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State-of-the-art review on power system resilience and assessment techniques

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Abstract: Modern societies these days are more dependent on electrical energy and they expect a continuous supply as per demand. In this regard, the complex power system is designed to supply electrical energy with a certain level of quality and continuity though it is still susceptible to vandalism, natural disasters, and extreme weather. The black sky event where the power grid goes down is more of a possibility nowadays than ever due to more frequent severe weather events. This in turn has increased the need to study resilience in the context of the power system. This study presents a comprehensive review of the literature on power system resilience from various perspectives. First, well-developed power system safety concepts are discussed and critically reviewed in view of large-scale power outages. Then, the various definitions and confounding features of resilience in the power system domain are presented. Subsequently, several frameworks, resilience curves, and quantitative metrics proposed in recent years for power system resilience are investigated, followed by a summary of hardening strategies. Next, a case study is presented to illustrate how the resilience of a 69-bus system is assessed against a hurricane. Finally, the study highlights challenges and proposes several future works to achieve a resilient power grid.

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1 Introduction

Critical infrastructures such as energy, health, banking, transportation, and telecommunication are usually interdependent to ensure efficient services offered. While it is good to have this interdependency, it also increases the vulnerability level of the complex system as a failure in one part might cause disruptions to the other parts. For this reason, governments and organisations are putting more effort in the planning and operation of their critical infrastructures. Among all, the power system could be considered as the most crucial infrastructure as a number of facilities such as emergency services, water and gas supply, banking and finance, and telecommunications are relying on a continuous, good supply of electric energy to operate properly. On the other hand, the electrical energy system is mostly reliant on lifelines for fuel supply and SCADA communication, as depicted in Fig. 1. An example of such interdependency was evidenced in the case that occurred in the southwest of USA in February 2011 when the pressure in gas pipelines dropped during extremely cold weather due to the high demand for heating. This in turn reduced the gas supply to the combined cycle power plants causing an interruption of electric supply to 4.4 million customers. The curtailment in the generation of electricity further affected the gas compression stations and worsened the situation [1]. Thus, it is evident that a continuous supply of electricity is needed for the proper functionality of community services.

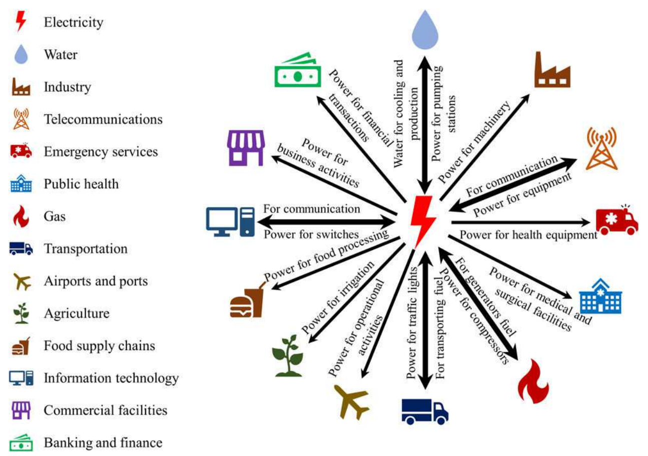

Fig. 1 *Visual representation of interdependency among electricity and other infrastructures of community*

However, maintaining a continuous power supply is a challenging task as the complex and interconnected nature of the electricity grid makes it vulnerable to external threats such as cyber-attack, vandalism, geomagnetic disturbance, coronal mass ejection, and natural disasters. Among these, severe weather is the leading cause of power outages as the majority of the grid exists above ground. Owing to the extreme weather, mega outages that happened in the last decade across the globe are listed in Table 1 [2–6].

The power grid of the USA is one of the massive grids in the world, supplying electricity to more than 144 million end-users. The grid, however, is believed to be unshielded against bad weather as the majority of the infrastructures are ageing [7]. During the period of 2014–2018, a total of 891 events of power outages have been reported in which severe weather events are the main cause, as shown in Fig. 2. Consequently, a rise in demand loss, as well as a significant increase in the number of affected customers, is evident as shown in Fig. 3 [8]. The inflation-adjusted cost of weather-related outages in the USA is estimated at $25 to $70 billion annually [9]. Recent weather events such as Hurricane Dorian, Typhoon Lingling, Typhoon Hagibis, and torrential monsoon rains in India have left millions of people without power. This alarming increase in calamitous events has demanded a smarter and stronger power grid that should be capable of predicting such events, mitigate their effects and bounce back to normal operation.

In this sense, a comprehensive study of power system resilience should serve as a basis to ensure a resilient power grid in the future against extreme events. This paper discusses power system safety concepts and describes multiple definitions, features, and frameworks of resilience in the context of the power system. Then, it thoroughly explains resilience curves, investigates several

Table 1 Million customer power outages across the globe because of severe weather

Country	Date	Approx. customers affected (Million)	Reason
Argentina and Uruguay	16 June 2019	40.00	Heavy rainfall
Philippines	15 July 2014	13.00	Typhoon Rammasun
Sri Lanka	3 March 2016	10.00	A severe thunderstorm
USA	29 October 2012	8.00	Superstorm Sandy
USA	27 August 2011	6.50	Hurricane Irene
USA	4 October 2016	3.50	Hurricane Mathew
China	10 August 2019	2.70	Typhoon Lekima
USA	9 October 2019	2.00	Forced power cut in California to prevent wildfires
South Australia	28 September 2016	1.70	A severe storm damaged several transmission towers
USA	20 September 2017	1.57	Hurricane Maria
United Kingdom	9 August 2019	1.10	Lightning strikes at a gas-fired station and offshore wind farm
Holland	27 March 2015	1.00	Bad weather conditions
Japan	9 September 2019	1.00	Typhoon Faxai

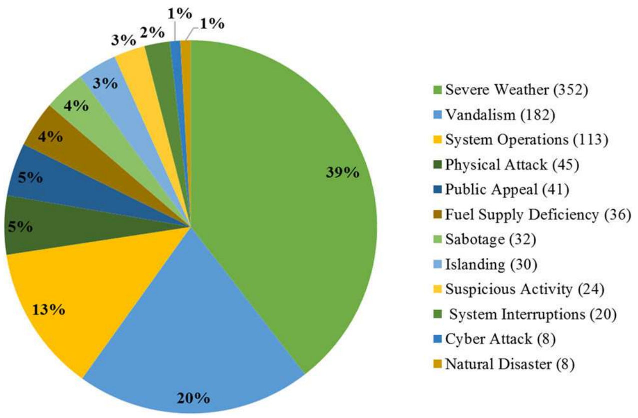

Fig. 2 *Different events of power outages reported in OE-417 (2014–2018)*

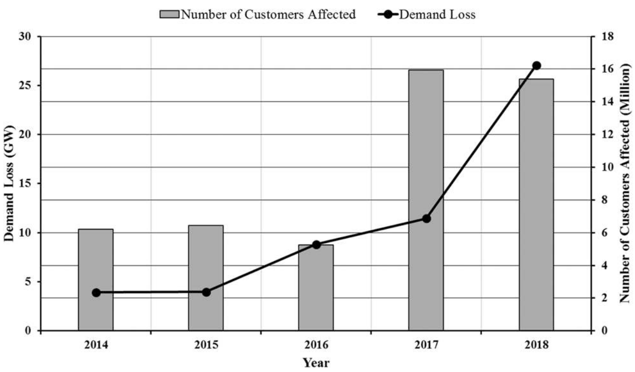

Fig. 3 *Number of affected customers and demand loss due to severe weather as reported in OE-417*

quantitative resilience metrics developed for the power system, and summarises different hardening strategies. Finally, it recognises challenges and proposes future works to achieve a resilient grid. Significant contributions of this paper are as follows:

- Comprehensive discussion on widely developed power system safety concepts that also highlights their limitations and shortcomings towards major disruptions.
- State-of-the-art review of resilience definitions, its confounding characteristics, frameworks of resilience, and resilience curves offered for a power system.
- In-depth analysis of a wide range of quantitative metrics proposed for power system resilience assessment in recent years.
- Resilience assessment of the 69-bus test system using an analytical metric and curve-based metric is included as a case study to comprehend the concept of power system resilience evaluation and visualise the effectiveness of smart grid technologies.

The rest of the paper is arranged as follows. Section 2 discusses power grid safety concepts: reliability; vulnerability and robustness; risk; and highlights their limitations in hazardous events. Section 3 covers multiple definitions and features of power system resilience offered by different organisations and researchers, explains frameworks and curves of resilience proposed in this area. It focuses on the in-depth analysis of several quantitative resilience metrics and summarises grid hardening measures. Section 4 presents a case study to better understand the concept of resilience assessment. Section 5 identifies challenges and future works in the subject matter. Section 6 concludes the whole review.

2 Power grid safety concepts

Reliability, vulnerability, robustness, and risk are highly developed concepts in the field of the power system. Those are relatively mature and widely accepted for planning, operations, and safety analysis of the power grid. Before moving towards power system resilience, these terms need to be clarified as often used in the literature and have their own strengths and weaknesses, which are summarised in this section.

2.1 Reliability

The overall ability of a system to perform a satisfactory operation is known as reliability. Power systems are designed to be reliable that is measured over a given time interval under certain conditions. Reliability evaluation techniques have been extensively developed utilising analytical and probabilistic methods. These techniques are, in general, grouped into two categories: analytical and simulation. Analytical techniques evaluate reliability indices from analytical models of the system using mathematical solutions, whereas simulation techniques estimate the indices by simulating random behaviour of the system. The former is more efficient, if a system is highly reliable and complex operating conditions are not taken into consideration; otherwise the latter is often preferable. The two fundamental aspects of power system reliability assessment are system security and system adequacy.

System security is related to the ability of a system to respond to transient disturbances arising from local and widespread disturbances and abrupt loss of transmission or generation facilities. It is associated with the situation that may lead to dynamic, transient, or voltage instability in a system. The UK has identified three elements of energy security, namely, physical security, price security, and geopolitical security. Physical security is to avoid involuntary physical interruptions of energy, price security is to prevent price spikes due to poor market operation, and geopolitical security is to maintain the maximum degree of freedom in foreign policy [10]. Due to the complexities of system modelling in the security domain, techniques to assess system security are limited. Probabilistic transient stability evaluation, methods for quantifying unit commitment and response risk are the very few to evaluate system security. The effect of insecurity can only be measured by assessing past system performance that must consider the effect of all faults and failures of the system irrespective of their cause. For this purpose, the data collected should be comprehensive and restrictive enough to avoid the evaluation of irrelevant statistics.

System adequacy, on the other hand, is associated with the static condition of the system that does not include dynamic and transient disturbances of the system. It is related to the existence of generation facilities to generate sufficient energy to meet the load demand and existence of associated transmission and distribution facilities to transport that energy to the load points [11]. According to the North American Electric Reliability Corporation (NERC), adequacy is 'The ability of the electricity system to supply the aggregate electrical demand and energy requirements of the end-use customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements.' [12]. Adequacy assessment is to be conducted separately in each of the three functional zones of a power system (generation, transmission, and distribution). Fortunately, many of the probabilistic techniques and indices, being used for reliability evaluation, fall in adequacy domain, and thus a wide range of adequacy indices is available for each of these three functional zones. Loss of energy expectation, loss of load expectation (LOLE), loss of load duration, and loss of load frequency (LOLF) are the indices for adequacy assessment of generating system. Expected demand not supplied (EDNS) and expected energy not supplied (EENS) are the commonly used transmission system adequacy indices [11].

For distribution system adequacy evaluation, IEEE Standards Association has standardised power distribution reliability indices as IEEE Std 1366-2012 [13]. System average interruption duration index (SAIDI), customer average interruption frequency index, and average service availability index (ASAI) are the reliability indices for the distribution system. These are being used for interruptions lasting >5 min. System average interruption frequency index (SAIFI) calculates the reliability in terms of outage frequency, whereas the customer average interruption duration index (CAIDI) is to measure even more precise impact on an average customer. The selection of a reliability index depends on the amount of input data and its ease of use as some indices are convertible or can be calculated from others (e.g. CAIDI can be reached by dividing SAIDI by SAIFI).

These reliability indices, in fact, are the measure of unreliability as higher the value, lesser is the reliability of the system. Based on these indices, the effectiveness of reliability investment is marked by the decrease in duration and frequency of service interruption. However, these indices are inappropriate for high impact low probability (HILP) events as the significance of such events is lost while the values are averaged out. Therefore, the data of a catastrophic event that is classified as a major event day (MED) are to be excluded to deal separately. Though SAIDI (in minutes per day) can help to identify MED, but massive input data are needed. Furthermore, the number of factors like system design, geography, planned interruptions, and occurrence of MED can cause variations in the values reported by different utilities [13]. Moreover, reliability captures the only binary state of a system that means either system is 'Functional' or 'Failed' [14]. It only considers high probability low impact events due to internal faults and does not take into account wide-spread outages caused by HILP events [15]. Above all else, reliability evaluates all outages equally irrespective of how they occur and reliability indices price lost load at a flat rate despite the fact that price is higher, the longer it is lost [16].

2.2 Vulnerability and robustness

Power systems are vulnerable to random failures of equipment and a wide range of shocks (natural or man-made). The vulnerability of an energy system is defined as 'The sensitivity of an energy system to external disturbance or internal malfunction. A vulnerable energy system lacks the capacity to recover speedily from shocks and may not be able to satisfy energy service needs affordably in the event of changed external circumstances.' [10]. The term is used to quantify network damages caused by rare extreme events and vulnerability function for a given hazard $H_i(H_i \subseteq H$, where H is set of possible hazards) is expressed in (1) [17]:

$$\text{Vulnerability}_i = f(\varphi | H_i) \times g(\xi | H_i) \tag{1}$$

where f is the conditional probability distribution function (PDF) for the hazard impact φ relative to the hazard H_i and g is the conditional PDF for the system capacity ξ relative to the hazard H_i.

Vulnerability assessment is a continuous process that includes system response before, during, and after disturbance. Diameter, connectivity loss, node centrality, algebraic connectivity, and node betweenness are some of the vulnerability indices. Vulnerability is analysed by employing topological models based on network theory and graph theory. Although these methods are computationally cheap and fast for efficient analysis of large size systems, the physical properties of the system are disregarded in these topological models, and there is no differentiation between components. Furthermore, vulnerability analysis is generally focused on network structure and gives no insights into detailed system operations [18].

Robustness, on the other hand, refers to the ability of a system to resist change without losing stability. The term is often considered as the opposite of vulnerability and is described as 'The ability of a system to cope with a given set of disturbances and maintain its functionality.' Robustness is concerned with the resistance and strength of the system to a set of disturbances. It is the system's design feature with a passive security approach like pole hardening and undergrounding selective lines. A system that is designed to be more robust against one disturbance will be more fragile to the other. Therefore, a high level of robustness leads to system brittleness and increases the vulnerability of a system to catastrophic failures via cascading events [17].

2.3 Risk

The term is rooted in economics and has been applied in financial management to measure the consequences of adversity those may or may not be of monetary value. According to the 2007 grant guidance of the Homeland Security Grant Program (HSGP) in the USA, the risk is defined as the product of the probability of attack, vulnerability, and measure of consequences [19]. In power systems, the risk of an event is measured by

$$\text{Risk} = \text{Probability of occurence} \times \text{Severity of event}. \tag{2}$$

Different risk indices like overload risk index, low voltage risk index, and loss of load risk index have been proposed [18]. These indices generally include two terms, a probabilistic term, and a severity term, to measure consequences on different features of a power system that truly represent system risk. However, each risk index extracts only a specific system feature, and a single index for all features is unavailable. In addition, probabilistic risk assessment methods rely on historical and available data where useful and valid data is expensive to be collected. Moreover, evaluation of indices depends on confidence and relevance of collected data.

In conclusion, the enormous catastrophic disruptions of electrical energy supply in recent years due to a rise in the frequency of extreme events have attested the need for a stronger power grid. These wide-spread outages highlight that existing power systems are ill-prepared for severe weather events. Thus, a resilient power grid in the future is inevitable as a highly reliable grid achieved using existing reliability indices is not necessary to be resilient [20].

3 Resilience: a novel concept of battling against disasters

The word 'Resilience' is derived from the Latin word '*Resilire*', that means 'the ability to spring back or rebound' [21]. In 1973, C.S. Holling was the first who used the term to describe the behaviour of ecological systems and introduced system resilience as distinct from system stability [22]. Since then, the term has been used extensively in social, economic and organisational domains with widely differing definitions, presented in [23]. The concept of resilience in these domains has evolved remarkably over several decades, but relatively young in power systems domain and still needs to be investigated [24].

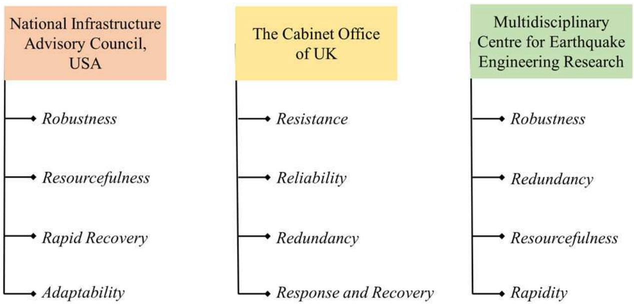

Fig. 4 *Characteristics of resilience recognised by different organisations*

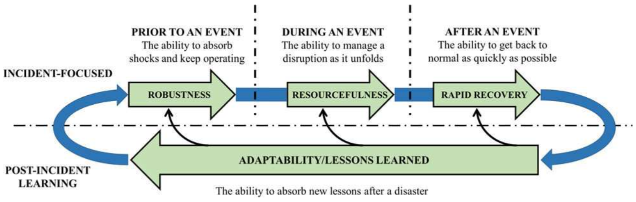

Fig. 5 *Resilience construct proposed by NIAC*

3.1 Defining the term in the context of power system

Despite various resilience-related studies recently conducted in this area, there is no standard definition of power system resilience [25]. Great strides have been made by the number of leading organisations towards defining resilience in this context and distinguishing from reliability [26]. To be clear and comprehensible, several definitions of resilience proposed by notable organisations and influential researchers in this subject area are furnished.

The UK Cabinet Office has recognised energy as one of the Critical National Infrastructures (CNI). The Office has defined infrastructure resilience as 'The ability of assets, networks and systems to anticipate, absorb, adapt to and/or rapidly recover from a disruptive event.' [27]. The National Infrastructure Advisory Council (NIAC) of the United States has identified energy as critical infrastructures and key resource (CIKR) sector. The Council has defined infrastructure resilience as 'The ability to reduce the magnitude and/or duration of disruptive events.' [28]. The definition is formalised by the US Presidential Policy Directive/PPD-21 as 'The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents.' [29]. According to the United Nations Office for Disaster Risk Reduction (UNDRR), the term is defined as 'The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions.' [30]. This definition is adopted by the United Nations to measure the global progress of 'Sendai Framework for Disaster Risk Reduction (2015–2030)' [31].

The UK Energy Research Centre (UKERC) has described the term as 'The capacity of an energy system to tolerate disturbance and to continue to deliver affordable energy services to consumers. A resilient energy system can speedily recover from shocks and can provide alternative means of satisfying energy service needs in the event of changed external circumstances.' [10]. According to the Power system Engineering Research Center (PSERC), the resilience of electric grids is 'Ability of a system to gradually degrade under increasing system stress, and then to return to its pre-disturbance condition when the disturbance is removed.' [32]. The National Association of Regulatory Utility Commissioners (NARUC) has defined resilience as 'Robustness and recovery characteristics of utility infrastructure and operations, which avoid or minimise interruptions of service during an extraordinary and hazardous event.' [16].

Besides, researchers working in this area have also offered their own definitions. The resilience of future energy networks is defined in [33] as 'The ability of a power system to withstand extraordinary and high impact-low probability events such as due to extreme weather, rapidly recover from such disruptive events and absorb lessons for adapting its operation and structure to prevent or mitigate the impact of similar events in the future.' Later, this definition is generalised for all systems, including power system as 'The ability of a system to anticipate and withstand external shocks, bounce back to its pre-shock state as quickly as possible and adapt to be better prepared to future catastrophic events.' [34]. Another definition is offered by Li *et al*. [35] as 'The ability of a power system to prepare adequately for, respond comprehensively to, and recover rapidly from major disruptions due to extreme events.'

Although the consensus on the definition of power system resilience is lacking, it is more important to know the characteristics of resilience in this domain. A comparative view of resilience characteristics, recognised by key organisations, is presented in Fig. 4. NIAC has recognised four features of resilience: robustness, resourcefulness, rapid recovery, and adaptability [36]. Robustness is the ability to withstand HILP events and remain functional, whereas resourcefulness is primarily linked to people and described as the ability to skilfully manage the crisis by identifying options and prioritising the tasks. Rapid recovery is a system capability to return to its normal operational state quickly after a crisis, while adaptability is the ability to learn new lessons from previous events utilising new technologies and tools. Based on these features, the council has presented a construct for the resilience of the electricity sector, as illustrated in Fig. 5.

As per the Cabinet Office of UK, four basic components of infrastructure resilience are resistance, reliability, redundancy, response and recovery [27]. Resistance is defined as the ability to resist the hazard and its impact to avoid damage and disruption. Reliability is to ensure that the infrastructure components are designed to operate under a range of certain given conditions and capable of mitigating damage. Redundancy is the element to deal with the design planning and capacity of the system to ensure continuity of services in the event of a disruption. Response and recovery components enable speedy and effective response and recovery from a disruptive event that is determined by planning efforts, preparedness, and in advance exercises. Multidisciplinary Center for Earthquake Engineering Research (MCEER) has proposed '4Rs' of resilience, namely, robustness, redundancy, resourcefulness, and rapidity [37].

To conclude the concept, authors are of the view that a resilient power system should have multi-faceted capabilities, namely anticipation, robustness, redundancy and resourcefulness, and adaptability. In brief, the system should be smart to predict the event prior to its happening, able to avoid the event, and prevent the effects of the hazard. As avoiding all the hazardous events is impractical, the system should be resistant enough during the event happening to minimise the damage. After the event, the system should be capable of reconfiguration with available redundant resources and adequate manpower with ample spares for the rapid recovery of damaged infrastructure to the pre-disaster level. Eventually, the system should learn from the experience to adapt and further enhance its capabilities.

3.2 Resilience vs robustness

Though resilience and robustness are being used interchangeably in the disciplines of social systems and organisational systems, however, these terms are considered distinct in the discipline of power systems, as depicted in Table 2. Resilience and robustness are, in fact, two different design philosophies. The former is related to system flexibility while the latter is related to system strength. Robustness is recognised as one of the four basic components of a resilient system and, thereby, falls under the umbrella of resilience. Resilience is integrated in operational components of a system, whereas robustness is typically embedded in the system's design. A robust grid may break like an oak tree in a storm, on the other hand, a resilient grid may bend and survive like a reed [17].

Table 2 Differences between resilience and robustness

Resilience	Robustness
• Ability to withstand external shocks and bounce back	• Ability to resisit change without loosing stability
• Demands flexibility, adaptability and agility	• Requires stronger coupling between network components
• Focuses on quality of service	• Focuses on asset utilisation
• An active approach	• A passive approach
• Segments network into multiple sub-systems to maintain functionality	• Segments network into few sub-systems to maintain functionality
• Relies on agility and flexibility to survive extreme disturbances	• Relies on component redundancy and topological changes to cope with specific threats
• Considers unexpected catastrophic failures caused by HILP events	• Considers only expected failures

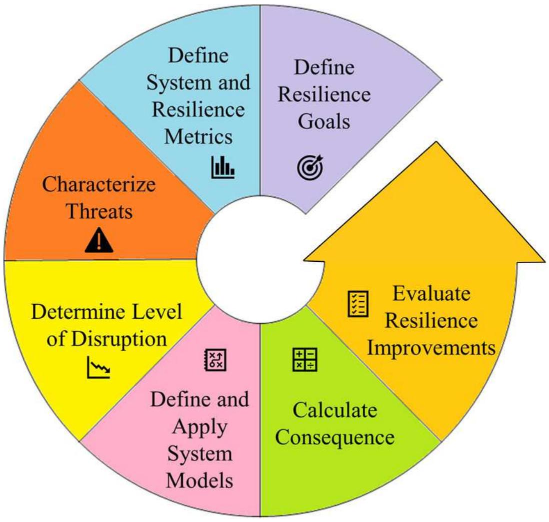

Fig. 6 *Sandia National Laboratories resilience framework*

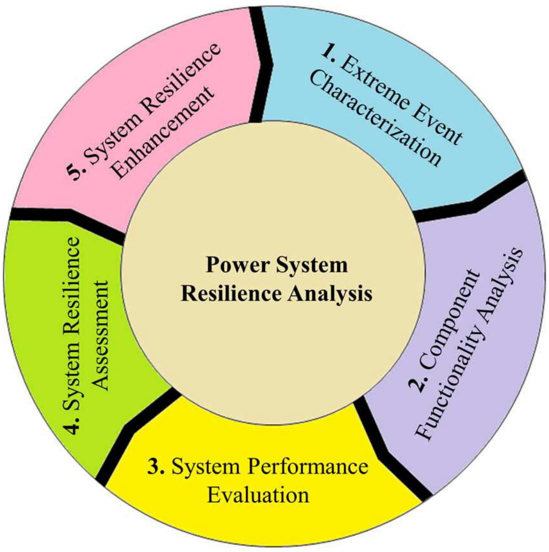

Fig. 7 *Framework for power system resilience analysis*

3.3 Frameworks of resilience

Resilience framework is a spatiotemporal representation to mark the beginning point in resilience enhancement of the system, in which researchers have proposed different frameworks to conceptualise resilience in power systems. A comprehensive framework is essential for distribution operators/utility owners for

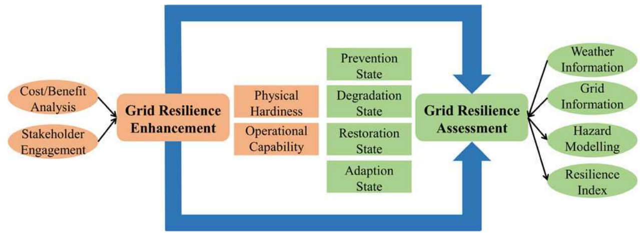

Fig. 8 *Bi-stage framework of grid resilience*

planning and operational decisions while achieving their resilience goals. A resilience framework to assess infrastructure planning and operational resilience of energy systems is introduced by Ellis [38]. The framework, exhibited in Fig. 6, suggests starting by setting the goals of resilience and defining a resilience metric to assess these goals. Next step is to characterise the threat and to determine the level of system disruption based on a different types of threats like natural disasters, extreme weather, ageing infrastructure, cyber and physical attacks. At the fifth stage, outcomes are to be calculated by utilising system modelling tools. Finally, system resilience is to be evaluated by applying pre-defined resilience metric, and improvements are to be marked.

Five-stage closed-loop generic framework exhibited in Fig. 7 is proposed in [35]. Taking into consideration the attributes of the event (e.g. type, pattern, intensity, duration), the first stage deals with characterisation and modelling geographical movement of the extreme event across the system. The functionality of components is to be assessed in the next step to identify the components that are failed directly or indirectly due to the cascading failures. Then, loss of components is translated to degradation of system functionality (e.g. loss of load, generation capacity) that can be calculated using probability density function. At the fourth stage, the resilience of the power system is assessed quantitatively using the resilience index, and finally, a resilience worthy strategy is planned for enhancing power system resilience.

A bi-stage closed-loop framework for grid resilience as shown in Fig. 8, is presented in [39] that comprises of assessment stage and evaluation stage. Modelling of a hazardous event, weather data along with system information, and definitions of resilience indices are integrated in the assessment stage. Four characteristics of resilience; anticipation, absorption, restoration, and adaptability are assessed at this stage. Cost/benefit analysis of resilience enhancement strategy and engagement of stakeholders for implementation of these strategies are made part of the evaluation stage to enhance the physical hardiness and operational capability of the power grid.

3.4 Curves of resilience

In power systems, resilience is presented graphically using geometrical shapes; triangle and trapezoid. These representations, in fact, are borrowed from the fields of earthquake engineering and structural engineering. The attributes of these shapes are transformed accordingly to make them coherent with power system terminologies.

3.4.1 Resilience triangle: Resilience triangle, as shown in Fig. 9 was first presented in [37] for quantitative assessment and enhancement of communities seismic resilience. The idea was originated while plotting the quality of community infrastructure over time to capture the performance ranging from 0 (no service) to 100% (no degradation). Loss of resilience for a specific earthquake was marked by the area of a triangle and was measured by the damage level of community infrastructure over restoration time ($T_0 - T_1$). The concept was extended in [40], in which the authors introduced linear, trigonometric, and exponential recovery curves during the restoration phase to indicate community preparedness and classified communities as average, unprepared and well-prepared, respectively. Later, the idea was applied in [41] to assess the resilience of power distribution system of Louisiana State for Hurricane Katrina.

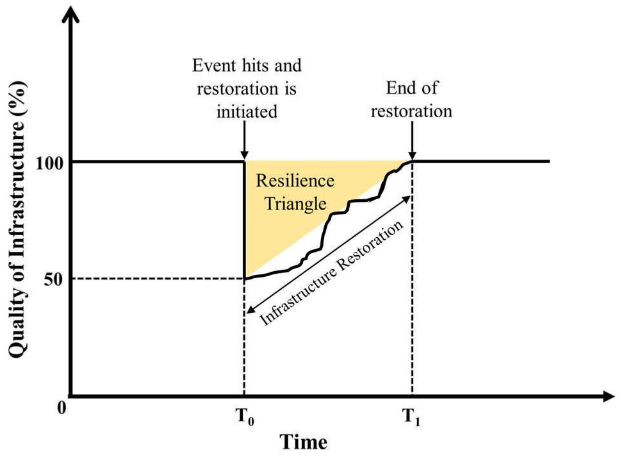

Fig. 9 *Conceptual curve to measure seismic resilience*

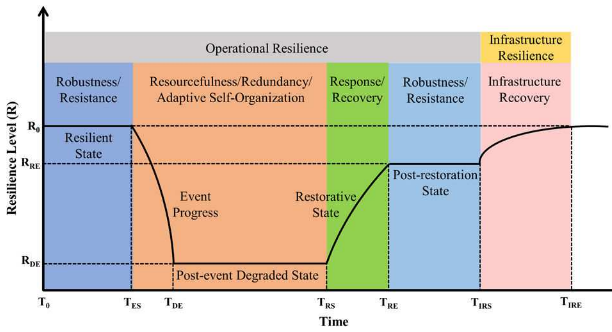

Fig. 10 *Curve for operational and infrastructural resilience*

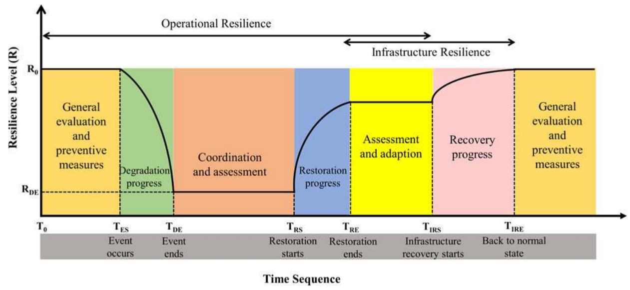

Fig. 11 *Curve for different resilience states of power distribution systems*

However, the resilience triangle assumes a sharp and immediate degradation in network performance level that makes it threat specific. Such a sharp decline in network performance only occurs during earthquake disasters whose duration is from seconds to minutes, but that is not the case of weather-related events. In case of hurricane or windstorm, that may last from hours to days; degradation worsens with time as the event traverses the network and network performance descends linearly as evident in [34]. Furthermore, network restoration is also assumed to be triggered at T_0 that is undoable. Operational recovery with network reconfiguration can be done immediately but infrastructure recovery is only possible with repair crew and spares that need some time for arrangements and mobilisation. Moreover, the resilience triangle of an event is to be drawn separately for operational and infrastructure resilience.

3.4.2 Multistate curves: To address the limitations of resilience triangle, a conceptual resilience curve of an event was presented by plotting resilience level vs time, as exhibited in Fig. 10 [26]. The curve is divided into five different states to mark '4Rs' of resilience proposed by MCEER. Resilience level of the system before the occurrence of an event is shown by R_0, where R is any suitable metric of resilience. Resilient state ($T_0 - T_{\rm ES}$), the first state, lasts until the event hits the network at $T_{\rm ES}$. During this state, preventive measures are advised, while the system should be robust

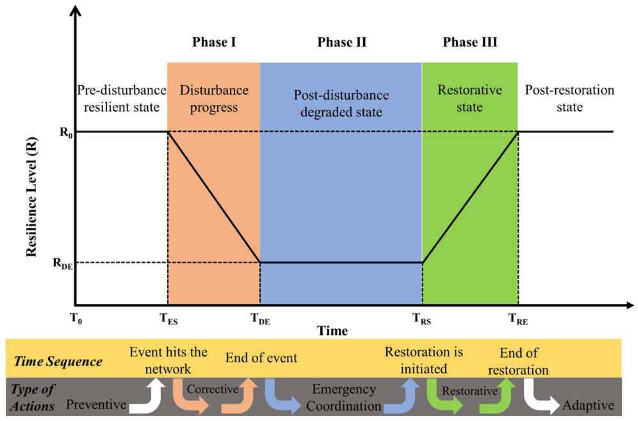

Fig. 12 *Resilience trapezoid for power system resilience associated to an event*

and resistant to demonstrate sufficient resilience. Contrary to resilience triangle, degradation of network resilience ($R_0 - R_{\rm DE}$) is reflected by a curve over the duration ($T_{\rm ES} - T_{\rm DE}$). To cope with the network reconfiguration planning by considering resourcefulness or redundancy for operational flexibility, post-event degraded state ($T_{\rm DE} - T_{\rm RS}$) is introduced as the second state. During restorative state ($T_{\rm RS} - T_{\rm RE}$), the network is restored to resilience level $R_{\rm RE}$ assuming linear recovery process. Post-restoration state ($T_{\rm RE} - T_{\rm IRS}$) considers travel time of repair crew and time required to arrange spares for infrastructure recovery while the network remains at resilience level $R_{\rm RE}$. During infrastructure recovery state ($T_{\rm IRS} - T_{\rm IRE}$), infrastructure is fully recovered and the network is finally restored to its pre-event resilience level R_0.

The curve reveals the importance of operational measures over infrastructure hardening measures, the former is time-efficient as operational recovery takes shorter than infrastructure recovery ($T_{\rm RS} - T_{\rm RE} < T_{\rm IRS} - T_{\rm IRE}$). Operational resilience ($T_0 - T_{\rm IRS}$) and infrastructure resilience ($T_{\rm IRS} - T_{\rm IRE}$) are also marked clearly in the curve but the curve is powerless in isolating operational and infrastructural degradations during the event progress. Furthermore, the post-restoration state ($T_{\rm RE} - T_{\rm IRS}$) is counted towards operational resilience even though the state is associated with infrastructure recovery planning that needs to be considered in infrastructure resilience.

In a recent effort, another multi-state resilience curve is proposed in [42] that counts post-restoration state ($T_{\rm RE} - T_{\rm IRS}$) towards both operational and infrastructure resilience, as illustrated in Fig. 11. Hence, operational resilience ($T_0 - T_{\rm IRS}$) remains the same as in [26], whereas the infrastructure resilience is changed from ($T_{\rm IRS} - T_{\rm IRE}$) to ($T_{\rm RE} - T_{\rm IRE}$). Furthermore, it is suggested to evaluate the effectiveness of microgrids during this state as their impact diminishes with the start of infrastructure recovery at $T_{\rm IRS}$. However, this curve is still incapable of distinguishing operational degradations from infrastructure degradations and operational resilience overlaps infrastructure resilience.

3.4.3 Resilience trapezoid: While plotting the system performance level vs time, a tri-stage performance curve is unfolded in [43] to assess power transmission system resilience against a hurricane. Later, this curve was revamped in [24] as a resilience trapezoid by plotting resilience level vs time to visualise the behaviour of the power system during extreme events. Pre-disturbance resilient state, disturbance progress state, post-disturbance degraded state, and restorative state are marked with $T_0 - T_{\rm ES}$, $T_{\rm ES} - T_{\rm DE}$, $T_{\rm DE} - T_{\rm RS}$ and $T_{\rm RS} - T_{\rm RE}$, respectively as shown in Fig. 12. Additionally, a post-restoration state is introduced that may be considered as a pre-disturbance resilient state for the next event. The resilience trapezoid considers pre-restoration delays of weather events where recovery works cannot be started immediately due to safety reasons. Such delays are successfully recorded in a post-disturbance degraded state as flat bottom of trapezoid. Furthermore, in the case of events where a network part is recovered immediately while other parts are still exposed to an event causing a recovery delay, multiple delays can be marked with different T_{DE} and T_{RS}. These features distinguish resilience trapezoid from resilience triangle, but network degradation and restoration are assumed linear that is not always the case. Moreover, resilience trapezoid is to be drawn separately for operational and infrastructure resilience like resilience triangle.

3.5 Resilience evaluation

Defining power systems resilience is imperative for the development of a suitable resilience metric. Since there is a lack of clarity on the definition, various metrics are suggested by the researchers and practitioners for the assessment of resilience; those can be classified as qualitative and quantitative [44]. The qualitative metrics though provide a general picture of the system but only helpful in long-term planning and decision making. These methods are based on a checklist and questionnaires [45, 46], metrics scoring various aspects of the system [47], analytical hierarchy process [48], belief function [49], and influence of humans [50] to assess resilience. Qualitative methods provide some valuable information about the influence of auxiliary infrastructures and services that are given either lesser or no importance in the quantified assessment. Additionally, qualitative methods can consider various aspects and resilience capabilities simultaneously. However, these models assess system resilience without numerical descriptors and probabilistic in nature; that is why prone to errors as the accuracy of the model and validity of the analysis depend on the assumptions made.

In this paper, the focus is on the quantitative assessment that is appropriate for engineering systems and helpful for comparison of two different systems. Quantitative resilience metrics proposed specifically for the power system in recent years are carefully selected. A comprehensive analysis is provided by categorising as analytical, probabilistic, curve-based and reliability-based metrics and comparison is presented in Table 3.

3.5.1 Analytical metrics: Emphasising performance perceived by customers, a work in [51] has defined multiple indices to measure the effect of hazard. In addition, the power grid is presented as a human–cyber–physical system and the effects of dependency and interdependency on system resilience are discussed for the first time. The framework is focused on four components of resilience as highlighted in [29] and can be used to characterise power supply performance planning, design, management, and operation. Resiliency for N loads (R_B) and outage incidence (θ) are the indices equivalent to conventional reliability indices (ASAI and SAIFI). While resistance (φ) and restoration speed ($\mathscr{V}_r$) represent withstanding capability and rapidity, respectively, preparation capacity and adaptation capability still need to be quantified. A resilience metric is suggested by Chanda and Srivastava [52] that is based on six factors linked with network topology, namely, critical fraction (f_c), graph diameter (D), average path length (l_G), betweenness centrality (C_B), clustering coefficient (C_n), and algebraic connectivity of the network (Λ_2). To take full advantage of short-term proactive actions like the placement of distributed generators (DGs), battery storage, and photovoltaic panels, authors have used percolation theory and Bayesian conditional probability to mark node failure probability. The analytical hierarchical process is used for resilience evaluation and system restoration to avoid outages. The proposed metric is normalised but disregards time factor and incapable to cover the entire framework of resilience. Multiplication inverse of weighted load loss ($\mathfrak{R} = (1/\mathrm{LOSS})$) is considered in [53] to mark resilience, and Monte Carlo simulation is used for evaluation modelling. The loss is defined by

Table 3 Comparison of selected quantitative resilience metrics proposed for power system resilience assessment

Ref.	Categorisedas	Real time	Network/event independent	Resilience indicators	States of resilience trapezoid considered			
					Pre-disturbance	Disturbance progress	Post-disturbance	Restorative
[51]	analytical metric	×	×	multiple	×	✓	×	✓
[52]		×	✓	network topological	×	×	×	✓
[53]		×	×	load loss	×	✓	×	×
[54]		×	✓	network topological	×	×	×	✓
[55]		×	×	multiple	✓	✓	✓	✓
[56]		×	✓	grid topological & operational functionality	×	✓	✓	✓
[57]		✓	×	robustness	×	×	×	✓
[58]		✓	✓	load restored	×	×	×	✓
[59]	probabilistic metric	✓	✓	multiple	×	×	×	✓
[25]		×	✓	risk	×	✓	×	×
[60]		✓	✓	generation loss	×	✓	×	×
[34]	curve based metric	×	✓	multiple	×	✓	✓	✓
[61]		×	✓	area above operability trajectory	×	×	×	✓
[62]		×	×	robustness, recoverability, rapidness	×	×	✓	✓
[63]		×	✓	area above and under the curve	×	✓	✓	✓
[64]		×	×	multiple	×	✓	✓	✓
[65]		✓	✓	area above and under the curve	×	×	×	✓
[66]	reliability based metric	✓	✓	energy index of reliability	×	✓	×	×
[67]		×	✓	LOLF, LOLE, EENS	××	✓	×	×
[68]		×	✓	resistancy, recovery, resiliency	×	✓	×	✓

Assessment/enhancement	Features of resilient power system marked by the metric				
	Preventive	Resistance	Resourcefulness	Recovery	Adaptability
assessment	×	✓	×	✓	×
assessment	×	×	×	✓	×
assessment	×	✓	×	✓	×
assessment	×	×	✓	✓	×
assessment	×	✓	✓	✓	×
assessment	×	✓	✓	✓	×
enhancement	×	×	×	✓	×
assessment	×	×	×	✓	×
assessment	×	×	✓	✓	×
assessment	×	✓	×	×	×
assessment	×	✓	×	×	×
assessment	×	✓	✓	✓	×
assessment	×	×	×	✓	×
enhancement	×	✓	✓	✓	×
assessment	×	✓	✓	✓	×
assessment	×	✓	✓	✓	×
enhancement	×	×	×	✓	×
assessment	×	✓	×	×	×
assessment	×	✓	×	×	×
assessment	×	✓	×	✓	×

$$\text{LOSS} = \int_0^t \frac{(1/M)\sum_{i=1}^{M} \Delta P(X_i)}{P_0} \mathrm{d}t \tag{3}$$

where

$$\Delta \mathrm{P}(X_i) = p_1 \cdot \Delta P_1(X_i) + p_2 \cdot \Delta P_2(X_i) + p_3 \cdot \Delta P_3(X_i)$$

$M, X_i, \Delta P(X_i)$ and P_0 are sampling number, fault scenario, comprehensive load loss in a certain scenario at a certain moment, and initial weighted total load, respectively. p_1, p_2, p_3 are weighted factors of the high, medium, and low priority loads, respectively. The methodology is probabilistic in nature, and the proposed metric is only focused on the amount of load lost, whereas other key aspects of resilience like resourcefulness, redundancy, and rapidity are still to capture.

Resilience quantification of the power distribution system is framed as a multi-criteria decision-making problem by Bajpai *et al*. [54], and resilience is quantified using various parameters of network topology. Choquet integral, an aggregation method, is used to account for these multiple interdependent characteristics that cannot be evaluated by additive means. The emphasis is on the restoration of critical loads with a minimal number of switching. The proposed metric is equally applicable in operational contingency and planning scenarios of both radial and meshed distribution network. However, unable to measure network rapidity, a key characteristic of resilience, as the time required for load restoration is not accounted. A tri-stage (pre-disaster, during-disaster and post-disaster) resilience assessment framework with multiple metrics for each stage is offered in [55].

In addition to probabilistic indices for pre-disaster toughness, indices are proposed to account for current and post-disaster load loss per cent, generation margin, and transmission system adequacy. Besides, metrics for restoration efficiency and economic cost of restoration are also presented. Many of the proposed metrics are focused on the transmission network, whereas economic analysis index has assumed fixed value for lost load rather than compounding value. Furthermore, defining miscellaneous metrics for each stage has added a significant computational burden. Focusing connectivity and operational functionality of the grid, a work in [56] has proposed assorted metrics for the transmission network. In addition to graph-oriented connectivity metrics, the operational functionality of the grid is marked with grid flexibility, outage recovery value, and outage capacity recovery metrics. The proposed set of metrics intends to quantify both infrastructure and operational resilience. However, grid connectivity metrics mark only resistance and robustness of infrastructure, while operational functionality metrics can only measure resourcefulness and recovery.

Nazemi *et al.* [57] defined the resilience metric as a ratio of the energy discharged from the battery system during the emergency interval to the energy demanded by the critical loads. The work is aimed at the sizing of the battery energy storage system (BESS) to serve critical loads in case of a seismic event. The problem is formulated as linear considering the resilience index as an objective function and optimisation tool is utilised to find the highest possible value of resilience that tends to be <1. The metric can gauge the effect of emergency response time, operational restoration capability, and investment in BESS for system resilience. However, operational and infrastructure degradations remain unaddressed. Furthermore, the metric is not applicable to the systems with energy resources other than battery and other key features of resilience (e.g. resistance, resourcefulness, redundancy) cannot be marked.

Another resilience index for critical load restoration in a hybrid microgrid is proposed in [58] to quantify the demand response program and to evaluate system performance during the emergency period, as expressed in (4). An acceptable bound is also defined for the index to assure the survivability of most critical loads. The index value ranges from zero (least resilient) to one (most resilient) and can be evaluated at any instant. Although both AC and DC microgrids are incorporated in the index, the focus is mainly on the amount of load restoration, where

$$\mathfrak{R} = \left(\sum_{n \in N} \rho_n \cdot \frac{\left(P^{al}_{t,\rho_n,r} + P^{dl}_{t,\rho_n,r}\right)}{\left(P^{al}_{t,\rho_n} + P^{dl}_{t,\rho_n}\right)} \right) / N \quad \forall\, n \in N, t \in T \tag{4}$$

where $P^{al}_{t,\rho_n,r}$ and $P^{dl}_{t,\rho_n,r}$ is the amount of load recovered on AC and DC side, respectively, P^{al}_{t,ρ_n} and P^{dl}_{t,ρ_n} is the actual amount of load on AC and DC side, ρ_n represents the priority of nth level, and N represents the maximum number of load levels in the microgrid.

3.5.2 Probabilistic metrics: To evaluate the resilience of mesh grid in the face of extreme events, Liu *et al*. [59] have proposed four key indices, namely the expected number of line outages (K), loss of load probability (LOLP), EDNS, and difficulty level of grid recovery (G) as expressed by

$$K = \int_0^{\infty} k\mathscr{P}_d(k|\mathscr{V})\,\mathrm{d}k \quad \text{and} \quad \text{LOLP} = \sum_{e_i \in S_e} \mathscr{P}_{e_i} \tag{5}$$

$$\text{EDNS} = \sum_{e_i \in S_e} \mathscr{P}_{e_i} \cdot C_{e_i} \quad \text{and} \quad G = \sum_{i=1}^{n} \omega_i \cdot \eta_i \tag{6}$$

where $k, \mathscr{V}, \mathscr{P}_d$ are number of lines on outage, severity level of extreme event, and probability of k line outages in $\mathscr{V}$, respectively. e_i, S_e, $\mathscr{P}_{e_i}$ and C_{e_i} represent ith extreme event, set of extreme events in which the load exceeds available generating capacity, probability of grid experiencing e_i, and load curtailment in e_i, respectively. ω_i and η_i are weight and value of ith the factor, respectively.

During contingency, the Markov chain is used to determine the state transition of the grid from normal to microgrid operation. The methodology has effectively demonstrated the benefits of smart grid technologies in case of extreme events but is only suitable for survivability and reliability evaluation. The proposed indices K and G are based on risk evaluation, whereas LOLP and EDNS are reliability indices for generation and transmission system adequacy. Furthermore, all these indices are probabilistic in nature and time independent. Hence, they are unable to describe the temporal characteristics of resilience. A risk-based metric for distribution system resilience introduced by Bazargani and Bathaee [25] is expressed as in (7). The proposed framework for resilience assessment is generalised that is equally applicable to all types of events. The essence of resilience is entirely different from risk analysis; the index is unable to mark inherent redundancy, resourcefulness, and rapidity, which are the key aspects of a resilient system.

Besides, computation of the probability of an event occurrence is probabilistic that is prone to error as it depends on several other factors. Moreover, the fragility model is based on a uniform cumulative distribution function that is not valid for all types of components, and event data from history books is required to evaluate past and current status of the system more accurately

$$\mathfrak{R} = \sum_{i=1}^{N} \mathscr{P}_{\alpha_i} \cdot \phi_{\alpha_i} \tag{7}$$

where N is the number of extreme events considered, $\mathscr{P}_{\alpha_i}$ is the occurrence probability of each event α_i and ϕ_{α_i} is the impact of the event α_i on the power system.

A probabilistic resilience metric, as expressed in (8), is proposed in [60] and point estimation method is utilised to address uncertainties of load consumption and photovoltaic generation. The methodology is proved to be time-efficient compared to MCS. However, resilience metric is over simple and probabilistic in nature, whose accuracy is dependent on short-term load demand and weather forecast data

$$\mathfrak{R} = \sum_{Nh=1}^{NH} P(Nh)\,.\,E\left[\frac{\int_0^T P_{\text{Avail}}(Nh, Pd_k(t), P_{\text{PV}}(t))\,\mathrm{d}t}{\int_0^T P_{\text{req}}(Pd_k(t), P_{\text{PV}}(t))\,\mathrm{d}t}\right] \tag{8}$$

where $k \in \{\text{residential, commercial, industrial, critical}\}$. Nh, NH and $P(Nh)$ are annual number of hurricane events, the maximum number of hurricanes considered, and the probability of Nh hurricane events during the period of study T, respectively. $Pd_k(t), P_{\text{PV}}(t), P_{\text{Avail}}$ and P_{req} are the percentage of nominal active power demand for load type k at the time t, photovoltaic generation, the available amount of active power, and amount of active power required.

3.5.3 Curve-based metrics: A set of time-dependent resilience metrics, ΦΛΕΠ (‘FLEP’), to distinguish infrastructure and operational resilience is presented in [34] that is based on resilience trapezoid as illustrated in Fig. 12. Φ-metric, Λ-metric, E-metric, and Π-metric are to measure the rate of degradation, level of degradation, the extensiveness of degradation, and rate of recovery, respectively. In addition, the area of a trapezoid is the fifth index that gives a comprehensive overview of system resilience. These metrics, as expressed in (9) and (10), characterise all of the three phases (I, II and III) of the trapezoid and are able to quantify the effect of operational and structural resilience enhancement strategies. However, they failed to provide an insight into the cost-effectiveness of these strategies

$$\Phi = \frac{R_{\text{DE}} - R_0}{T_{\text{DE}} - T_{\text{ES}}}, \quad \Lambda = R_0 - R_{\text{DE}} \quad \text{and} \quad \mathrm{E} = T_{\text{RS}} - T_{\text{DE}} \tag{9}$$

$$\pi = \frac{R_0 - R_{\text{DE}}}{T_{\text{RE}} - T_{\text{RS}}} \quad \text{and} \quad \text{Area} = \int_{T_{\text{ES}}}^{T_{\text{RE}}} R(t)\,\mathrm{d}t\,. \tag{10}$$

Tan *et al.* [61] suggested a resilience metric based on operability trajectory $\mathscr{Q}(t)$ as depicted in [41] and further bounded from above by $\mathscr{Q}_{\text{ideal}}(t)$. With the formulation of a bi-stage stochastic problem, scheduling of post-disaster repairs and selection of components to be hardened are considered in conjunction. The resilience metric represents the area under the trajectory; larger is the area, higher is the resilience. The metric is merely focused on the restoration phase, hence unable to gauge degradation progress, post-event degraded state, and post-restoration state of the system. A resilience index based on the social welfare concept is introduced in [62] as expressed in (11). A two-stage stochastic methodology is proposed for power and water network restoration and planning. Normalised robustness, recoverability, and rapidness are proposed as sub-indices of resilience metric that is based on social welfare curve. A plot of measurement of performance (MoP) vs time and its value ranges from 0 to 3

$$\mathfrak{R} = \mathscr{R}_{\min} + \frac{\int_{t_0}^{t_{\text{ER}}} \text{MoP}(t)}{t_0 \times t_{\text{ER}}}\mathrm{d}t + \frac{t_{\min}}{t_{\text{FR}}} \tag{11}$$

where $\mathscr{R}_{\min}$ is the minimum social welfare, t_0 is the time for the start of reduction, $t_{\min}$ is the minimum interval to enhance the performance, t_{ER} is the expected time for restoration and t_{FR} is the time at which the social welfare will go back to its initial state. The resilience metric is aimed at customer load points whereas resistance, redundancy, and adaptability are overlooked. Yang *et al.* [63] formulated a resilience metric, as expressed in (12) by considering the duration of disruptive events based on the resilience curve proposed by [24] and illustrated in Fig. 12

$$\mathfrak{R} = \sum_{k=1}^{K} \mathscr{P}_k \left[\frac{\text{Area}_1}{\text{Area}_1 + \text{Area}_2} \cdot \frac{T_{\text{DI}}}{T_{\text{RE}} - T_{\text{ES}}}\right] \tag{12}$$

where $\mathscr{P}_k$ is failure probability calculated by MCS, Area_1 and Area_2 are the area above the curve and under the curve, respectively. T_{DI}, T_{RE}, and T_{ES} are the duration of disaster influence, restoration end time, and event start time, respectively. The metric can successfully mark the effects of repair crew shortage on system resilience and its value is normalised, hence, can be used to compare resilience of different systems. However, the exact knowledge of different time stamps is required to construct the curve, and consumer side benefits are unconsidered.

A tri-stage resilience assessment method based on the framework of [42] is proposed by Amirioun *et al.* [64]. Vulnerability index (VI), degradation index (DI), restoration efficiency index (REI) and microgrid resilience index (MRI) are defined to measure degradation level, temporal degradation, restoration efficiency, and microgrid resilience, respectively. These indices are normalised (range 0–1) to ease the comparison of different power systems under various operating conditions, although unable to capture preventive, post-degraded, infrastructural recovery, and adaptive resilience of the grid. The methodology assumes that only six overhead lines are vulnerable to an approaching windstorm while the remaining is undergrounded. Furthermore, all of the components are supposed to be affected at

$$\begin{array}{c|c|c|c|c|c|c|l} & 10^6 & 10^5 & 10^4 & 10^3 & 10^2 & 10^1 & Seconds \\ \mathfrak{R} = & A & B & C & D & E & F & \end{array}$$

Fig. 13 *Variables of resilience metric to record integer values*

the same time and a predefined load restoration is performed with islanded microgrid. Cumulative percentage of restored performance, defined as a ratio of the system performance recovered at time t, i.e. $[F(t) - F(t_d)]$ to maximum performance loss $[F(t_0 - F(t_d)]$ caused by the disruptive event, is used as resiliency measure in [65]. The metric, as expressed in (13), is included in the multi-term objective function that is maximised using the Gurobi optimisation solver. The approach is based on resilience curve but restricted to the restoration phase only and has not considered other stages of resilience

$$\mathfrak{R} = \int_{t_s}^{t} \frac{F(t) - F(t_d)}{F(t_0) - F(t_d)} \mathrm{d}t \,. \tag{13}$$

3.5.4 Reliability-based metrics: To avoid the exact knowledge of recovery time, a code-based metric is offered in [66] to quantify the resilience of the power distribution system as defined by (14). The repair work, that may last from seconds to days and even months in some cases, authors have assumed that it can be accomplished anywhere in between 10^0 and 10^6 s. Considering the energy index of reliability (EIR), a ratio of energy actually supplied to total energy demand, an empirical equation is formulated to measure unscaled resilience of network against an event that may last for α s

$$\mathscr{R} = \mathscr{C}\left(\alpha + e^{\mathrm{EIR}}\right)(1 + \mathrm{EIR}) \tag{14}$$

where $\mathscr{R}$ is the unscaled value of resilience and $\mathscr{C}$ is a binary variable that shows the occurrence of an event in the considered time frame.

The resultant fractional values are scaled to integer values ranging 1 (less resilient) to 9 (highly resilient) and recorded in corresponding variables of resiliency metric (A, B, C, D, E, F) against respective outage duration magnitude as shown in Fig. 13.

The proposed metric quantifies resilience of a system in real-time without having low-level information of system infrastructure. Furthermore, the metric can be easily evaluated by utilising the existing mathematical tools, and the results can be transformed into a financial loss of utility. However, the proposed metric is powerless in quantifying and comparing network resilience for disastrous events (prolonged recovery time, i.e. 10^4 to 10^6 s) as its value remains close to 1 for such events. Lastly, the suggested metric is based on the adequacy index used for generation capacity assessment.

In response to the demand–supply changes and infrastructure development policies in future electricity networks, work in [67] has taken advantage of existing adequacy indices, LOLF, LOLE, and EENS to mark resilience of transmission system against windstorm. Although the severity of generation deficiencies, frequency and duration of load loss are marked by these indices, the focus is on the assessment of generation capacity and transmission system adequacy, whereas distribution level adequacy is not addressed. Furthermore, EENS shows the difficulty in converging that results in slower convergence speed. Multiple metrics, as expressed in (15)–(17), are defined by Mousavizadeh *et al*. [68], and a two-stage framework is presented to maximise the power of restored loads using linear optimisation model

$$\text{resistancy} = \frac{\sum_{i \in N_{\text{Uninterrupted}}} \left(\mathrm{Pr}_{i,t}^{L} \times P_{i,t} \right)}{\sum_{i \in N} \left(\mathrm{Pr}_{i,t}^{L} \times P_{i,t} \right)} \tag{15}$$

$$\text{Recovery} = \frac{P_{\text{Restored}}}{\sum_{t \in T} \sum_{i \in N_{\text{Interrupted}}} \left(\text{Benefit}_{i,t}^{L} \times P_{i,t} \right)} \tag{16}$$

$$\text{Resiliency} = \frac{P_{\text{Restored}} + \sum_{t \in T} \sum_{i \in N_{\text{Uninterrupted}}} \left(\text{Benefit}_{i,t}^{L} \times P_{i,t} \right)}{\sum_{t \in T} \sum_{i \in N} \left(\text{Benefit}_{i,t}^{L} \times P_{i,t} \right)} \tag{17}$$

where N is set of the nodes in the network, $\mathrm{Pr}_{i,t}^{L}$ is the priority of load i at the period t. P_{Restored}, $P_{i,t}$ and $\text{Benefit}_{i,t}^{L}$ are power of the restored load, predicted load i at the period t, and benefit of load i at the period t, respectively.

The methodology considers renewable energy resources, microgrid formation and demand response. However, budget constraints of deploying a significant number of distributed energy resources (DERs) are ignored; those are of much importance for distribution operators. Although resistancy and recovery metrics are distinguishable, all three metrics are static in nature, and resistance is the same as the EIR used by Chanda *et al*. [66].

To summarise, there is a lack of standard resilience metric and a single all-purpose metric does not exist. Majority of the proposed resilience metrics are focused on system degradation and restoration while none is able to capture preventive and adaptive capabilities of a power system, as depicted in Table 3. Apart from these shortcomings, resilience metrics in each category have their own merits and demerits. Analytical metrics can reflect the impact of graded load on power system resilience, however, these metrics are computationally expensive and do not consider the time of degradation and restoration. Probabilistic metrics are proven effective to estimate resilience as probabilistic evaluation can predict not only the severity of an event and its impact on the system, but also the likelihood of its occurrence. However, many assumptions are to be made while modelling the system and significant errors may be introduced through oversimplification. Thus, the validity of the analysis is directly related to the accuracy of the model. Curve-based metrics are good to visualise and measure the operational as well as infrastructure resilience of a power system, however, accurate time stamps are needed to mark various states of the system. Further to this, these metrics treat all loads equally irrespective of their classification and pay no attention to financial loss. Reliability-based metrics utilise system adequacy indices that are highly developed, standardised, and easy to calculate. However, these indices do not deal with catastrophic failures caused by extreme events.

3.6 Resilience enhancement strategies

Resilience evaluation is the basis for resilience enhancement, and various enhancement strategies are being practised that can be classified as planning and operational measures. Planning measures are related to the physical hardening of system components to a higher standard and are used to reduce the impact of events by decreasing the magnitude of degradation. Operational measures are related to smart grid technologies that enable system operators to take operative measures within minutes of disruption to reduce restoration time. The former is resilience efficient but requires huge investment while the latter is cost-effective and time-efficient. Furthermore, it is notable that an enhancement strategy effective in a specific event may have a negative impact on another event. For example, undergrounding of power lines may increase infrastructure resilience against windstorms but may cause longer restoration time in case of flood or earthquake because of difficulties to trace the fault. Hence, a careful decision for implementation of enhancement measures is required by system planners to prioritise specific characteristics of the utility grid and to keep a balance between different types of measures. Common practices and techniques to enhance system resilience are summarised in Table 4.

4 Case study

To provide important insights into power system resilience evaluation, the resilience of a test system was assessed using two different resilience metrics (analytical- and curve-based) in this

Table 4 Planning and operational measures for resilience enhancement

Planning measures	• Upgrading poles with stronger material like steel or concrete • Strengthening poles by installing guy wires • Vegetation management/tree trimming • Undergrounding selective transmission/ distribution lines • Elevating substations in flood prone areas and installing water barriers • Relocating facilities and rerouting lines to areas less susceptible to hazards • Redundant transmission routes • Reserve planning and black-start capabilities • Installation of DGs
Operational measures	• Accurate weather forecast and estimation of severity • Advanced visualisation and situation awareness systems • Disaster assessment and priority setting • Network reconfiguration and microgrid island operation • Advanced protection schemes and decentralised control • Demand side management • Repair crew mobilisation and coordination • Installation of mobile or emergency generator

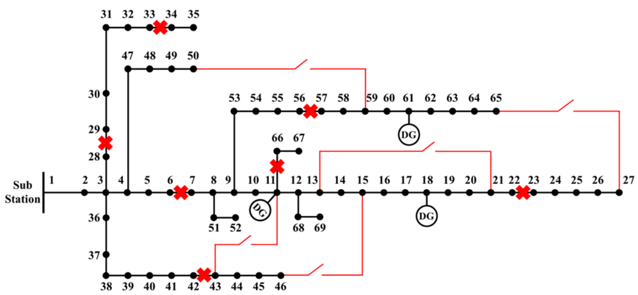

Fig. 14 *Modified 69-bus overhead distribution system*

Table 5 Nodes classification of 69-bus system

Critical nodes	Semi-critical nodes	Non-critical nodes
11, 18, 24, 61, 64, 65	10, 13, 21, 26, 27, 39, 40, 49, 50, 59, 62, 68, 69	the rest

Table 6 Results of analytical metric for 69-bus system

	Case-I	Case-II	Case-III	Case-IV
resilience	1.267	4.943	7.189	83.857

work. The computational tasks are performed on a personal computer, with Quad-Core Processor (2.66 GHz) and 4-GB RAM, using MATLAB and MATPOWER [69]. For the case study, a 69-bus distribution system whose characteristics are given in [70] is selected as a base case and three DGs are placed optimally [71]. All the lines and poles are assumed of same design standard except L1-2 and L2-3, that are reinforced. A wind fragility model has been adapted from Ma *et al*. [72] to calculate the failure probability of an overhead line against a category-4 hurricane [73], and Monte Carlo simulation is used to generate random failures of distribution lines. The seven failed lines (L6-7, L11-66, L22-23, L28-29, L33-34, L42-43 and L56-57) are marked in Fig. 14.

Network restoration is done, using AMPL, with an objective to serve maximum possible load subject to radiality constraints, and radial power flow is executed to verify the feasibility of restored network.

Different scenarios of network restoration have been considered as follows:

- *Case I:* There is no tie line and no DG in the system.
- *Case II:* There are five tie lines and no DG in the system.
- *Case III:* There is no tie line but three DGs in the system.
- *Case IV:* There are five tie lines and three DGs in the system.

4.1 Resilience evaluation with analytical metric

Luo *et al.* [53] have proposed a resilience metric as a reciprocal of weighted load lost. The metric has been explained in Section 3.5.1, and weighted load lost has been expressed as (3). To assess the resilience of 69-bus system with this metric, we have classified the loads into critical, semi-critical, and non-critical loads for the purpose of assigning weights to system nodes. As an illustrative example, weights assigned to the nodes serving critical, semi-critical, and non-critical loads are 3, 2, and 1, respectively. The division of nodes based on their load importance is depicted in Table 5, and the weighted load of the system is calculated as 8.512 MW.

The weighted loads lost for Case-I, Case-II, Case-III, and Case-IV are 0.789, 0.202, 0.139, and 0.012, respectively. The corresponding values of resilience metric are shown in Table 6. It can be seen that the value of the metric is increasing as the weighted load lost is decreasing and vice versa. It is observed that the values of the metric ranges between unity and infinity. The unity value indicates total load loss, thus represents a least resilient system, whereas infinity indicates no-load loss and represents a most resilient system.

The metric is focused on critical loads and a good choice to indicate the impact of different grades of load on the resilience of a distribution network. However, there are some demerits of this resilience metric. Unlike curve-based metrics, this metric is unable to measure infrastructure resilience. The metric merely accounts for the loss of load and does not consider the rate of system degradation and speed of restoration. Further to this, the vast range of its values makes it difficult to assess the degree of resilience. Moreover, it has been observed that the change in values of assigned weights significantly affects the resilience value, thus making this metric useless to compare the resilience of different networks.

4.2 Resilience evaluation with curve-based metric

The resilience is now assessed using a well-known curve-based metric (ΦΛΕΠ) proposed in [34] and discussed in Section 3.5.3. To draw the resilience trapezoid, it is assumed that the event hits the network at 11th hour that continued till the 27th hour, resulting in linear degradation and repair work of damaged infrastructure is started after 15 h. The average repair time of a distribution line is assumed 6 h, whereas the travelling time of the repair crew is disregarded. The operational and infrastructure trapezoids for Cases I–IV are exhibited in Figs. 15 and 16, respectively. Here, the amount of load connected is indicative of operational resilience and the number of lines online is chosen as infrastructure resilience indicator.

The values of five resilience metrics, as presented in Table 7, are calculated to evaluate both operational and infrastructure resilience in all four cases. Φ-metric shows how fast the amount of connected load and number of online lines are degraded, and therefore values of this metric are negative. As the slopes of degradation become less steep from Case-I to Case-IV, the magnitude of this metric is the smallest in Case-IV. Λ-metric is a measure of how low resilience is dropped; hence the values for this metric are also negative. Like Φ-metric, the values of this metric are decreasing from Case-I to Case-IV. It means that boosting the robustness of infrastructure and increasing system flexibility can reduce the values of both metrics. Then, *E*-metric shows how long the network remains in the degraded state after the event, hence captures post-disturbance response that means improving network

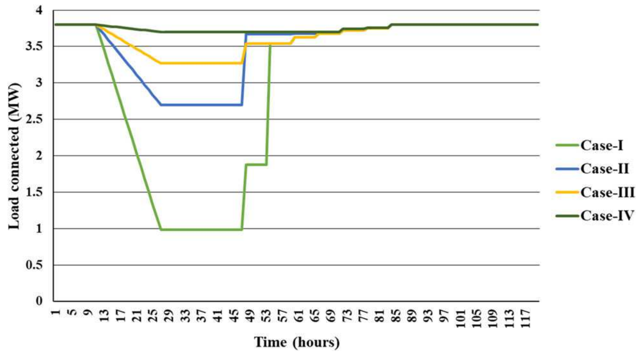

Fig. 15 *Operational trapezoids of 69-bus system for all cases*

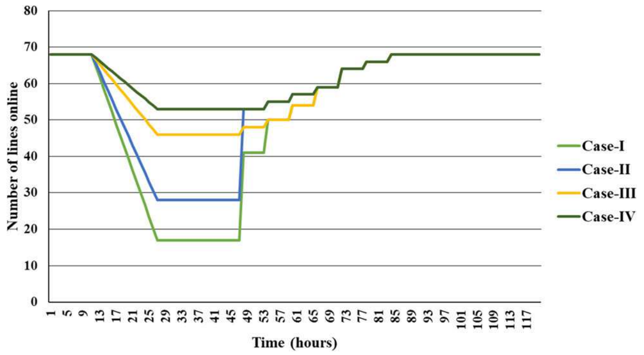

Fig. 16 *Infrastructure trapezoids of 69-bus system for all cases*

Table 7 Results of curve-based metric for 69-bus System

Resilience metric	Case-I	Case-II	Case-III	Case-IV
Operational resilience				
Φ-metric (MW/h)	−0.176	−0.069	−0.033	−0.006
Λ-metric (MW)	−2.820	−1.100	−0.530	−0.100
E-metric (h)	20	20	20	20
Π-metric (MW/h)	0.076	0.030	0.014	0.003
area of trapezoid (MW × h)	95.060	35.120	19.650	4.650
Infrastructure resilience				
Φ-metric (number of lines tripped/h)	−3.188	−2.500	−1.375	−0.938
Λ-metric (number of lines tripped)	−51	−40	−22	−15
E-metric (h)	20	20	20	20
Π-metric (number of lines restored/h)	1.378	1.081	0.595	0.405
area of trapezoid (number of lines in service × h)	1914	1390	1023	697.50

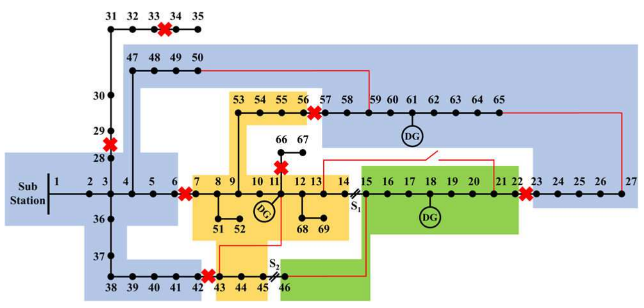

Fig. 17 *Reconfiguration of 69-bus system to recover loads*

operator's responsiveness to the event will result in lower values or vice versa. In this case, the value of this metric is the same (i.e. 20) in all cases, as the same response has been assumed for all scenarios. Next is Π-metric which measures how fast is operational and infrastructure recovery after post-disturbance degraded state. The level of degradation, availability of repair resources, and sequence of the repair will affect the values of this metric. Alike Φ-metric and Λ-metric, reduction in the values of Π-metric are obvious owing to added flexibility. Finally, the area of a trapezoid is calculated, which is an indicator of the overall impact of the hurricane on the network where larger value represents a higher impact.

Here, it should be noticed that although network robustness is the same in all four cases, infrastructure trapezoids are not identical, as shown in Fig. 16. This is mainly due to the reason that the test network is radial and thus seven damaged lines (L6-7, L11-66, L22-23, L28-29, L33-34, L42-43 and L56-57) have interrupted 44 more distribution lines in the downstream network. However, with the help of tie lines and DGs, 11, 29, and 36 disconnected lines are restored in Case-II, Case-III, and Case-IV, respectively. Due to this varying degree of flexibility of each network, infrastructure trapezoids of four cases are differing in shape.

In summary, curve-based metrics are useful for assessing both operational and infrastructure resilience. In addition to this, these metrics provide better visualisation of system performance. However, accurate time stamps are needed to reproduce these curves those are difficult to collect during an emergency scenario. Moreover, these metrics consider all loads equally irrespective of their criticality and thus pragmetic overview of the system performance is not offered.

4.3 Significance of smart grid technologies

To verify the importance of modernisation of the existing grid for resilience enhancement, it is assumed that 69-bus system is equipped with sectionalising switches, tie lines and DGs. After a disaster, the system is split into six unconnected areas due to failure of seven distribution lines, marked in Fig. 14. By reconfiguration, majority of unserved loads are recovered with the formation of two islands as depicted in Fig. 17. DG connected to node 61 is operating in grid mode while the other two DGs are operating in islanded mode. With this new configuration, it can be noted that the loads connected to nine buses (29–35 and 66–67) are not being served that is resulting in a load loss of only 0.10 MW (2.6%). Additionally, load served and online branches for the four cases of network restoration along with base case are depicted in Fig. 18. There are 68 distribution lines in this system and total load demand is 3.80 MW. After the occurrence of faults, 17 lines (25%) are operational and only 0.98 MW (26%) load is served. With the help of tie lines (Case-II), 11 more lines are recovered that raises the number of operational lines to 28 (41%) and 2.70 MW (71%) load can be served. By using DGs (Case-III), 46 lines (68%) can be energised and thus 3.27 MW (86%) load can be recovered. With the combination of DGs and tie lines (Case-IV), 53 lines (78%) can be restored. Consequently, 3.70 MW (97%) of load demand can be served that attests the effectiveness of tie-lines and DGs during adversity.

Thus, deployment of smart grid technologies such as automatic feeder switches and smart meters may further increase flexibility, visualisation, and situational awareness. Automatic feeder switches can open or close either due to local fault conditions or by the control signal sent from a remote location. These switches immediately reroute power among circuits by isolating faulted section and thus allow for a more efficient response to disruptions while providing more flexibility with network reconfiguration. In the conventional grid, customers must report the outages themselves, and therefore, utilities have incomplete information of outage locations that result in a delayed response. On the other side, smart meters have capabilities to notify outages in real-time as well as the precise location of disruption and restoration time. These features of smart grid technologies can significantly enhance power system resiliency by reducing restoration time with efficient deployment of repair crews.

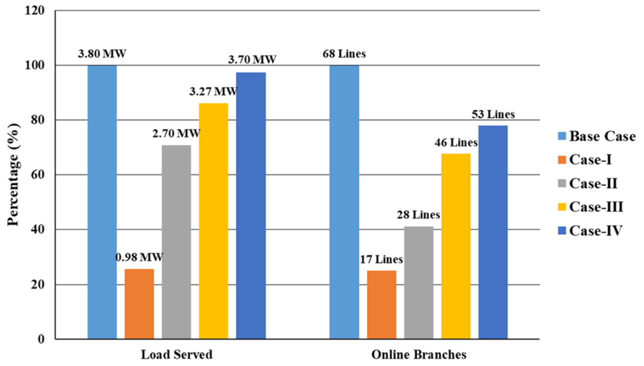

Fig. 18 *Load served and online branches of 69-bus system*

5 Looking forward

5.1 Barriers in realising DERs potential

DERs, DGs, and microgrids have proven their capabilities as fast and optimal load restoration in emergency scenarios. Many utilities are still reluctant to leverage these resources for resilience enhancement due to cost, financial constraints, and existing regulatory policies of islanding (e.g. IEEE Standard 1547). Moreover, there is no incentive for the owners of DGs to provide extra energy to restore loads after disasters. With the ever-increasing penetration of DERs and validated role of microgrids in disaster restoration, the government and regulators should revisit existing islanding functions of DGs and microgrids. Keeping in view of different ownership structures in electricity subsector, liability protection during events and outcome-based market incentives can also encourage exceptional resilience improvements. Additionally, reducing the cost of DERs can play a vital role in promoting their utilisation. At the same time, remedial measures are also necessary to avoid adverse impacts of DERs as they lower system inertia, increase air pollution, and introduce negative environmental issues at the end of the lifespan.

5.2 Lack of design standards and common agreement

There is no agreed standard or design criteria that utilities and government should work together to enhance power systems resilience during catastrophic outages. Likewise, there is no common agreement on the level of resilience to lessen the impact of large-scale outages. Without consistent design standards, it is difficult for utility operators to build a system with a realistic and sensible level of resilience. Therefore, the design basis from the government is necessary that can provide the framework needed for investments to meet enhanced design criteria and preparedness standards. It should provide economic justification for hardening investments to receive regulatory approval and should serve as a basis to develop appropriate incentives.

5.3 Standardisation of resilience definition

Frequent and more damaging natural hazards are causing severe disruptions in electricity supply, affecting the overall well-being of community members. Consequently, resilience is of the essence and becoming an essential part of power systems design, planning, and operations. In this respect, many definitions of resilience have been offered by different organisations and practitioners, however, widely varying, and there is a lack of standardisation. Thereof, existing resilience metrics are not well-developed and significantly overlap with indices of reliability, risk, and vulnerability. Thus, a consensus on the definition of resilience is much needed, and a common definition will help to develop a resilience metric in a consistent manner. Without this, design and operational decisions, hardening investments, and allocation of resources may not be aligned with resilience goals.

5.4 Taking advantage of machine learning

A close examination of historical data provides system operators valuable insights into extreme events and system resilience that serves as a basis of effective preventive measures. Though comprehensive and restrictive data are expensive to collect, but not to collect such data will cost even more in the long run. Hence, there is an ever-increasing need for data collection to understand, assess, and enhance system resilience. With the evolution of machine learning algorithms, the ability to automatically apply complex mathematical calculations to big data is enhanced significantly. Recent machine learning models can produce reliable, repeatable results and decisions. These machine learning tools are thus helpful in modelling damages, predicting outages, and assessing power system resiliency. However, insufficient historical data owing to ignorance from operating personnel or difficulty of collection process during emergency make it difficult to get the advantage of these tools. Further to this, the integration of diverse data, data cleaning, and processing of big data in a short time is also challenging tasks. At the same time, data protection and data privacy need to be considered as well to realise the promise of big data.

5.5 Dependency on other infrastructures

Power system resilience is not merely linked with infrastructure and system operation but also associated with other lifeline facilities. Electricity–water network is studied in [62] from the planning perspective to reduce water network dependency during hurricanes. In [74], a stochastic method for resilience improvement of the electricity–traffic system was proposed. Similarly, electricity–gas networks are explored from a resilience perspective to identify critical elements [75–77]. This interdependency has recently emerged in the form of an integrated energy system (IES) that combines multiple systems, thus further increasing system complexity. Resilient operation and planning of these complex systems are a promising topic, and there are a few work that investigated these integrated systems [78, 79].

5.6 Leveraging microgrid

In recent years, the value of microgrids for load restoration is well recognised as they add active components at the distribution level and enhance operational flexibility during natural disasters. Che and Shahidehpour [80] have highlighted the economic benefits of AC and DC microgrids during emergencies, while in [81, 82] the role of microgrids for enhancement of power systems resilience was reviewed. Considering stability, a work in [83] has restored critical loads using microgrid, while work in [84, 85] has proposed multiple microgrids formulation in a resilient distribution system. A work in [86, 87] has devised a two-stage framework for efficient utilisation of microgrid's unused capacity, whereas a work in [88] has presented a bi-layer communication model for networked microgrids. A two-stage stochastic approach is presented in [89] that claims networked microgrids as the most cost-effective resilience strategy in scenarios where the cost of line hardening is higher than generators.

Although microgrids can ride through extreme events as their components are less susceptible to such events, full potential is not yet realised by the large-scale system due to existing regulations. Moreover, the existing policies are deficient governing the economics of energy exchanged between multiple microgrids. Hence, there is a dire need to reconsider existent regulations and policies for the growing needs of networked microgrids such as higher penetration of DERs, islanding, and capacity of energy storage in each microgrid. Additionally, microgrids have stability issues as discussed in [90], thus more sophisticated controls are required while supplying power to complex loads. These efforts can eventually boost the potential of microgrids in emergency conditions, making the power system more resilient.

5.7 Use of cutting-edge technologies

To take advantage of cutting-edge technologies, a work in [91] has introduced a bi-stage model to optimise investment in mobile energy storage systems (MESSs) units to avoid load shedding during disruptions. Lei *et al.* [92] have co-optimised dispatch of repair crews and mobile power sources (MPSs), whereas a work in

[93] has considered pre-positioning, resilient routing and scheduling of MPSs to enhance resilience. Scenario decomposition algorithm is applied in [94] for pre-positioning and real-time allocation of mobile emergency generators to minimise the outage duration. The graph-theoretic approach is proposed in [95] to locate truck-mounted mobile emergency resources for critical load restoration. Yao *et al.* [96] have implemented MESSs while Yao *et al.* [97] have utilised transportable energy storage systems in post-disaster restoration to reduce total system cost. Although the effectiveness of these resources in resilience enhancement is well demonstrated, stability issues of formed microgrids and dependency on communication systems require further investigation.

6 Conclusions

Global climate change has imposed unprecedented challenges to the existing power grids. Recent wide-spread power outages indicate that the systems are not well-prepared for high impact events that used to be very low in probability. In this regard, present safety concepts towards major disruptions are deemed inadequate and thus attests the need of a resilient grid. Resilience is a relatively new idea to strengthen the existing power grid against HILP events. Various commendable efforts have been made to explain the notion in recent years. In this paper, several definitions and characteristics of resilience are reviewed, different frameworks are discussed, and various curves of resilience are explained. Additionally, quantitative resilience metrics proposed in recent years are critically investigated, and it is worth noting that none of these can measure preventive capability and adaptability of the system. Planning and operational measures to enhance the resilience of the power grid are summarised. Illustration of resilience evaluation and effectiveness of smart grid technologies is shown by the assessment of 69-bus system resilience against a hurricane utilising existing resilience metrics. Challenges such as under-utilisation of DERs potential, the need for standard design criteria, and the emergence of the IES are discussed, and limitations of cutting-edge technologies in post-disaster load restoration are also highlighted.

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