opportunity exists to improve these works by placing greater emphasis on capturing resilience's inherent time-dependent nature and essential characteristics, defining clear boundaries and establishing the status of resilience in power systems.

This review aims to offer a fresh perspective on power system resilience by highlighting limitations in prior studies. It meticulously traces past research, revealing gaps, and covers all aspects of power system resilience, including definition, metrics, assessment frameworks, system modelling, and enhancement strategies. Various classification techniques for real-world scenarios are considered. Attempts have also been made to delineate the difference between resilience and some similar yet different concepts, such as reliability, to clarify apparent misconceptions. The remainder of the paper is organized as follows. First, Section 2 highlights the importance and main characteristics of resilience in power systems through a step-by-step discussion, including an explanation of extreme events and an analytical comparison between resilience and reliability. Next, the various resilience assessment frameworks, metrics, and evaluation techniques are analyzed in Section 3. Subsequently, the enhancement strategies, including long-term and short-term, are reviewed in Section 4. Finally, existing gaps are identified, and potential directions for future investigation are presented as the conclusion in Section 5.

2. Resilience in power systems

2.1. Extreme events: A new challenge to the operation and control of power systems

What are extreme events? In power system literature, several terms have been used interchangeably to refer to extreme events. They are called high-impact rare events [11], severe events [12], high-impact low-probability events [3,13–18], and high-consequence low-probability events [19–21]. In [11], events were categorized based on their probability distribution function (PDF) into known, unknown, and unknowable events. Known events have definable odds and outcomes through PDFs, while unknowable events pose challenges in their characterization using PDFs. Unknown events, in contrast, only allow for the definition of outcomes through PDFs. Extreme events inherently possess unpredictability and uncertainty when establishing the probability of occurrence and consequences.

In contrast, the frequency of extreme events can be defined by statistical and historical data [22]; hence, it is more appropriate to categorize events as High Impact and Low Frequency (HILF) and Low Impact and High Frequency (LIHF) events [23]. The frequency and intensity of extreme events have notably increased due to climate changes and the extensive integration of computer and network systems into infrastructure. This impact spans various geographic areas, encompassing extreme weather events and incidents caused by human activities, demanding heightened attention [24].

Why are extreme events important for consideration? Accurate extreme event prediction is often challenging, making these events a primary power system concern. Between 2018 and 2022, extreme events were responsible for over 40 % of power outages in the United States and have similarly caused several major outages globally [25]. Technical errors caused outages for over 50 million in the US and Canada in 2003. Japan's 2011 earthquake and tsunami and China's 2008 windstorm affected millions, causing billions in damages [26]. The 2021 Texas power crisis left over 4.5 million customers without electricity. In 2015, a cyber-attack in Ukraine affected 200,000 people. These events can cause large-scale blackouts, prompting a more risk-averse approach from policymakers and stakeholders due to growing electricity dependency [27]. While many of these events are uncontrollable, anticipating and preparing can reduce their impact and expedite recovery. To achieve this, fundamental changes in power system design, control, analysis, and implementation are necessary [28].

2.2. From reliability to Resilience: Why a fresh concept is needed

The justification for developing a forward-looking design and analysis concept is grounded in identifying the gaps and areas for improvement within existing related concepts. To this end, a thorough examination of well-established terms such as reliability and robustness, which have been widely used for many years, is essential. This section briefly examines the overlooked aspects of these concepts regarding application and assessment metrics, explicitly focusing on reliability. Four zones are defined in Fig. 1 to support the examination process based on event types and time frames.

2.2.1. Application

The reliability of a power system can be defined as "the degree to which the performance of the elements in a bulk system results in electricity being delivered to customers within accepted standards and in the amount desired" [29]. This concept is generally used to identify system weaknesses, and improvements can be made through redundancy, diversity, and system hardening. Reliability has primarily focused on Low-Impact High-Frequency (LIHF) events, emphasizing the pre-disruption period (Zone I in Fig. 2), driven by the significance of event frequency and reliance on known probability density functions. These functions are typically defined based on power system network analysis, historical equipment failure data, or estimated values.

In the context of robustness, this concept is defined as a power

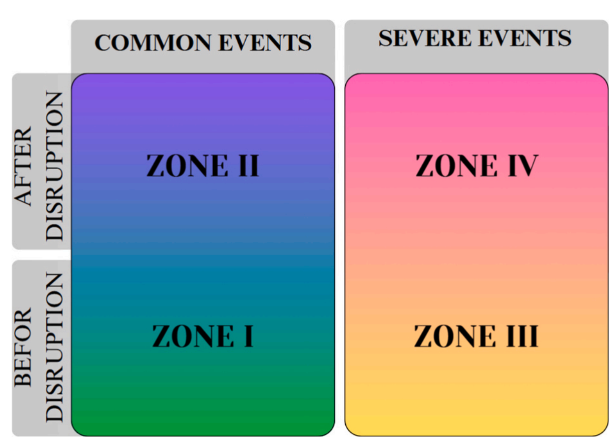

Fig. 1. Different types of events based on event progress.

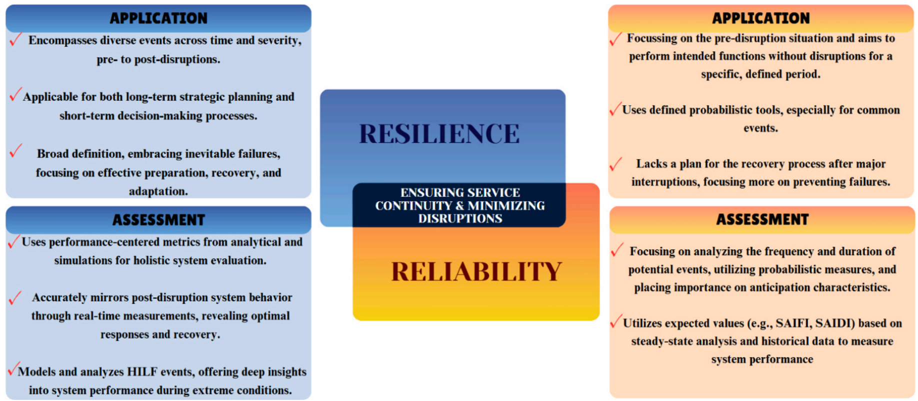

Fig. 2. Resilience vs. reliability.

system's inherent ability to maintain functionality in changing external conditions, even tolerating slight performance degradation [30]. Thus, robustness offers a broader scope than reliability and extends it by ensuring consistent performance under changing conditions and minor disturbances, specifically covering Zones I and II, as shown in Fig. 2. However, as the frequency of extreme events continues to rise, their classification as HILF events become less suitable, prompting the need for dedicated attention to Zones III and IV. These high-impact events come with inherent uncertainties regarding their consequences and probabilities. Thus, traditional design and analytical methods lose their effectiveness in this case, and common strategies to enhance reliability and robustness may encounter limitations, particularly when budgetary considerations come into play. For example, a study conducted in [27] investigates the role of reliability in analyzing system performance enhancements under the impact of extreme events. This analysis employs Expected Energy Not Supplied (EENS) as a reliability metric and Conditional Value at Risk (CVaR) as a metric for rare events, discussing options for improvement in a simplified test system with two busbars, a 500-MW generating unit and a 500-MW constant load. EENS calculates the mean power not supplied across all events, while CVaR focuses on extreme events. The paper defines events less likely to occur than specific values as extreme events. However, extreme events should be defined based on their severity and consequences. In the first scenario, transitioning from N-0 to N-1 by adding a redundant transmission line significantly improves EENS by 93 % but only boosts CVaR by 6 %. In another scenario, reducing repair times under severe conditions enhances EENS by 13 % and CVaR by 35 %. Although redundancy and N-1 or N-2 criteria notably enhance system reliability, they provide limited advantages against extreme events with more failures and outages than N-1 or N-2 criteria can handle.

2.2.2. Assessment

Reliability metrics quantify interruption duration and probability, considering customer impact, load centers affected, and economic implications [29]. For instance, Loss of Load Probability (LOLP) assesses power supply adequacy, especially during peak demand periods, aiding long-term decision-making. Additional reliability metrics measure power availability under specific conditions, such as EENS, which estimates potential power deficits due to system failures. Commonly used reliability metrics, like SAIFI (System Average Interruption Frequency Index), SAIDI (System Average Interruption Duration Index), and CAIDI (Customer Average Interruption Duration Index), are outlined in IEEE Standard 1366 [31]. These metrics guide infrastructure improvements aimed at enhancing reliability.

Regarding robustness, various metrics encompass shaded loads, frequency and voltage stability, and connectivity, among other factors. Some studies apply reliability and robustness metrics to analyze extreme events' impact on power systems. A method assessing system adequacy under diverse weather conditions has been proposed [32]. The effects of high winds on transmission and distribution networks have been investigated with the help of the reliability concept [33]. Reliability-based metrics were applied in [34], and the results demonstrated that extreme weather can significantly impair system performance and extend restoration times. Reliability metrics are used to assess resilience, with SAIDI for extreme event resilience evaluations [35]. Nonetheless, these metrics struggle to fully depict dynamic, time-dependent system conditions in all event phases, particularly during extreme events. These are primarily passive metrics focused on the pre-event phase, failure rates, and repair times, relying on known probability density functions. Thus, they cannot measure all aspects of Zones III and IV in Fig. 2.

In summary, reliability is a fundamental concept that forms the base. Robustness extends from reliability by ensuring consistent performance under varying conditions and minor disturbances. However, to address the gaps, the new concept is needed to take a step further by incorporating both aspects and extending the approach to effectively manage major disruptions and ensure prompt recovery [36,37]. Specifically, the new concept and its associated assessment metrics should address all four zones by quantifying the spatiotemporal dynamics of system performance under both typical and extreme events. This includes capturing system.

behavior before and after the event, assessing the magnitude of damage and event duration, and prioritizing the recovery process [16,38]. For clarity, essential distinctions and shared objectives of reliability and resilience are outlined in Fig. 2.

2.3. Resilience: The ability to mitigate adverse impacts and enable rapid recovery

The issues identified in Sections 2.1 and 2.2 call for a distinct power system design and analysis paradigm to deal with the undesirable effects of both extreme event and common events overlooked by the traditional safety concepts [39]. The resilience concept considers the occurrence of faults caused by any type of event, including severe or common, as inevitable in the system and tries to keep the efficiency of the system at the highest possible level after the failures and speed up the recovery process. To facilitate the above paradigm shift, the following techniques are in order:

- Developing methods and evaluation tools to cover extreme events and study their impacts accurately and
- Designing effective operation and control methods to minimize the adverse consequences of any event and to expedite the recovery process.

It's worth noting that challenges in the power industry are not unique; various other industries encounter similar issues. Resilience originated in psychology and ecology, balancing conflicting characteristics and goals with efficiency and strength [40]. Resilience is a system property characterization applicable to diverse fields, including energy, civil, computer science, and climatology [6]. Numerous general definitions of resilience revolve around a system's capacity to endure and recover rapidly from disruptions beyond its design basis, adapting for the future [41–44]. Infrastructural resilience, as outlined in [45], includes prediction, absorption, adaptation, and swift recovery from disturbances. Cyber network resilience, defined in [46], refers to a system's capability to perform intended functions continually in the face of cyber events, including cyber-attacks. The American Society of Mechanical Engineers (ASME) characterizes resilience as a system's ability to maintain uninterrupted performance by tolerating various disturbances [47]. Further definitions of resilience in multiple fields can also be found in [48–57].

In recent decades, the electrical power industry has increasingly embraced the concept of resilience. This term first appeared in a technical power systems journal in [63], marking the growing interest in the power system community. Numerous working groups were formed, with specialists from various organizations collaborating closely to establish a shared definition of resilience (Table 1). For example, the IEEE PES Task Force introduced resilience as a relatively new concept in the power system domain [18]. They aimed to propose a comprehensive definition to facilitate the practical application of resilience in power system design and operation. The CIGRE definition also comprehensively addresses the principles of resilience by incorporating anticipation, preparation, absorption, sustainment, rapid recovery, and adaptation as its main characteristics [60]. A similar definition is presented in [59], and this study further distinguishes between common blackouts and major disasters. Common blackouts result from temporary power interruptions due to load curtailments and unplanned contingencies, which can be rapidly resolved with reliable power systems and effective control procedures. Conversely, in disaster scenarios, blackouts occur under unprecedented conditions across vast areas and can persist for an extended duration [64]. Hence, a well-designed power system should be reliable for common blackouts and resilient for major disasters.

Table 1
Summary of main existing definitions of resilience in power systems.

Organization/Author	Definition	Reference
IEEE PES Task Force, 2023	"Power system resilience is the ability to limit the extent, system impact, and duration of degradation in order to sustain critical services following an extraordinary event. Key enablers for a resilient response include the capacity to anticipate, absorb, rapidly recover from, adapt to, and learn from such an event. Extraordinary events for the power system may be caused by natural threats, accidents, equipment failures, and deliberate physical or cyber-attacks."	[18]
UK Energy Research Centre (UKERC)	"The capacity of an energy system to tolerate disturbance and continue delivering affordable energy services to consumers. A resilient energy system can speedily recover from shocks and provide alternative means of satisfying energy service needs in the event of changed external circumstances."	[58]
M. Panteli and P. Mancarella	"The ability of a power system to recover quickly following a disaster or, more generally, the ability to anticipate extraordinary and high-impact, low-probability events, rapidly recovering from these disruptive events, and absorbing lessons for adapting its operation and structure for preventing or mitigating the impact of similar events in the future."	[59]
CIGRE WG C4.47	"The ability to limit the extent, severity, and duration of system degradation following an extreme event."	[60]
S. Espinoza et al.	"The ability of a power system to withstand the initial shock, rapidly recover from the disruptive event and apply adaptation measures for mitigating the impact of similar events in the future."	[61]
IEEE, technical report PESTR65	"The ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event."	[62]

2.4. Identified gaps and proposed new insights

Almost all the main definitions mentioned in Table 1 accurately capture the core aspects of resilience and emphasize that resilience is not an inherent attribute of a system but a specific ability and state, applicable only to systems capable of recovery. Resilience assesses a system's performance under specific threats, and a system may be resilient to one set of threats but vulnerable to others. However, resilience still lacks a consistently applied, one united universally accepted definition in industry, codes, and standards, due to their lack of battle-proven nature and the complexity of the problems it tries to cover. This complexity arises from the vast scope that the resilience concept intends to cover, which includes economic, social, technical, and policy.

While these definitions emphasize extreme events, it is also important to recognize that certain common events can cause substantial performance degradation if not properly addressed in the reliability design process. If resilience is to serve as a broader safety concept that complements and extends beyond traditional approaches, its scope may also benefit from encompassing such events by covering all four zones in Fig. 1. Placing greater emphasis on severity of consequence in addition to event type could provide a more inclusive and distinctive framing. In this context, resilience can be viewed as an overarching concept that draws on reliability and robustness to manage a broad spectrum of events, while also addressing both common and extreme situations that fall beyond the scope of traditional safety concepts. Second, the anticipation characteristic is largely based on foreseeable scenarios, which can conflict with the nature of many extreme events that are inherently unpredictable and have unknown consequences. Moreover, including stability within the sustainment characteristic could enrich the definition, given stability's central role in maintaining performance during disturbances and enabling effective recovery.

This study endeavours to address the gaps and to facilitate understanding resilience based on the framework consisting of three steps: 1- Defining its key characteristics, 2- Focusing on the temporal conceptual resilience curve, and 3- Integrating insights from past studies and addressing the identified gaps. As a preliminary step, the key characteristics of resilience are outlined in Table 2. These attributes are achieved through various system abilities, including reliability, robustness, and more. The second step involves an evaluation of temporal curves in resilience definitions, often referred to as resilience or performance curves [5,10,18,38,59,65,66]. One example of such curves is shown in Fig. 3 to describe the progression of the system characteristics. For comparison, Fig. 3 includes two system designs: one adhering to resilience design (System A) and another following a traditional approach (System B), showcasing diverse design philosophies. This figure illustrates the conceptual behaviour of both systems, clearly delineating the time boundaries of characteristics for System A. Additionally, it marks the effective areas for reliability and robustness in the behaviour of this system. It is important to note that, in system analysis, each system typically identifies a key parameter to serve as primary performance indicator. In power systems, this performance indicator may include supplied load, voltage, frequency, number of operational lines, or other relevant factors used to track the system's dynamic behavior.

Based on the timeframe shown in temporal curves in Fig. 3, the time

Table 2
The definition of the main characteristics of resilience.

Characteristic	Definition	Reference
Resistance	This characteristic entails a multi-faceted objective. First, it ensures reliability by consistently performing its intended function and resisting failures. Second, it emphasizes robustness, enabling the system to maintain functionality even when subjected to minor degradations. Lastly, in the event of severe degradation, the objective is to withstand the initial impact, allowing for a gradual decline in performance rather than a sudden, sharp drop. This controlled decline is vital when system reliability and robustness are compromised, preventing equipment damage and giving operators time for effective mitigation.	[4,18]
Absorption	The capacity of a system to minimize damages caused by events. This attribute defines the average performance deduction and assesses the system's capacity and strength to absorb the damages resulting from the event.	[6,7]
Preparation	This attribute reflects a system's capability to swiftly prepare prerequisites for recovery, encompassing detailed planning and formulating strategies designed to optimize emergency responses and accelerate recovery.	[6,54]
Recovery	Reflects the system's aptitude to bring back to normal performance promptly. This attribute consists of the operational restoration and infrastructural recovery.	[4,18]
Stability	The stability characteristic denotes the system's capability to sustain stability and robustness in the aftermath of an event. Successful recovery efforts hinge on the system's ability to maintain stability during restoration. High fluctuations in performance can severely damage the systems, making the recovery process considerably more challenging.	[36]
Adaptivity	This attribute involves utilizing learning and improvement mechanisms derived from past disruptions. It embodies the system's capacity to assimilate insights from historical data, past experiences, and simulations, thus enhancing its ability to respond in future scenarios.	[59]

scope of resilience can be categorized into three phases as follows:

- Pre-disruption phase: The pre-disruption phase encompasses the period preceding a significant performance reduction, one that surpasses the typical boundaries of reliability and robustness (before T2). Resilience strategies in this phase are mostly long-term, passive, and oriented based on the *resistance* characteristics. This means that the main objective of this phase involves enhancing the system's ability to resist events, striving for no failure or minimal degradation

within feasible financial and technical constraints. This objective is addressed through reliability and robustness.

- Event impact phase: This period begins the event occurrence and extends until the restoration part of the recovery period concludes [T2, T6]. The resilience strategies in this phase encompass active (real-time) actions, incorporating characteristics like *resistance*, *absorption*, *preparation*, *recovery*, and *stability*. Following the potential loss of reliability and robustness, the resistance characteristic strives to ensure smoother performance reductions, while absorption, in subsequent stages, aims to minimize the average performance reduction. These attributes are addressed through various strategies, such as predictive analytics and early warning systems. Preparation endeavors to swiftly manage the situation and prepare the requirements for initiating the recovery process, employing strategies like optimal network reconfiguration, efficient repair crew scheduling, and more. The recovery process focuses on temporarily restoring operations through power sharing, load prioritization, leveraging distributed energy resources, etc. Stability plays a crucial role in enhancing the system's robustness, keeping system fluctuations minimal, and preventing further performance reductions after the commencement of the recovery process.
- Post-disruption phase: This phase commences with the infrastructural recovery process and extends to the upgrading actions after the event based on *adaptivity* characteristics [T6, T7]. During this period, necessary modifications and system hardening are implemented based on insights gained from past events. The strategies in this phase are inherently passive and long-term, aiming to return to normal conditions and enhance the future response of the system.

For clarity, the detailed sequence of the temporal curves in Fig. 3 is clarified. Before an extreme event, both systems are designed to endure common shocks, ensuring reliability. When a severe event occurs at T1, both systems initially strive to maintain critical performance levels with minimum degradation due to robustness. However, by T2, the severity of the event begins to overwhelm the robustness, leading to a further decline in systems performance. During the interval [T2, T3], System A experiences a significant decrease in performance (less than System B) and endeavours to smoothen and minimize this reduction by leveraging resistance and absorption characteristics while preparing for the

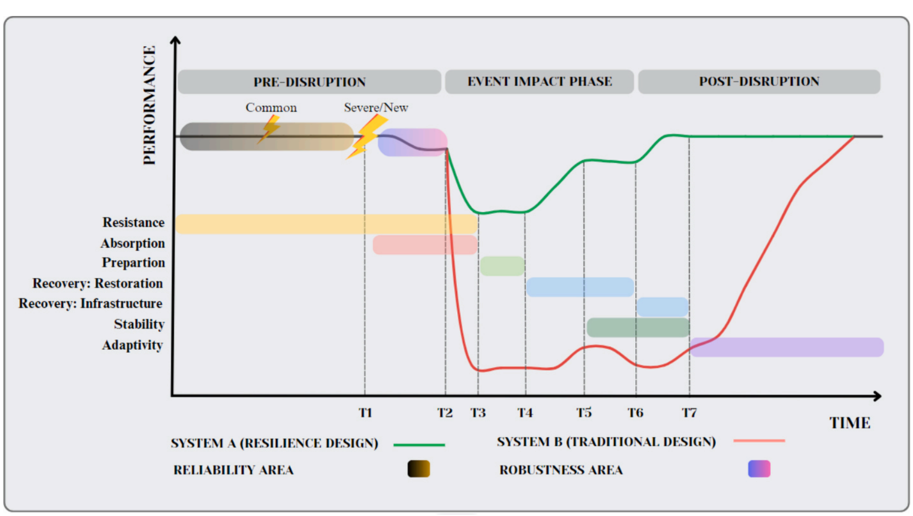

Fig. 3. Behaviors of systems with resilient and non-resilient designs in response to an external event.

recovery process in the [T3, T4]. At T4, System A begins recovery to restore performance temporarily as much as practically possible as an interim step. Full recovery might take a long time, depending on event intensity and infrastructure damage.

In contrast, system B starts the restoration by delay after T4. All efforts between [T2, T5] will be in vain if System A fails to sustain stability and prevent additional performance decline, similar to System B. Thus, a resilient system must retain essential features like voltage and frequency stability during recovery. Several studies define the time span from [T2, T6] as the *operational resilience period*. During this period, the system can adapt to a new state and restore its performance by implementing various short-term and real-time strategies. On the other hand, the period after T6, extending to adaptivity, constitutes the *infrastructural resilience period*, which focuses on long-term and passive actions. Through these curves, one can demonstrate how a resilience design maintains essential system properties riding through events. In summary, the performance of the system with traditional design deteriorates faster and more than that of resilient design after the event. Consequently, the restoration and recovery process might take longer for systems with conventional designs.

In the third step of the framework towards paving the way for establishing a standardized resilience definition, an analysis of prior studies was conducted, specifically focusing on the definitions in Table 1. Some definitions lacked clear distinctions between resilience and related concepts and fell short of encompassing all essential characteristics and specifying the applicable events and contexts for resilience [35,61,62,67,68]. Some definitions aimed to emphasize differences but employed vague terminology [57,58]. Authors in [43] extensively addressed the time-dependent aspect and included cost parameters but omitted the passive aspect of resilience (reliability) and did not cover all characteristics. Authors in [59] highlighted most attributes but confined resilience to high-impact, low-probability events. High-impact low-frequency, as discussed in Section 2.1, is a more appropriate term. Moreover, it is crucial to recognize that resilience is an ability designed to cover unprecedented and unpredictable events, where anticipating extraordinary events is often infeasible. In summary, it is suggested that a comprehensive definition of resilience in power systems should address the following key considerations:

- Encompassing a broad range of events: Resilience should be designed to address a spectrum of events, ranging from common and predictable events to extreme and unpredictable ones. It should incorporate passive and long-term strategies, as well as real-time and short-term, covering all periods from pre-disruption to post-disruption. Thus, resilience adopts a broader perspective compared to reliability and robustness.
- Incorporating essential characteristics: Resilience should contain the critical characteristics outlined in Table 2, including resistance, absorption, preparation, recovery, stability, and adaptivity. These attributes collectively define the system's ability to endure, recover, and adapt in the face of disruptions.
- Acknowledging unpredictability and emphasizing rapid recovery: Given the inherent unpredictability of unprecedented and severe events, resilience should acknowledge that anticipating all consequences is often impossible. Despite resisting events, resilience views failures as inevitable in a system. It focuses on a swift recovery process, utilizing all the characteristics to restore the system to normal operational states.

3. Resilience assessment

The primary aim of resilience assessment is to define the system's resilience level. In [11], resilience level is defined as the degree to which a system deviates from nominal performance during disruptive events, with higher resilience indicated by minimal deviation. Notably, resilience level can also be a system state rather than just an ability, as [43] indicates. For example, a distribution system relying on underground cables may be resilient to windstorms but vulnerable to earthquakes. As a quality measure of system features, resilience level can be qualitatively or quantitatively measurable [65,69–71]. Qualitative assessment describes resilience level in terms of the characteristics in Table 2. However, this type of assessment may require greater tangibility, typically serving as a starting point for more detailed quantitative analysis. For instance, three qualitative measures [65,71] have been proposed as guidance for decision-making in utilities, as depicted in Fig. 4. On the other hand, quantitative assessments are based on system performance measures, aiming to capture performance variations, the extent of system damage, and readiness for functional restoration. Analytical and simulation-based methods have been employed for quantitative resilience assessment [11]. Statistical methods have also been considered [65,71]. Simulation-based methods are more prevalent, given their capabilities in modelling disaster scenarios, calculating disastrous consequences, and simulating large-scale, complex systems. Resilience assessment methods have also been categorized into qualitative and quantitative approaches [69], with quantitative approaches further divided into semi-quantitative, deterministic, and probabilistic methods. Deterministic methods provide precise solutions for each input set, whereas probabilistic methods consider uncertainty analysis and semi-quantitative methods use both quantitative and qualitative indicators. However, the outcomes from these classifications are general. Regarding the power system resilience assessment, more systematic and transparent assessment methods and categorization are required. Considering all the issues mentioned above, three essential tools are needed for a comprehensive resilience analysis: (1) assessment framework, (2) evaluation metrics, and (3) evaluation techniques. These three tools and their effectiveness in electrical power systems will be examined in the following.

3.1. Resilience assessment framework

Frameworks serve as roadmaps for evaluating resilience levels by providing essential structural layers, functional components, and procedural guidelines for the implementation and assessment [7]. Several resilience assessment frameworks have been developed, and the assessment structures have been clarified. A resilience assessment framework of seven stages is proposed in [11], encompassing metric definition, threat characterization, scenario specification, proactive management, system degradation definition, recovery process, and resilience evaluation. Another resilience framework [72] centers on grid information, vulnerability analysis, and resilience operation. Grid information includes characteristics, topology, and operational constraints. Vulnerability analysis and operational resilience consider system responses, damage tolerance, and rapid recovery. In [65], as shown in Fig. 5, the framework first defines the characteristics of an extreme event, followed by resilience metrics. Metric selection hinges on criteria like restoration time and load-shedding priorities. The evaluation methodology is then chosen from simulation-based, probabilistic, or statistical analysis methods. Weaknesses in system resilience can be identified and rectified based on the evaluation results. A five-part approach to a generic resilience framework is proposed [37]. It defines extreme event characteristics, analyzes system component functionalities, evaluates power system performance through component simulation, assesses resilience by the developed metrics, and enhances resilience based on various extreme event scenarios.

However, these frameworks face certain limitations in serving as standard structures for resilience assessment. Determining metrics before characterizing threats carries the risk of missing critical points because metrics can depend on threat types [43]. Notably, threat characteristic stages in most frameworks apply to known events, and for unknowable events, proactive management might be able to facilitate recovery through specific procedures. Moreover, these frameworks were often impractical when applied to real-life situations due to unrealistic

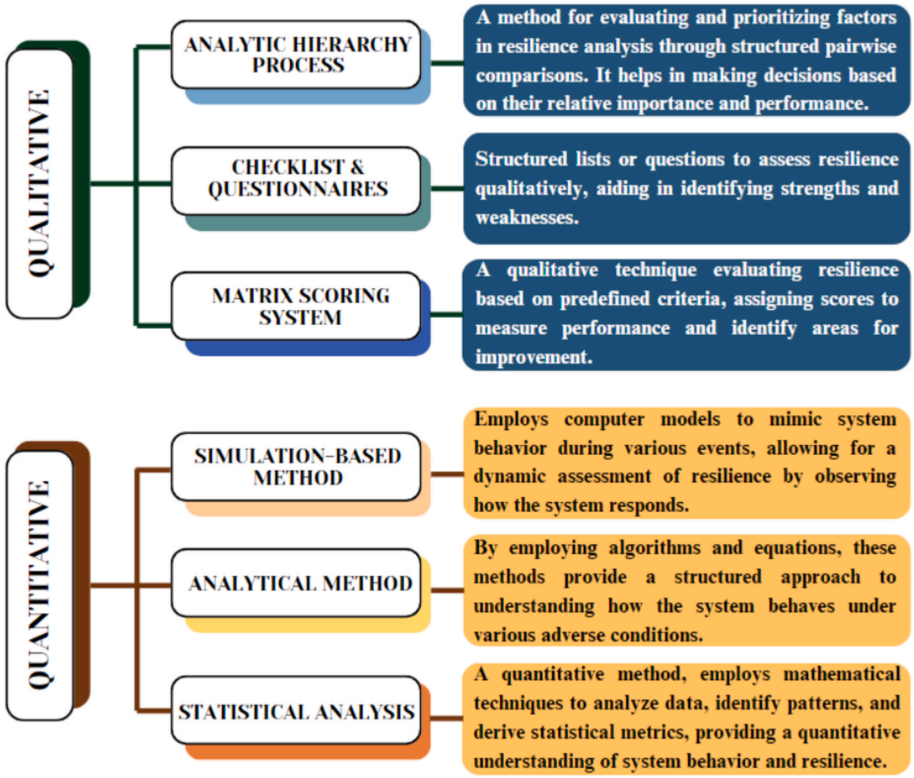

Fig. 4. Evaluation procedures for resilience in power systems [65,71].

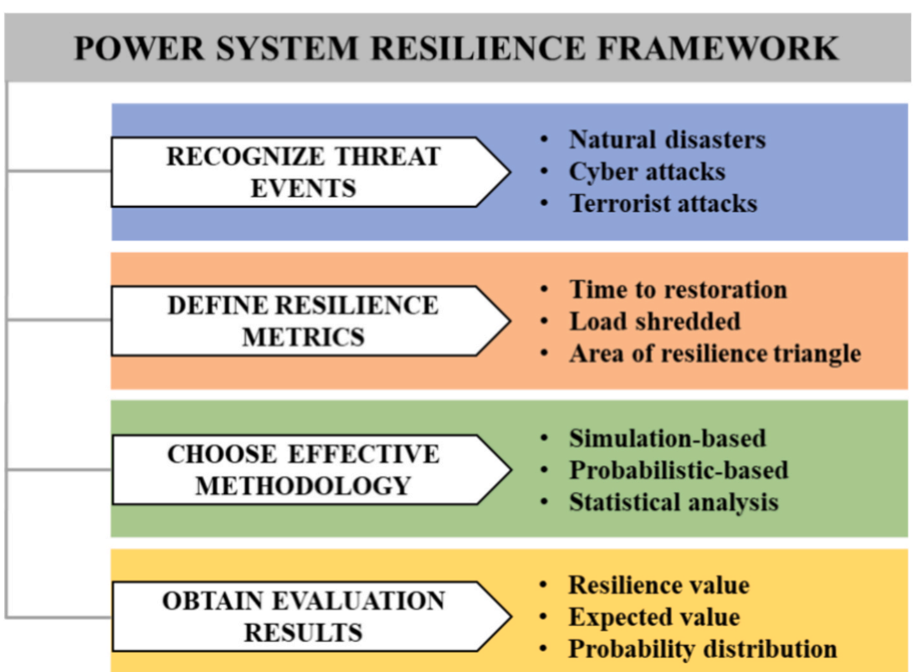

Fig. 5. A systematic design and analysis framework for resilience in power systems [65].

assumptions and a lack of consideration for the interdependencies among infrastructures [73]. Ultimately, they failed to comprehensively consider all resilience characteristics and often overlooked integrating the resilience definition within their frameworks as the context of qualitative assessments.

3.2. Resilience assessment metrics

The second key element in resilience assessment involves defining a set of measures linked to specific properties, often referred to as metrics, resilience indexes, or indicators. Resilience's multidimensional nature in different situations makes it challenging to quantify with a single measure, leading to varying considerations [43]. Nonetheless, these metrics serve to plan preventive actions to mitigate adverse event consequences and pinpoint strengths and weaknesses in a system. Several general features for resilience metrics have also been proposed [21,59,74]:

- HILF events and their consequences should be prioritized in the development of resilience metrics;
- Reflecting the reality of systems' uncertainties and interdependencies among infrastructures;
- Being spatiotemporal, consistent, and performance-based.

A list of general features for resilience metrics, including compliance with the resilience definition, reflecting the differences between resilient and non-resilient systems, and applicable to operation and planning states has been presented in [22]. However, these features remain largely subjective, highlighting the need for more detailed criteria. Power system resilience metrics can operate at the component or system levels, addressing three fundamental questions: (1) resilience in what part of the system? (2) resilience to what events? and (3) resilience under what conditions? The first question often pertains to the distribution network due to the multitude of potential faults at that level. The second question involves assessing not only rare but extreme events but also common events. For the third question, resilience results may differ under peak and light load conditions [11]. Some studies have used similar concepts like vulnerability to define resilience metrics [58]. However, vulnerability measures the sensitivity of a power system to external or internal disturbances without considering the recovery and restoration process. A conceptual method in [21,22,75] classifies resilience metrics into two major categories: performance-based and non-performance-based. Performance-based metrics are calculated by defining system performance and quantifying the degree of resilience. Non-performance-based metrics assess the impact of events on the economy, society, and the environment through site visits and questionnaires using "Yes" or "No" responses to identify critical attributes such as robustness and resourcefulness. While these classifications are general and applicable to various contexts, more specific categorization is needed, focusing on key resilience features. For instance, the severity of extreme events has prompted the emergence of resilience in power systems, necessitating detailed, technical classifications based on the types of extreme events.

A summary of well-known resilience metrics based on their attributes and limitations is presented in Table 3. These metrics can be classified into four categories: reliability-based metrics, trend-based metrics, optimization-based metrics, and performance-based metrics. A comprehensive and methodical evaluation of the gaps in current resilience metrics has been provided in [76]. Using well-constructed numerical examples, the study critically examines the four principal categories against the demands of real-world applications. It shows that existing metrics often neglect essential spatiotemporal system dynamics, interdependencies among system components, stability, and realistic recovery pathways, particularly under HILF events.

While some attempts have been made to modify reliability metrics for resilience assessment, as mentioned in Section 2.2, they are not inherently designed for extreme events, lack suitability for HILF events, and fail to capture time-varying system behavior. In contrast, resilience metrics should reflect dynamic and spatiotemporal system behavior, considering the system's situation both before and after events. Trend-based metrics offer a more accurate representation, defining resilience level reduction, speed of reduction, extensivity of the post-event state, and recovery process speed. These types of metrics have some obstacles in the way to becoming universally accepted metrics. Although novel work has been done in developing F, L, E, and P metrics, it remains unclear which parameters are most critical for accurately comparing resilience [16,38]. In fact, these metrics fail to deliver a unified and integrated value for quantifying resilience.

Additionally, it is essential to note that applying such metrics often requires simplifying the performance curve into basic geometric shapes, such as trapezoids, which can introduce calculation errors. Optimization-based metrics aim to find time-saving and cost-effective restoration processes by optimizing system operational and topological conditions. They often rely on probabilistic and simplifying assumptions made before events, making assessments impractical, especially during HILF events with unpredictable consequences.

Table 3
The summary of existing resilience metrics.

Metric	Category	Limitations	Reference
Load-shedding investment cost Restoration saving cost Algebraic connectivity Adaptability percentage	Optimization-based	• Rely on pre-event probabilistic models, making them unsuitable for HILF events with unknown consequences. • Depend on simplifying assumptions to ease computation for large systems, which can misrepresent actual recovery under real-world operational constraints.	[77]
Outage cost recovery Outage recovery capacity			[78]
F or ϕ (decline rate) L or Λ (damage magnitude) E(disturbance duration) P or Π (recovery rate)	Trend-based	• No single unified resilience value, limiting comparability. • Require performance-curve simplifications (e.g., trapezoids) that can cause calculation errors.	[16,38]
Loss of Load Frequency (LOLF) Loss of Load Expectation (LOLE), Energy Not Supplied (ENS)	Reliability-based	• Not designed for HILF events due to reliance on average expected values. • Fail to capture dynamic, time-varying behavior of the system and key resilience characteristics.	[79]
Number of failed lines Loss of Load Probability (LOLP) Expected Demand Not Supplied (EDNS) G (Grid Recovery Index)			[15,80]
System Average Interruption Duration (SAIDI) System Average Interruption Frequency (SAIFI) Mean Time Between Failure (MTBF) Customers' Average Interruption Duration (CAIDI)			[31,35,81,82]
1/ (Performance Loss)	Performance-based	• Limited in capturing real-time dynamics under adverse conditions.	[37]
$R = \frac{\int p(t)dt}{\int p_0 dt}$, $p(t)$ *is performance function* $R_{triangle} = \frac{\int (p_0 - p(t))dt}{\int p_0 dt}$		• Do not represent performance decline rates accurately. • May overlook instabilities during recovery.	[11]

Performance-based metrics, although useful for comparison among utilities, have limitations in capturing the dynamics of the system under adverse conditions, including the rate of performance degradation and the minimum performance level, particularly for critical loads such as hospitals and sensitive equipment.

3.3. Resilience evaluation techniques

Resilience evaluation techniques encompass problem formulation and mathematical modelling. Initially, events and potential failures must be identified and modelled. Subsequently, resilience levels are calculated using selected metrics based on the system's performance under the impact of the events and their associated outcomes. However, the unpredictability of severe and unprecedented events necessitates incorporating uncertainty analysis into the evaluation process. A comprehensive study, detailed in [5], addresses extreme event modeling, failures, and system dynamics. Additionally, [75] offers diverse failure modes and event modeling. To illustrate, we will explain each main step of the evaluation process and present existing study results.

3.3.1. Extreme event modeling

Extreme events can be modeled and classified based on their unique characteristics. According to [5,68,83–85], extreme events can be classified into physical attacks, cyber-attacks, and cyber-physical attacks. However, a more comprehensive categorization has been proposed in [11], encompassing extreme natural events, cascading technical failures, and both cyber and physical attacks. Extreme natural events can be modelled based on historical or prediction data. Historical data can be obtained by climate and geographical models and real measurements. Obtained data can be used to fit parametric models or incorporated into extreme value theory [86]. A wind field model has been used by [87] to determine the wind speed of typhoons and event duration. Satellite data were used to define the path of a hurricane [88]. HAZUS (Hazard US) has developed various models with the help of simulations, including a hurricane model and a flood model [89,90]. A model for wildfires has been proposed based on the spread rate, solar radiation, and heat flux [91]. In [92–94], a model for earthquake, flood, and ice disasters is presented.

Furthermore, space weather events with a space origin can be classified as extreme natural events. For example, a solar storm in 1989 led to half-cycle transformer saturation. Electromagnetic waves also can affect transmission lines and lead to extensive outages.

Technical cascading failures result from uncontrolled cascade failures, causing power system instability and exceeding N-1 or N-2 criteria. For example, the 2003 U.S.-Canadian blackout affected over 50 million customers, with external triggers leading to cascading failures stemming from technical errors and software bugs in the control room. Various modeling approaches can be applied, including topological, scenario-based, high-level statistical, and dynamic simulation models [11]. Topological models, such as maximum flow models, are straightforward for implementation and can handle complex situations. Scenario-based models, like the Probabilistic Risk Assessment tool and Markov chains, effectively account for human faults [95,96]. High-level statistical models enhance computational efficiency by omitting details; examples include the CASCADE algorithm and branching process models [97,98]. In contrast, dynamic simulation models offer accurate dynamic system behavior but often require longer run times. Notable models in this category include COSMIC (Cascading Outage Simulator with Multi-process Integration Capabilities), multi-time scale, and PRA models [99–104]. In a study outlined in [105], the authors analyzed power system resilience during a persistent hurricane leading to cascading failures. They identified three cascading phases: 1) line snapping, 2) line overloading due to redistribution, and 3) a combination of wind speed and exceeding current limits causing further line failures. These phases were effectively modeled. However, it's essential to note that the developed metric, based on grid damage concerning event intensity, is more suitable for vulnerability analysis than comprehensive resilience analysis. This metric is time-independent, whereas considering the dynamic system behavior post-event plays a crucial role in understanding resilience.

Cyberattacks and physical threats pose growing challenges in modern power systems, with smart systems integral to the infrastructure. The 2013 California substation attack, damaging 17 large transformers and causing major outages, is illustrative. Modeling these attacks involving dynamic nodes, PMUs, and local cyber controllers is achieved through complex network-based and hierarchical cyber-physical models [11]. Cyberattacks can be classified as communication disruptions, information distortion, device malfunctions, secrecy breaches, and application misconfigurations [5]. A comprehensive analysis in [8] categorized attacks into passive and active groups. Passive attacks relate to traditional external hazards, while active attacks encompass cyberattacks and human-intervention-induced faults. A key concern emphasized in the study is that modern information systems enhance power system resilience while increasing vulnerability to cyberattacks. Models for well-known malware, such as the Erebos trojan, are presented in [106,107]. In [108], the study examined the structure of cyber-physical power systems, focusing on the impact of a typhoon and modeling power line, tower, and information line failures. It also addressed the positional correlation between power and information lines (Optical Ground Wire) on the towers. To account for manual adjustments during information line failures, the study introduced a delay time. Although it claimed to use time–space metrics for resilience analysis, it primarily relied on reliability-based metrics and the area under the curve to define resilience.

3.3.2. Failure modeling

Modeling failures fall into two categories: system-level and component-level. In system-level modeling, statistical regression and tree-based mining are often used [109–111]. Component-level modelling includes a random outage model, scenario-based modelling, and fragility curves. The random outage model selects random element failures without real-time considerations [15,112], while scenario-based models investigate event occurrences in practical power systems [112–114]. Fragility curves have also been used to estimate component failure probabilities based on event characteristics [16,59,61,80,87,91,115,116]. A study in [117] discusses challenges in enhancing resilience against ice disasters, offering a resilience assessment based on fragility models for lines and towers, specifically related to ice thickness. The study explores technical challenges and interdependencies among power systems and connections with critical infrastructures. Challenges include accurate extreme weather event forecasting, transportation management, and efficient de-icing processes. Moreover, it's worth noting that some studies use simplified assumptions, potentially affecting accuracy. For instance, in [80], due to limited data, line failure probability was approximated using pole failure probabilities. In addition, uncertainty analysis is often overlooked in these models.

3.3.3. Evaluation methods

This section determines power system damages via various scenarios to calculate resilience levels. The evaluation process integrates the developed failure model for specific events with the power system model. Methods for this purpose include analytical and simulation-based approaches [11]. Analytical methods utilize the Optimum Power Flow (OPF) algorithm to define system degradation through sequential chains created using a Markov process [118,119], suitable for smaller networks. On the other hand, simulation-based methods are used in complex networks, showing event sequences in chronological order, with Sequential Monte Carlo Simulation (MCS) generating different outage scenarios [87]. Power outage modeling is also categorized into statistical and simulation-based models [120], aligned with quantitative assessment approaches. The accuracy of statistical models depends on data sufficiency and the choice of fitting models. However, extreme events can lead to new consequences that differ from statistical results [111], making simulation-based models a more specific and practical choice for evaluation.

Several evaluation modeling and formulations of previous studies are summarized in Table 4. These studies mainly considered windstorms and hurricanes as extreme events, fragility curves for failure modelling, and simulation and optimization-based methods for resilience evaluation. Other types of extreme events, particularly hybrid-attacks, and failure modelling, including deterministic methods and uncertainty analysis, have yet to be studied sufficiently.

4. Resilience enhancement strategies in power systems

The main application of resilience evaluation guides the development of effective enhancement strategies to elevate and strengthen system resilience. A wide range of resilience enhancement methods aim to reduce performance degradation and accelerate restoration by leveraging resilience characteristics before, during, and after disruptive events. The resilience enhancement methods can generally be divided into two main categories according to the nature of the resilience curve and characteristics including long-term planning/physical-based methods and short-term operational enhancement methods [5,6,11,38,65,126,128]. Table 5 presents a wide range of such methods, briefly explained and classified accordingly.

4.1. Long-term planning/physical-based methods

This category of enhancement methods typically involves physical strategies—such as facility elevation, vegetation management, redundancy, risk analysis, flexibility, and system hardening—aimed at ensuring compatibility with extreme events, drawing on prior operational experience.

Numerous studies place strong emphasis on system hardening and redundancy, which often entail higher costs and necessitate long-term planning. In [8], various physical resilience enhancement techniques are discussed including boosting the main infrastructures, retrofitting of substations, and redundant communication systems to address the cyber-physical dimensions of power systems, which represent a critical and emerging complexity in modern grids. Room Temperature Vulcanising (RTV) silicone rubber coatings on high-voltage insulators maintain long-term hydrophobicity, improving pollution performance and significantly reducing the risk of contamination-induced flashovers under severe environmental conditions [139]. Anti-torsional devices, mounted on shield wires, limit wet-snow sleeve accretion and the resulting torsional imbalances that can jeopardize conductor clearances or cause structural failures [140]. Preventive actions, such as predictive maintenance, represent another widely applied strategy that, through real-time monitoring, condition-based diagnostics, and data-driven scheduling, reduces the likelihood of unplanned failures and prevents equipment deterioration from escalating into dynamic instability events [134].

Although numerous studies have focused on enhancing resilience through physical long-term strategies, there remains a need for approaches that effectively address emerging challenges in modern power systems including the integration of distributed energy resources (DERs), large load interconnections such as data centers, and novel events with unknown consequences, while maintaining an optimal balance between effectiveness and cost-efficiency. A promising approach is the modular design strategies, in which regional power provision is organized into small, well-connected modules that emphasize diversity [170]. When a module fails, it can be swiftly isolated and replaced by other modules, which can enhance the flexibility of the system and recovery speed. Deploying microgrids and DERs, along with power-sharing techniques, are key examples of the modular design approach. Another interesting long-term physical strategy is the "bend rather than break." This strategy focuses on flexibility of the system in absorbing the initial shock of an identified event though risk analysis with minimal adverse consequences while also preparing for rapid

Table 4
System models used in previous studies.

System modeling	Event modeling	Failure modeling	Evaluation method	Metrics	Model parameters
The South Korean distribution system [6]	Typhoon	Real scenarios	Statistical-based	Affected customers	• Using real data from Bolaven and Sanba Typhoon. • Recovery time: 6 and 12 hr.
Two-line parallel redundant system [118]	Severe weather	Fragility curve	Analytical-based using Markov approach	Damaged lines	• Using IEEE Standard 346 for weather data categories. • MTTR: 7.5 hr.
IEEE 33-Bus & real Chinese distribution system [65]	N/A	Multiple random faults	Simulation-based by solving a MILP	Restored loads	N/A
IEEE 118-Bus [121]	Hurricane	Fragility curve		Restored loads	• Doubly Periodic Poisson models used for data collection.
Radial test system [122]				Optimal swtching	• Using historical storm data.
33 & 118-Bus [80]				Damaged lines	• Using historical data for hurricane category 3.
IEEE 118-Bus [123]				Frequency stability	• Historical Pacific Ocean hurricanes data. • Failure rate of HVDC lines: 0.03 per year. • Frequency stability time: ~60 s.
IEEE 33-Bus [124]				EENS	• Using historical typhoon path data at coastlines. • MTTR: 2 hr for lines.
IEEE 69-Bus [125]	Windstorms			Relaibility-based metrics	• Using mathematical model for storm data and repair process.
IEEE 14-Bus [3]				Energized lines	• Using historical wind profile. • Total recovery time: ~70 hr.
29-Bus test version of Great Britain [38]			Simulation-based by using MCS	FLEP	• Using wind-dependent failure probabilities. • MTTR: adaptive based on wind speed.
IEEE 6-Bus by considering DC power flow [126]				LOLF & LOLE	• Using regional wind profile. • MTTR: 50 hr for towers.
IEEE RTS 79 [127]	Hybrid-attacks	Random faults		Restored loads	• Using regional wind profile.

Table 5
The resilience enhancement methods.

Category	Strategy	Description	References
Planning/physical-based and long-term enhancement methods	Subsurface and elevating	Undergrounding power cables and elevating or shielding facilities, while relocating critical assets from high-risk to safer locations.	[19,129–133]
	Preventive maintenance	Using real-time monitoring, diagnostics, and data-driven scheduling, prevents some failures and avoids dynamic instability.	[134]
	Vegetation management	Tree trimming and clearance definition to prevent faults from fallen trees.	[11,116,135,136]
	Upgrade standards	Revise and strengthen equipment standards to prepare for extreme events.	[137,138]
	Physical system hardening	Using stronger materials and advanced technologies (e.g., anti-torsional devices, RTV coatings) to reduce failure rates under both normal and extreme conditions.	[80,124,135,139–141]
	Redundancy	Availability of spare parts and skilled crews is vital for rapid post-event restoration.	[114,142,143]
	Probabilistic Risk Analysis and flexibility	Risk analysis identifies high-risk events, while probabilistic analysis estimates their likelihood and sequence to guide effective resilience enhancement.	[59,68]
	Microgrids and DERs	Taking advantages of microgrid concept, DERs, and backup resources to supply localized loads during system disruptions when traditional systems fail.	[15,91,144–154]
Operational/smart-based and short-term enhancement methods	Network reconfiguration	Reconfiguring the network after faults to optimize system performance through disconnectors, redundant lines, protection devices, generation rescheduling, and backup generation facilities.	[15,88,155–159]
	Backup resources	Accessing backup emergency energy storage and mobile resources during extreme events supports restoration, supplying alternative power when the primary system is out of service.	[11,88,91]
	Load restoration	Implement fast and efficient programs to restore power to critical loads through skilled repair crews and spare parts managemnet.	[64,87,143,160–163]
	Advanced forecasting	Effective preparation plans, aided by accurate forecasting and weather monitoring, can alert operators and enable proactive measures to mitigate extreme event impacts.	[164–166]
	Advanced communication	Employing advanced and secure communication systems to access and comprehend vast amounts of data quickly, providing an effective way to manage severe events.	[108,167–169]
	Demand-response program	Effective demand-response management enables targeted and prioritized load curtailment.	[58]
	Advanced protection	Implement adaptive protection to minimize the impact of cascading failures.	[11,65]

recovery. This strategy has been used in [59] by combining system hardening and intelligent operation methods.

4.2. Short-term operational enhancement methods

These methods generally require real-time temporary corrective actions, especially during and after disruptive events, including network reconfiguration, deployment of distributed energy resources, temporary restoration programs, backup and emergency plans, demand-response management, and more. In [23], a stochastic-robust investment planning approach is introduced to enhance resilience using microgrid design in unscheduled islanding scenarios, helping prevent cascading disconnections of distributed energy resources. In line with the modular design strategy, the capability of network reconfiguration is critical. Real-time pricing metrics are employed to analyze resilience under extreme events [132], and a topology optimization method for resilience enhancement is proposed. This method can be implemented with the help of line-switching and bus-splitting facilities [114]. In [123], a two-stage stochastic approach, the frequency-constrained unit commitment (FCUC), was employed to bolster resilience during transmission line failures. This involved satisfying frequency security constraints and optimizing the scheduling of generators and flexible loads. In [155], a multi-stage approach focused on reconfiguring and coordinating the power system distribution and district heating system to enhance resilience. The study emphasized the potential for faults to propagate among units, highlighting the substantial resilience improvement achieved through reconfiguring network heating systems with valves and remote controls. However, the study solely considered curtailed load as the resilience metric, primarily addressing the passive aspect of resilience similar to reliability, without accounting for uncertainties related to random component faults.

Similar to the physical long-term resilience enhancement strategies, this category also requires fresh, innovative approaches capable of addressing evolving power system challenges. An emerging and promising method is the deployment of networked microgrids with dynamically adaptable boundaries. In [144], a comprehensive review explored networked microgrids' impact on resilience. This method comprises physically connected and functionally interoperable microgrids emphasizing dynamic boundaries for adaptable operations and boundary adjustments. The study highlighted specific implementation challenges for networked microgrids, including the need for essential infrastructure like advanced inverters with grid-forming and black-start capabilities, communication-independent decentralized control, smart protective relay coordination, and an enhanced coordination framework. However, this study lacked an in-depth examination of the challenges and drawbacks of this type of system. It also asserted a significant distinction between networked microgrids and other concepts, like multiple microgrids or nested microgrids, primarily based on dynamic boundaries, without robust references or reasoning.

5. Conclusions and potential issues for future considerations

The concept of resilience encompasses analysis tools, design strategies, and operational control schemes to enhance systems sustainability and its ability to cope with challenging conditions, mitigate adverse event consequences, and expedite recovery. Despite recent progress, achieving absolute resilience in power systems remains in the early stages. This paper aimed to identify gaps through a comprehensive review of power system resilience studies, paving the way for standardized definitions and assessment frameworks. Potential directions for future research are summarized below.

- The accelerating adoption of DERs, vehicle-to-grid (V2G) fleets, and large-scale flexible loads such as data centers and AI compute hubs presents both opportunities and challenges for grid resilience. While renewable integration can strengthen resilience, its inherent uncertainty complicates modeling, protection coordination, and operational control areas still underexplored. Furthermore, as emerging large loads, data centers can significantly influence system stability and resilience, yet systematic, resilience-focused studies remain scarce.
- Resilience is ultimately about readiness for the unknown. Although substantial research exists, relatively few studies focus on ensuring system survivability under unforeseen hazards, keeping performance

above the non-recoverable threshold even under deep uncertainty. Achieving this will require the development of adaptive operational strategies and self-healing control architectures capable of responding dynamically to evolving conditions in real time.

- While numerous assessment methodologies exist, the field still lacks a standardized, end-to-end design framework for embedding resilience into grid planning and operations, essentially, a practical roadmap for utilities and developers aiming to design or upgrade energy systems to meet defined resilience targets. Future research should prioritize scalable, repeatable design processes that integrate resilience objectives from the earliest stages of infrastructure planning, with particular attention to multi-energy systems and sector-coupled infrastructures where electricity, heat, communications, and energy security are increasingly interdependent.
- Despite growing regulatory interest, most existing frameworks remain descriptive and lack quantitative thresholds or standardized metrics for resilience performance. For example, FERC Order 1920 requires resilience analysis every three years for at least one severe event but provides no measurable targets for acceptable performance [171]. Addressing this gap will require the development of universally accepted, scenario-independent, and time-dependent metrics that capture resilience characteristics and can be integrated into regulatory compliance, long-term planning, and investment decisions.
- Many current resilience studies oversimplify nonlinear system dynamics, failure modeling, and optimization problems for tractability, potentially producing enhancement strategies that are unrealistic in real-world conditions. Future work should embrace advance modeling that accounts for practical operational constraints and, where possible, directly solves nonlinear formulations, despite the added computational burden, to produce more accurate and implementable solutions.

CRediT authorship contribution statement

M. Ghanbari: Writing – original draft, Visualization, Validation, Software, Methodology, Conceptualization. **J. Jiang:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Investigation.

Declaration of competing interest

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Data availability

Data will be made available on request.

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