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Trends in modern power systems resilience: State-of-the-art review

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ABSTRACT

The power system is vital to energy security, emergency services, critical infrastructures, and the economy. Resilience of the power system against high-impact low-probability events is of particular importance to ensure the stability and reliability of the system planning and operation. The challenges and opportunities towards both the evaluation and improvement of resilience of the power system are explicitly reviewed in this paper. Appropriate criteria with a comprehensive understanding of resiliency are emphasized. In addition, to improve the modern power system resilience, this article considers the short and long-term plans with different categorizations, along with a detailed analysis of the corresponding challenges. Short-term plans refer to resilience-oriented scheduling, and long term plans indicate fundamental corrections such as hardening and equipment upgrades. Practical methods are discussed in the paper to evaluate and improve the modern power system resilience. Furthermore, some common metrics for long-term and short-term resilience assessment are evaluated and compared. The investigations have shown that microgrids have a high potential to improve resilience of the power system by bringing energy sources closer to load centers, and reducing the grid dependence on transmission lines, which are the most vulnerable equipment against natural disasters.

1. Introduction

As a result of global warming and climate change, extreme weather events have become more frequent in recent years. While still relatively rare, these events have devastating effects on the utility industry, for which recovery can take months [1]. Power systems are usually designed to be able to operate normally even with the outage of one or two components, which is referred to as an $N-1$ and $N-2$ contingency analysis [2,3]. In the context of resilience of the power system, however, such high-impact, low-probability (HILP) events as superstorm Sandy (2012, US) [4], hurricane Katrina (2008, US) [5], the Texas freeze of February 2021 (US) [6], and the Fukushima earthquake and tsunami (2010, Japan) [7], can be disastrous. In these events, millions of outages in the power grid occurred [8]. Specifically, Katrina caused almost three million [9]. In the Texas freeze, approximately 10 million people in Texas alone lost electricity, for several days [6]. And, in the aftermath of Hurricane Maria in September 2017, 1.5 million customers were left without electricity in Puerto Rico to live in the dark for up to 120 days [10].

The weather-related events associated with a high percentage of power system outages in the United States [11] also incur enormous annual costs of between $18 billion and $70 billion [10]. The cost of reconstruction following superstorm Sandy reached $65 billion in 2012 [12], while that of Texas freeze has been estimated at $130 billion in Texas and $155 billion nationwide [6]. Governments and the private sector have, generally speaking, adopted two approaches to tackling these challenges. On the environmental front, strict laws that are formulated to reduce the amount of pollution in the air, especially CO_2 emissions, may have positive effects in the long term [13]. The second approach, which has been widely raised in both industry and academic circles in recent years, has considered the readiness of human infrastructure to deal with these events and reduce their destructive effects in the context of resilience [14].

While this second approach–from the standpoint of resilience–has been the subject of some review papers [11], an extensive analysis of applications of smart grids to assess and improve resilience has not yet been undertaken. The primary objective of [15], for example, is fundamentally related to investigations of resilience of the power system.

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Nomenclature

Acronyms

BNI	Branch number impact
CA	Contingency analysis
CHP	Combined heat and power
CL	Critical load
CO	Cabinet office, UK
DAD	Defender–attacker–defender
DER	Distributed energy resources
DS	Distribution system
FI	Fragility index
FN	Feasible network
HILP	High-impact low-probability
HIR	High-impact rare
LLI	Lost load index
MG	Microgrid
MVI	Microgrid voltage index
NIAC	National infrastructure advisory council, USA
NoR	The number of resources
OB	Overlapping branches
OPF	Optimal power flow
PCWL	Path combination without loop
PN	Possible network
PoA&PF	The probability of accessibility and penalty factor
RA	Risk assessment
RA	Route abundance
REI	Restoration efficiency index
RPS	Resilience of the power system
SA	Switching actions
SAA	Sample average approximation
SFC	System functionality curve
TS	Transmission system

Indices & Symbols

h, t	Index of hours
j	Index of loads
k	Index of buses
s	Index of scenario

Parameters

χ_s	A binary variable (0/1)
Λ	Compatibility index
λ	The dominant eigenvector that is calculated based on the topology of the system
v_s	The probability of scenario s
Ω_s	The amount of lost load in scenario s
$\Psi^{\lambda}_{i,n,d,t}$	The flexibility of demand d at load point n when adopting the network reconfiguration plan i at time t
$\Psi^{\mu}_{i,n,d,t}$	Outage cost recovery of demand d at load point n when adopting the network reconfiguration plan i at time t
$\Psi^{\partial}_{i,n,d,t}$	Recovery capacity of demand d at load point n when adopting the network reconfiguration plan i at time t
$\mathfrak{R}$	Resilience function
$\Upsilon, , R_N$	Fragility index
ε	Amount of damage for different infrastructures
f_s	Fragility function in scenario s
G, Ψ	Restoration index
k_s	Number of lines on outage in scenario s
$M(t)$	SFC at hour t
M_p	Pre-event SFC
M_{pe}	Post-event SFC
M_{pr}	Post-restoration SFC
N	Number of Loads
n	An event that makes voltage deviation
N_s	Number of scenarios
P_s	Probability of event in scenario s
P_s^{chare}	Probability of event characteristics (i.e. type and severity) in scenario s
P^L_{nts}	The total demand of bus n, at hour t and scenario s
P^{shed}_{nts}	The shed load in bus n, at hour t and scenario s
$\mathcal{S}(t)$	Supplied load
t_d	Time of degradation start
t_e	Time of event start
t_r	Time of restoration start
t_{ir}	Time of infrastructures restoration start
t_{pe}	Time of event end
t_{pir}	Time of infrastructures restoration end
t_{pr}	Time of restoration end
V^*_n	The scheduled voltage of bus n
V_{nts}	The real-time voltage of bus n, at hour t and scenario s
w_i	Weight Coefficient for recovery index

It deals with classifications of HILP events and the main differences between resilience and other similar concepts in the area of power system planning and security. In [16], Hussain et al. conduct a three-stage analysis that seeks to define the role of microgrids in resilience of the power system, elaborating on the comprehensive background of resilience and HILP events and on applications of microgrids for resilience enhancement. The proactive actions are further carried out to reduce damage from an extreme event. In [17], Bhusal et al. provide recommendations for future definition, evaluation, and improvement of resilience of the power system, presenting a critical analysis to identify the current limitations and suggest future directions. In sum, although the above papers have generally addressed the concept of resilience, no critical perspective has yet been presented on mathematical criteria for assessing resilience and the potential value of smart grids at various stages of resilience. In light of the pervasiveness of microgrids and the increasing levels of automation in power systems, this paper will explore in detail resilience of the power system as it relates to smart grids. Its main contribution will be to highlight the usefulness of smart grids in the evaluation and improvement of resilience of the power system. First, the paper will examine the definitions of resilience in different types of infrastructure, explain it specifically with reference to power systems, and compare it with similar concepts, including reliability, contingency analysis, and risk assessment. Next, it will review different mathematical criteria for resilience and disadvantages of each in terms

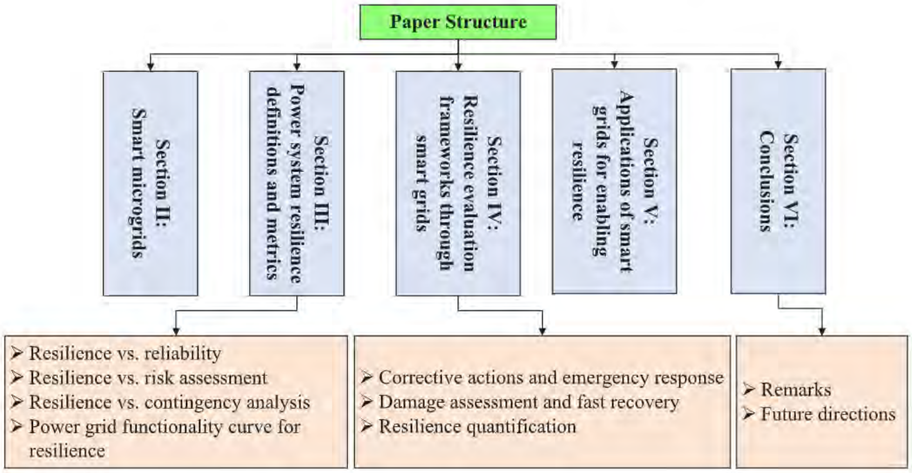


Fig. 1. The overarching structure of the paper.

of inclusion and standard concepts of resilience are further presented. The applications of smart grids for improving resilience are divided into five categories: converting power systems into microgrids, deploying dynamic microgrids, networked microgrids, multiple microgrids, along with other methods. Papers covering these areas will be comprehensively reviewed, with detailed extractions on the corresponding main contributions, size of the test system, and defects. Finally, the remarks and results of the research are summarized, and the research gaps and directions for future research in this area are discussed. Specifically, this paper will make the following contributions:

- It will investigate the resources and methods proposed for modern power systems resilience from the perspective of smart grids.
- It will reveal the great potentials of smart grids for improving resilience of the power system.
- It will assess the proposed mathematical metrics for power grid resilience in terms of inclusion and definition.
- It will numerically evaluate common metrics for assessing and enhancing short-term and long-term resilience

As Fig. 1 illustrates, the remainder of the paper is organized as follows: Section 2 describes the pervasiveness of smart grid technologies, while Section 3 investigates the standard definitions and criteria pertaining to resilience of the power system. Various resilience evaluation frameworks in smart grids are presented in Section 4, and Section 5 further characterizes various applications of smart grids in enabling and improving resilience of the power system. The paper concludes in Section 6.

2. Smart microgrids

A microgrid consists of a set of energy sources and loads within limited electrical security and operational constraints to satisfy the loads to the upstream network in either a connected (on-grid) or a disconnected (off-grid) way [18]. Most microgrid projects were carried out in the United States before 2016, with East Asia and Latin America ranking the second and third in the deployment and operation of microgrids since then. Until 2017, microgrid deployment projects totaled only 1,869 globally, with an aggregate capacity of approximately 20.7 GW [19,20]. This trend rapidly increased, with the number of microgrids rising to 6,610, with a generation capacity of 31.7848, GW by 2020. (see Fig. 2) [21].

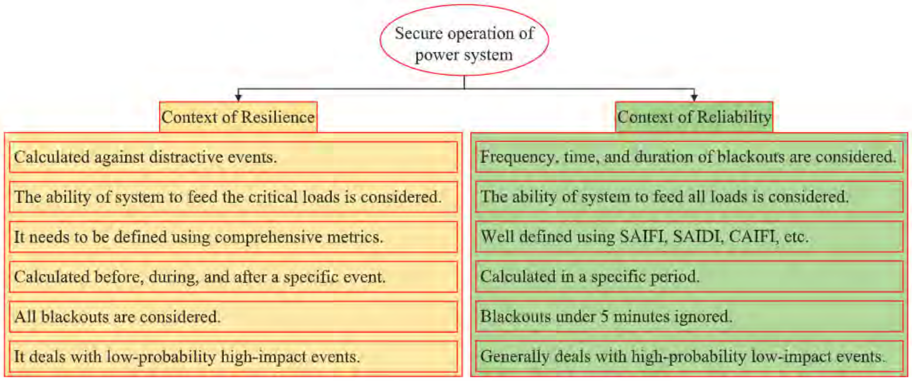
3. Resilience of the power system definition and metrics

The recent jump of the number and frequency of natural disasters and their increasing impacts on power systems has heightened the need to improve resilience of the power system. Power system reliability is a well-known and well-established concept that has been widely studied by power system engineers and academics. Although there have been various refinements and definitions of resilience developed in the literature over time. The concept of resilience, on the other hand, is less well known and defined. Derived from the Latin "resilio" the word "resilience" was coined by C.S. Holling in 1973 for ecological systems. Today the term is used to describe a very new and evolving notion in the field of power systems that is explained as "a measure of the persistence of systems and of their ability to absorb change and disturbances and still maintain the same relationships between populations or state variables" [22]. In general, resilience is defined as the ability of equipment, networks, and systems to predict, absorb, and quickly recover from catastrophic events [23].

For the energy infrastructure, particularly the power system, many definitions of system resilience have been proposed, with a focus on the ability of the system to deal with interruptions. U.S. Presidential Policy Directives-21(PPD-21), for instance, defines resilience as "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions" [24]. According to the U.K. Cabinet Office, resilience is the ability to "anticipate, absorb, adapt to and/or rapidly recover from a disruptive event" [25]. Although no definition of resilience is universally accepted, the essence of these and all other definitions rests on system performance before and after disasters, either natural or manmade. Therefore, resilience can be expressed as the ability of an entity or a system to anticipate, resist, absorb, respond to, adapt to, and recover from a disturbance [26]. Moreover, deregulation of electricity industries around the world has resulted in rapid changes to their structure and operations.

In other words, the resilience of a power system is precisely, defined as "*the ability of the system to deal with low-probability events with severe destructive effects by using an efficient method in such a way that the minimum possible load is interrupted and the system quickly returns to normal operation*" [27]. Therefore, it is necessary to first explain the fundamental differences between resilience and other similar concepts including reliability, contingency analysis (CA), and risk assessment (RA) in power systems, and then to characterize its definitions and criteria.

Fig. 2. The globally rising trend of microgrids deployment.



Context of Resilience	Context of Reliability
Calculated against distractive events.	Frequency, time, and duration of blackouts are considered.
The ability of system to feed the critical loads is considered.	The ability of system to feed all loads is considered.
It needs to be defined using comprehensive metrics.	Well defined using SAIFI, SAIDI, CAIFI, etc.
Calculated before, during, and after a specific event.	Calculated in a specific period.
All blackouts are considered.	Blackouts under 5 minutes ignored.
It deals with low-probability high-impact events.	Generally deals with high-probability low-impact events.

Fig. 3. Overarching secure operation of power system.

3.1. Resilience vs. Reliability

The big difference between resilience and reliability is that reliability deals with events with a high probability of occurrence and low destructive effects such as common errors in power systems, while resilience deals with events with a low probability of occurrence and high destructive impacts, such as severe storms [28]. Resilience and reliability are distinguished from one another in terms of the criteria that define them and how those criteria are calculated. The overarching key differences between resilience and reliability are shown in Fig. 3[29].

3.2. Resilience vs. Risk assessment

Risk in power systems is the probability of an event occurring that reduces the reliability of the power system to an unacceptable value [30]. The reliability assessment in power systems is based on risk management. In other words, in the risk assessment problem, the probability of outages and the result of the corresponding occurrence in the power system are deterministic [31]. Therefore, reliability and RA can be considered as two aspects of one reality. The difference is that increasing system risk represents decreasing the reliability, and vice versa [30].

3.3. Resilience vs. Contingency analysis

Contingency analysis in power systems considers several potential events that are reasonable to occur. In CA, it is assumed that the probability of the event occurrence and its consequences are already given. CA evaluates the ability of the power system to cope with a situation in which there are several components on outages, for example, $N-1$, $N-2$, $\ldots N-k$, where k is less than 5. Increasing the value of k increases both the cost of power system planning and the complexity of the problem [32]. Since reliability criteria are used in CA, it can also be classified in the category of reliability assessments [33]. It should be noted that resilience of the power system cannot be guaranteed by using CA. Such an example can be found in hurricane Sandy happened in 2011 in the USA, where there were $N-90$ events awaited to be analyzed [34].

In essence, main differences between resilience and other similar concepts including reliability, risk assessment, contingency analysis, etc., are depicted and shown in Fig. 4. It can be revealed in Fig. 4 that, the assessment of reliability concepts that considers the event characteristics such as types, severity levels, and the impacts of other human infrastructures including transportation systems, communication systems, health care in power systems against major outages bring together in a broader sense called resilience of the power system.

To this end, an appropriate and achievable solution to improve resilience is to expand the scale of microgrids and increase the level of automation in distribution systems [35]. Bahramirad et al. in [36] highlighted the critical achievable opportunities through the community microgrids in terms of security, resilience, reliability, carbon emission reduction, and energy efficiency. As mentioned earlier, a microgrid refers to a small-scale power system with at least one distributed energy resource (DER) and one load over distinct electrical boundaries that can meet the loads in both connected and islanding modes [37]. The process of resilience can be divided into two main areas: (i) Before

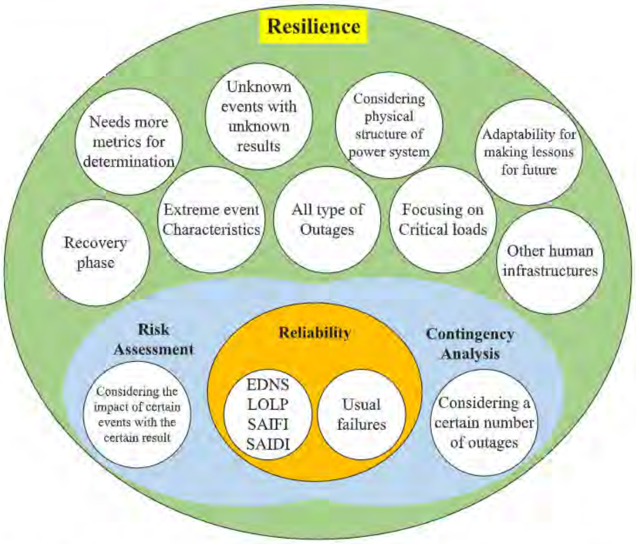


Fig. 4. The level of coverage from resilience concept under the secure operation of the power system.

Table 1
Highlighted definitions of resilience for engineering infrastructures.

Ref.	Definition
[45]	"The ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events"
[46]	"Engineering resilience is the time of return to a global equilibrium following a disturbance. Ecological resilience is the amount of disturbance that a system can absorb before it changes state"
[47]	"Resilience means four "R"s, namely robustness, redundancy, resourcefulness, and rapidity"
[48]	"The ability of a system to recover from hardness to its original state or to a new stable state based on the new conditions."
[39]	"Infrastructure resilience is the ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event."
[49]	"Coordinated planning across sectors and networks, responsive, flexible, and timely recovery measures, and the development of an organizational culture that has the ability to provide a minimum level of service during interruptions, emergencies, and disasters, and return to full operations quickly."
[50]	"A resilient system is trusted and effective out of the box in a wide range of contexts, easily adapted to many others through reconfiguration or replacement, with graceful and detectable degradation of function."
[51]	"The ability of a system to withstand a severe event with an acceptable degradation and to recover as fast as possible"
[52,53]	"The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions."

the event; (ii) During and after the event. Pre-event measurements including physical upgrading system equipment and hardware as well as disaster forecasting can significantly improve the system's preparedness to deal with these extreme events. Actions taken during and after a disaster are the actions to reduce the destructive effects of these events. Such actions include load shedding, islanding plans, fast recovery, etc.

Various definitions of a resilient system have been presented in the literature [38]. Nevertheless, a comprehensive definition is still missing and thus must be proposed with a consideration of all the above-described aspects to emphasize resilience of the power system. Standard definitions for resilience established by the National infrastructure advisory council, USA (NIAC) and Cabinet Office, UK(CO) are shown in Figs. 5 and 6, respectively.

Resilience can be defined in different sectors such as infrastructure systems [39], safety management systems [40], organizational systems [41], social–ecological systems [42], economic systems [43], and social systems [44]. Since the primary objective of this paper is to study resilience for engineering systems, resilience of engineering infrastructures is considered and highlighted with the underlining definitions. In this regard, the prominent definitions of resilience in the field of engineering infrastructures are summarized in Table 1. With various definitions of resilience shown in Table 1, it is clear to see that resilience includes the ability to withstand, the rate of robustness, and the recovery efficiency of a system against a destructive event.

Undoubtedly, the concept of resilience is reflected and measured with the corresponding defined criteria. A comprehensive measure for resilience must be approachable, usable, comparable, inclusive, scalable, quantitative, and analytical. Furthermore, the system and events uncertainties should be also considered. Characteristics of a resilience measure are shown in Fig. 7 [54].

3.4. Power grid functionality curve for resilience

A typical system functionality curve (SFC) is depicted in Fig. 8 [55,56]. Various components of the power grid can be used to obtain the SFC [57]. Different parameters such as the percentage of supplied loads, the number of fed costumers, the percentage of active system equipment like overhead power transmission lines, quality aspects of the system such as voltage, frequency, or a combination of each can be used for this aim [58]. In Fig. 8(a), the blue area represents the impacts of microgrids. The system copes with the critical situation through the microgrid operation at the posterior end of the event. In addition, the impacts of the microgrid on the other phases of the system after the event are shown in Fig. 8(b). As we can see, microgrid does have the capability of improving both the withstand ability of the system against the event and the recovery process. In essence, the green dashed area shows the impressive impact of a microgrid on SFC to make the system more resilient.

4. Resilience evaluation frameworks through smart grids

The resilience of a power system consisting of multiple microgrids depends on the resilience of each microgrid [59,60]. The strategy of a power system that consists of multiple microgrids to deal with an HIR event is shown in Fig. 9. In this mechanism, microgrids affected by the event are disconnected from the main grid to cope with the disaster on an island mode [61]. After the event, the recovery process is started and the microgrids can be connected to the upstream network after essential requirements are satisfied [62,63].

One way to improve the resilience of the power grid is to upgrade the infrastructure from centralized power plants to customers who are considered as the end loads of the grid [64]. Nevertheless, this will not be economical due to the need for large financial capital and the time-consuming nature. A good alternative approach is to use microgrids since the loads are close to energy sources. Although it is not possible to use microgrids to feed all the loads, yet they can feed the critical loads as well as improve social welfare [65]. In recent years, several studies have been conducted to develop new methods to improve the resilience of the power grid against natural disasters. These researches can be divided into five main categories: (a) disaster forecasting and estimation; (b) upgrading system equipment and hardware; (c) corrective actions and emergency response; (d) damage assessment and fast recovery; (d) resilience quantification. This classification in a time base model is further depicted in Fig. 10.

4.1. Corrective actions and emergency response

Corrective action and emergency response are actions that are taken during and after a disaster to improve social welfare. Identification of

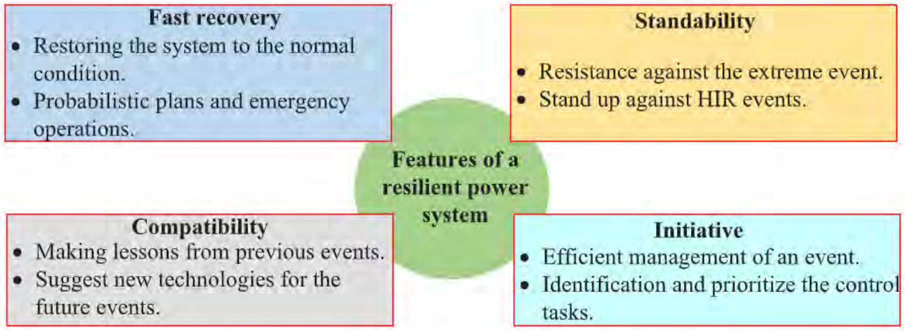


Fig. 5. Main characteristics of a resilient system based on $NIAC$ [39].

Fig. 6. Main characteristics of a resilient system based on *CO, UK* [25].

sensitive loads, emergency load shedding, as well as defensive islanding strategies, are some of the schemes that need to be implemented with a fast response for this stage. A hierarchical outage management strategy for microgrids after the extreme event is proposed in [27], in which each microgrid calculates the output of the corresponding excess/deficit power. The microgrids are finally connected to the existing lines to feed the critical loads. While defining a criterion for measuring the resilience of the distribution system, Liu, et al. in [28] have shown that controllable and island-able microgrids can improve the resilience of the power grid. However, the issue of the simultaneous islanding of many microgrids is ignored in the paper. In other words, if the number of microgrids being disconnected increases, challenges that attack the system vulnerability in making the system more different to operate with a normal range may occur, and thus jeopardize the security, stability, reliability, and resilience of the system. To solve the issue, a self-healing strategy for islanded microgrids is presented in [66]. In the proposed method, two neighboring microgrids are connected under certain conditions to establish a larger microgrid and vice versa. The proposed strategy is employed during and after the event to reduce the times of outage occurrences. The microgrid scheduling for a resilient operation is investigated in [67], in which the system uncertainties are being considered. A two-stage objective function is proposed based on the microgrid socio-economic costs and is optimized by considering the uncertainties within the wind turbines, electric vehicles, and real-time market price. The basic premise of the paper is that the microgrid operator owns all the power resources and storage devices, and as a result, planning for energy reservation and purchasing capacity from independent sources and storage devices are not considered to compensate for the power deficit. Younesi et al. in [61] revised the objective function of [67] and integrated the cost of purchasing the power and reserve from independent energy resources. Furthermore, four resilience metrics were proposed and integrated into the main objective function which only considers the economic aspects in [67]. A two-objective resilience-economic optimization model for microgrid scheduling was finally proposed in the paper. Demand reduction, generating the power close to the load centers, storage facilities, advanced controls, and independence from the main grid show capabilities that distinguish the role of microgrids in improving resilience [68,69]. The application of remedial measures and operational strategies using microgrids to improve resilience is investigated in the literature.

Actions such as defensive islanding [16,34], hardening and smart operational strategies, and the probabilistic framework for integrating renewable energy resources [70] have been proposed for enhancing the power network resilience. Optimal operation and self-healing of a distribution system are proposed in [71] through minimizing operating costs in a bi-level stochastic formulation. Upgrading and operational recovery metrics are combined in [72] to improve resilience of the power system using a tri-stage defender–attacker–defender method. Hardening of power system, assessment of damages due to possible attacks, and providing solutions based on the analysis of previous stages are respectively followed in the first, second, and third stages. Biswas et al. in [73] attempt to formulate a distribution system partition problem utilizing the sample average approximation method addressing the uncertainties of DERs to enhance resilience of the power system. Based on the behavior of the power system during an extreme event, resilience of the power system is investigated in [74]. A set of metrics is then considered for assessing resilience based on historical data of power systems. Ref. [75] further considers a three-stage stochastic scheduling method through planning and emergency response against extreme events. This paper also suggests using robust methods for forming islanding microgrids during events to reduce damage and the amount of load shedding.

4.2. Damage assessment and fast recovery

In the resilience literature, a general agreement among all researchers is that the speed of the restoration phase after a catastrophic event is considered as one of the most important features for a resilient system [15,76]. After a massive blackout caused by a natural disaster, one of the most important tasks for distribution system operators is to recover the system as quickly as possible to restore the critical loads while minimizing the economic costs for consumers. Based on the time-dependent restoration characteristics, a quantification method is introduced in [77] with resilience trapezoid. An integrated restoration planning approach for different subsystems is introduced in [78], in which the recovery process is introduced, along with the possibility of being considered to sectionalize the system into different subsystems to recover them in parallel. A model predictive control method is used in [79] to adjust the system topology and DERs to perform an efficient dynamic restoration scheme against potential hazards. The Graph theory and a hierarchical method for multiple microgrids are presented in [29] to enable and improve the resilience of the distribution system against

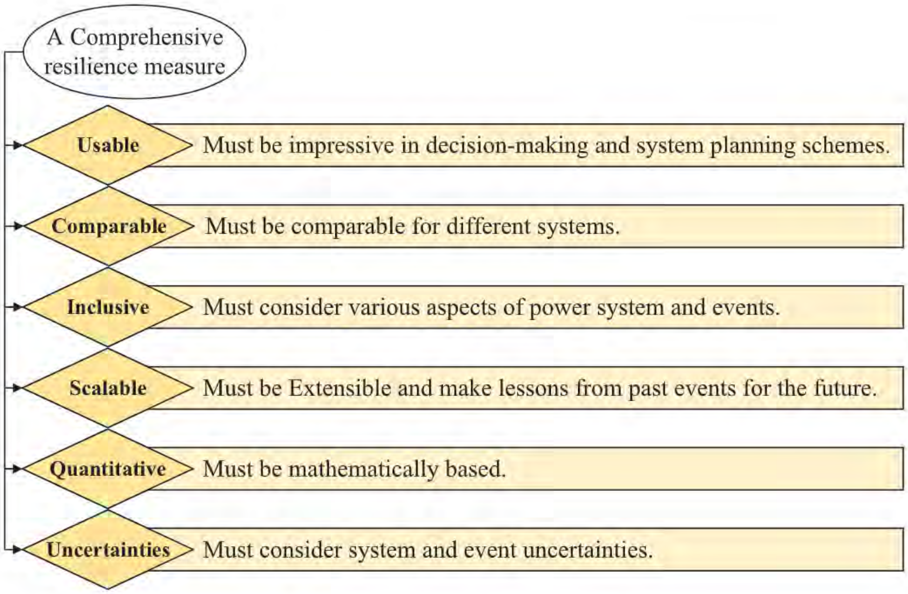


Fig. 7. Key characteristics of a resilience metric.

HIR events. Considering the structure of the distribution systems, graph theory has been identified as an effective way of measuring resilience [80]. Balasubramaniam et al. in [81] present an energy management strategy through load shedding for improving the resilience of a distribution system that considers multi microgrids. Using microgrids for identification and restoration of sensitive loads to consider the limitations of energy storage devices and power generators is proposed in [82]. The use of networked microgrids with two levels of control and the connection of microgrids with each other is an effective solution to reduce the lost loads and to increase the system recovery speed after a HILP event [83]. Based on the controlled islanding of microgrids a simple and effective strategy is proposed in [49] to enhance resilience. In the suggested strategy, in case of a perturbation occurs in the upstream network, the centralized controller switches the microgrid to an island mode, by utilizing the received information. The microgrid then returns to the first stage (grid-connected) after the error/outage is resolved in the upstream system [37]. Moreover, Younesi et al. in [84] have mathematically underlined the critical impacts of microgrids on reducing the lost load and improving resilience.

4.3. Resilience quantification

In this section, the developed criteria for resilience are firstly investigated with detailed analysis on advantages and disadvantages of each criterion. Simulations are further used to numerically evaluate some of the criteria.

4.3.1. Resilience metrics

Microgrids do not affect the formulation of criteria when it comes to quantifying the power system resilience [85]. The impacts of microgrids are focused on the system functionality under different phases of the event, including during event, degradation, and recovery phases [86]. The numerical value of resilience is finally achieved with the presence of microgrids [84,87]. Various criteria such as reliability criteria, disaster-related criteria, including different types, severity levels, and criteria based on the grid's physical structure, have been used to quantify resilience in the power system [88]. Some proposed criteria for resilience of the power system in the literature are summarized in Table 2. It should be noted that in Table 2, each criterion is examined in terms of four vital characteristics including reliability, extreme event properties, physical system structure, and the compatibility. (i) The reliability measures are important because they reflex the performance of the power system during the event. (ii) The extreme event characteristics such as type and intensity level must be considered to conduct with more realistic and practical results. (iii) The physical structure of the power system is considered since it shows the withstanding ability of the power system against disasters. In addition, it can be also used to perform different operational strategies. (iv) The compatibility property is important because it shows how the system learns the lessons from the occurred events to better cope with future disasters. As a result, a comprehensive resilience measure must be considered with all the above-mentioned properties. Advantages and disadvantages for each resilience metric are shown in Table 2 accordingly. Advantages are marked with a blue tick and disadvantages are labeled with a red cross. Moreover, the implementation characteristics of each criterion in terms of system-level and time horizon are also specified in this table.

In recent years, researchers have made a lot of efforts in creating resilience measures through planning and response decision-making [91], as well as the fundamental properties of power systems including small-signal stability, transient stability, communications in power systems, and physical degradation [92]. Various refinements developed in the literature have presented different criteria for resilience and have generally used the same concepts from some of the criteria listed in Table 2 [93]. Farzin et al. in [27] present an overview with a conclusion that the percentage of lost loads in the literature is a key criterion for resilience, however, a comprehensive understanding of resilience is not fully provided.

To better understand the position of microgrids in the resilience of the power system context Fig. 11, clearly shows that microgrids can play a key role in various stages of the power system in dealing with natural disasters. In an emergency condition caused by adversity, controlled islanding to defend against the event, separating the faulty parts from the healthy parts, and helping to feed the sensitive loads through the connected microgrids together can improve the overall resilience of the system.

4.3.2. Numerical evaluations

As shown in Table 2, some resilience metrics are calculated in a more comprehensive way to have a better comparison with other metrics [89,90]. Under this section, some of the criteria shown in Table 2, are considered as more commonly used metrics in the literature, and thus are numerically calculated based on the information provided from

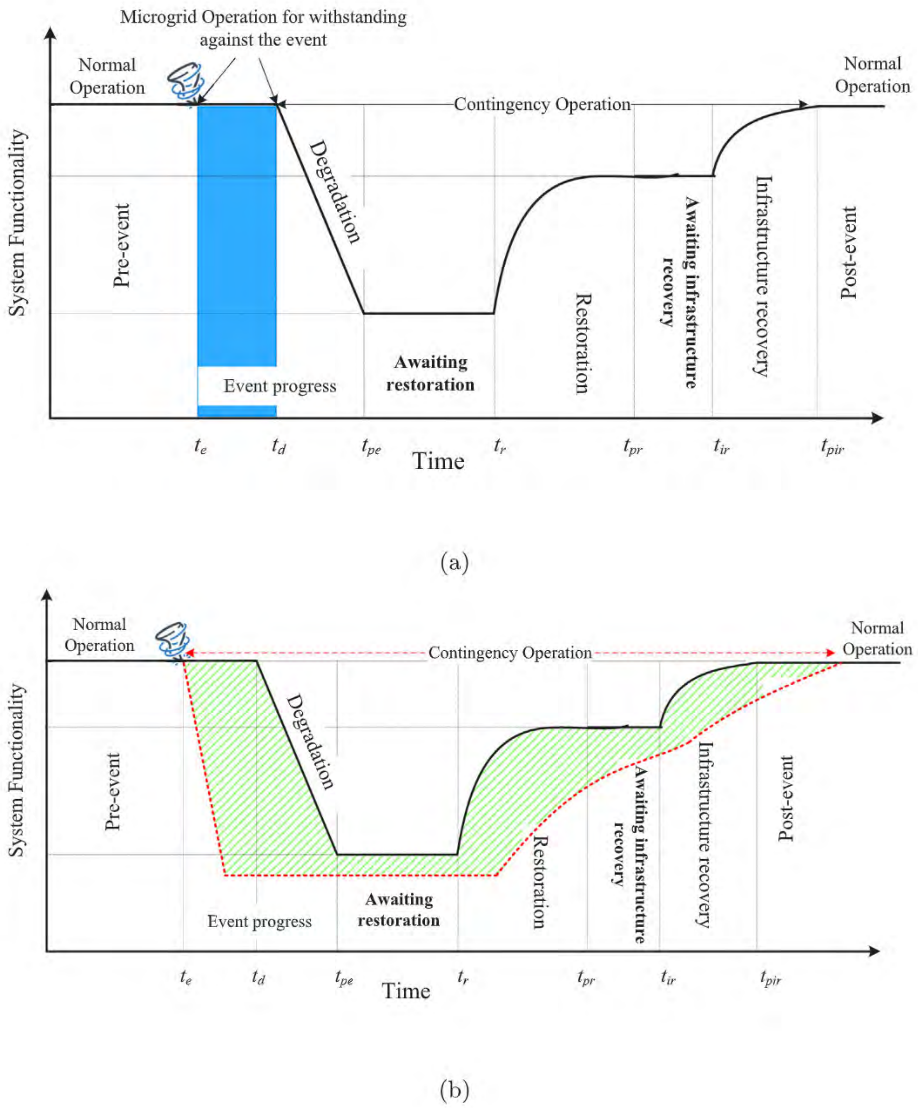


Fig. 8. Resilience curve of the power grid with the impacts of microgrids.

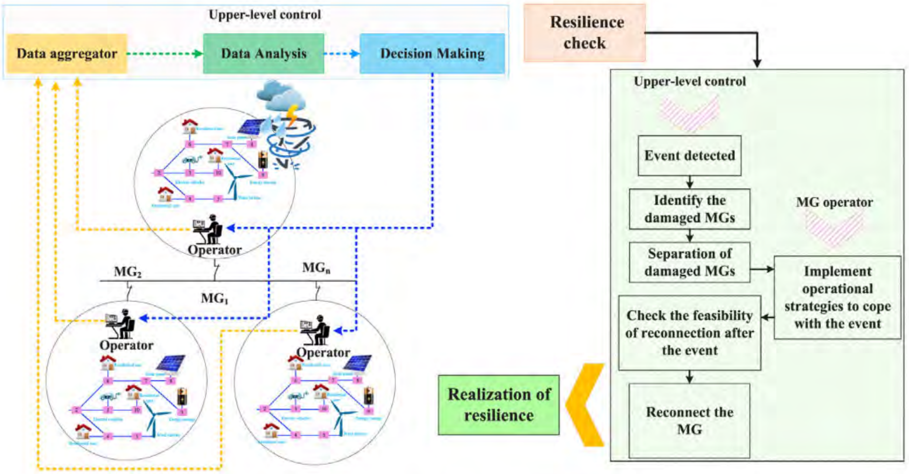


Fig. 9. Realization of resilience in a power system consisting of multi-microgrids.

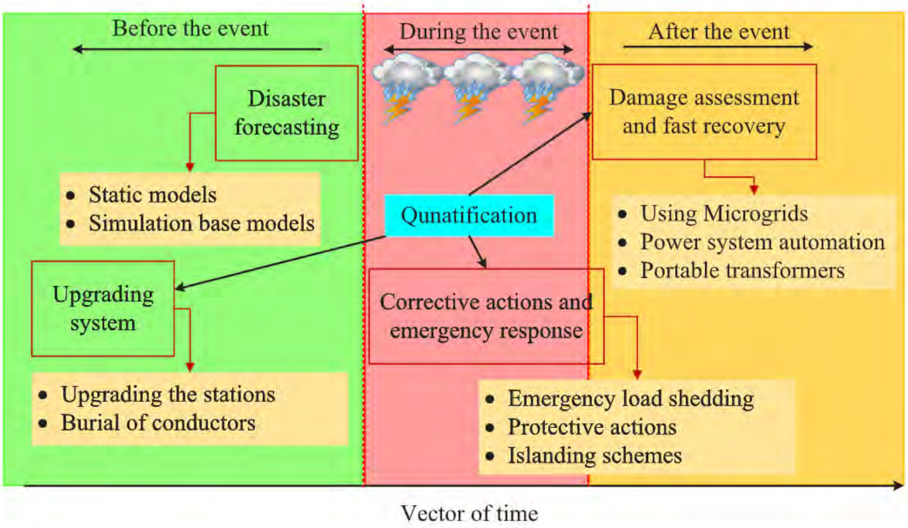


Fig. 10. The chronological order of the necessary actions in the power system to deal with natural disasters.

Table 2
Proposed metrics for resilience of the power system.

$Ref.$	Metric	Reliab.	Event	Phy. struct.	Compat.	Appl. level	Time Horiz.
[9]	$\mathfrak{R} = \int_t S(t)dt$	√	×	×	×	DS	Short
[9]	$\mathfrak{R} = \sum_i^n$	√	×	×	×	DS	Short
[9]	$\mathfrak{R} = \frac{\sum_{i=1}^{n} t_{up,i}}{\sum_{i=1}^{n}(t_{up,i}+t_{down,i})}$	×	×	√	×	DS	Short
[29]	$\mathfrak{R} = \sum_{j=1}^{N} V(j).\lambda(.,j)$	×	×	√	×	DS	Long-Short
[89]	$\vec{\mathfrak{R}} = [F_c, D_G, l_G, C_B, C_n, \Lambda_2]$	×	×	√	×	DS	Long-Short
[80]	$BNI_q = \frac{\sum_{k=1}^{N_q} \frac{\text{Nodes in PCWL for } kth \text{ PN}}{\text{Number of CLs in } kth \text{ PN}}}{N_q}$	×	×	√	×	DS	Long-Short
[80]	$OB_q = \frac{\sum_{k=1}^{N_q} \text{Common branches in } kth \text{ PN}}{N_q}$	×	×	√	×	DS	Long-Short
[80]	$NoR_q = \frac{\sum_{k=1}^{N_q} \frac{\text{Resources supplying all CLs in } kth \text{ PN}}{\text{Number of CLs in } kth \text{ PN}}}{N_q}$	×	×	√	×	DS	Long-Short
[80]	$RA_q = \frac{\sum_{k=1}^{N_q} \text{Routes joining CLs to sources in } qth \text{ FN}}{N_q}$	×	×	√	×	DS	Long-Short
[80]	$PoA\&PF_q = \frac{\sum_{k=1}^{N_q} RoA \times PF \text{ for } kth \text{ PN}}{N_q}$	×	×	√	×	DS	Long-Short
[90]	$\mathfrak{R} = [\Psi^{\lambda}_{i,n,d,t}, \Psi^{\mu}_{i,n,d,t}, \Psi^{\partial}_{i,n,d,t}]$	×	×	√	×	DS	Long-Short
[27]	$\mathfrak{R} = \frac{1}{NT} \sum_{h=1}^{NT} \sum_{l=1}^{N} \sum_{t=h+1}^{h+H} \Delta t.LS$	√	×	×	×	MG	Short
[77]	$\mathfrak{R} = \Im(V_{LL}, N_L, I_L, R_N)$	√	×	√	×	DS	Long-Short
[28]	$\mathfrak{R} = \xi(LOLP, EDNS, F, G)$	√	×	√	×	MG	Short
[58]	$\mathfrak{R} = FI + (1 - REI) + MVI + LLI$	√	√	√	×	MG	Short
[55]	$\mathfrak{R} = \xi(LOLP, EDNS, Y, \Psi, \Lambda)$	√	√	√	√	TS	Long

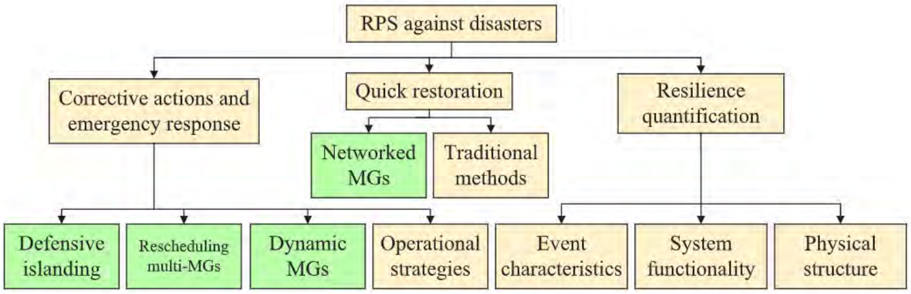


Fig. 11. The role of microgrids in the resilience of the power system context.

the corresponding literature. It should be noted that the primary goal in this paper is to present a view of numerical calculations for different resilience criteria, and therefore the evaluation of resilience is out of the scope and thus is not examined in detail.

The first set of metrics that are considered for numerical evaluation in this paper consists of LOLP, EDNS, fragility index (Y), and restoration metric (Ψ), which are commonly used for long term resilience assessment in the literature. According to [55], the mesh view of the power system and the Monte-Carlo simulation method are used for calculating these metrics. By applying the mesh view, the locations of all equipment and components of the power system, including buses, lines, loads, and generation units are first determined. Different scenarios are subsequently generated by creating random extreme events in different locations upon the transmission system. The amount of damages is

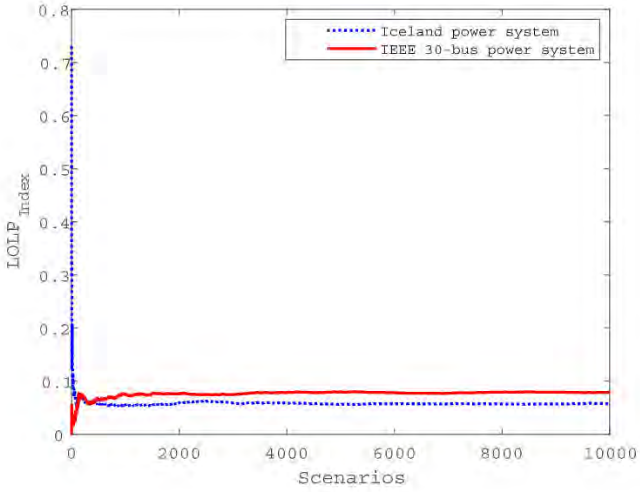


Fig. 12. The convergence of the LOLP index through the Monte-Carlo simulation.

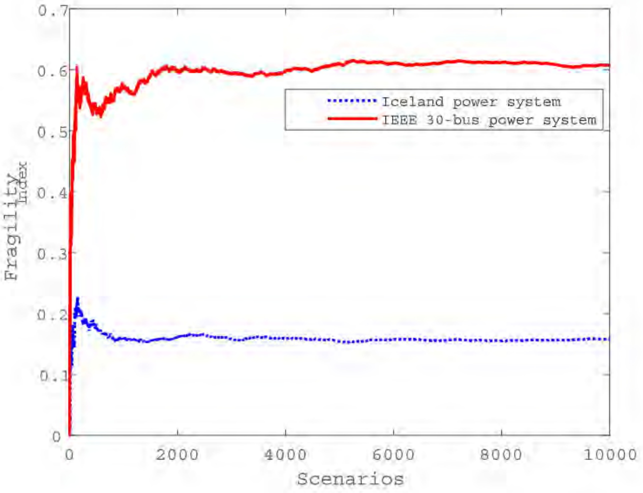


Fig. 14. The convergence of the fragility index through the Monte-Carlo simulation.

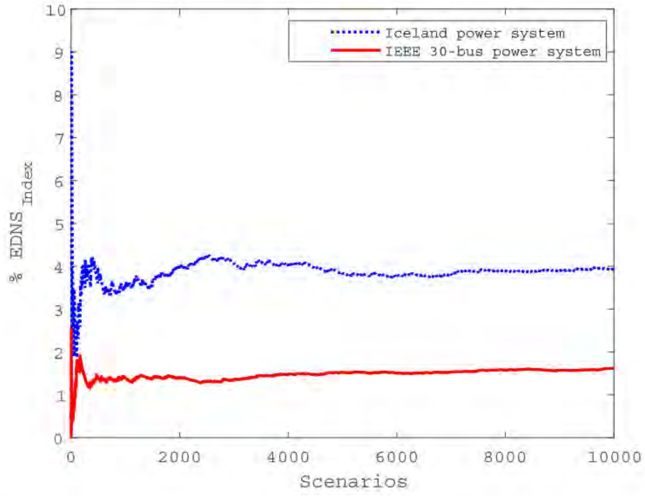


Fig. 13. The convergence of the EDNS index through the Monte-Carlo simulation.

evaluated and the resilience criteria are finally calculated using the OPF program. The proposed metrics are expressed and shown in (1) – (4), where N_s should be great enough.

$$LOLP = \frac{1}{N_s} \sum_{s=1}^{N_s} \chi_s \times P_s \tag{1}$$

$$EDNS = \frac{1}{N_s} \sum_{s=1}^{N_s} \chi_s \times P_s \times \Omega_s \tag{2}$$

$$Y = \frac{1}{N_s} \sum_{s=1}^{N_s} \int_0^{\infty} k_s f_s(k) dk \tag{3}$$

$$\Psi = \frac{1}{N_s} \sum_{s=1}^{N_s} \sum_{i=1}^{5} w_i \varepsilon_i P_s \times P_s^{char} \tag{4}$$

The proposed metrics are calculated under both the IEEE 30-bus standard test case and the practical wide-area Iceland 187-bus power system with 10 000 scenarios (i.e. $N_s = 10\,000$). The data of two system cases are extracted from [55]. The results are plotted in Figs. 12–15.

To better validate the calculated criteria, the comparison between the IEEE and Iceland power systems has been evaluated in terms of resilience. For example, in terms of the LOLP standard, the Iceland power system is more resilient than the IEEE system in the face of a destructive event. From the viewpoint of EDNS, in the case of an extreme event, approximately 1.39% of IEEE system loads and 3.86% of Iceland system load are expected to be lost. Therefore, it can be concluded that the IEEE system is more resilient if compared to the Iceland system in terms of EDNS. As shown in Fig. 14, for the fragility index that is calculated based on the lines on outage due to the event, the IEEE test system is more vulnerable than the Iceland system. This criterion is related to the topology of the systems. It is obvious to see that, the IEEE system has a better performance compared to Iceland. The geographical extent of the systems also has an impact on this metric.

Furthermore, these metrics can be used for long-term resilience enhancement programs. The power system operator and planners can use these measures in finding the weaknesses of the system and upgrading them to improve the resilience against future extreme events.

Some of the other criteria shown in Table 2 are classified as short-term resilience assessment metrics. These parameters are calculated using the real-time performance of the power system against a destructive event. Criteria such as the withstand ability of the system to cope with the event (FI) and restoration efficiency index (REI) show the recovery speed of the power system after the event. These two measures are calculated using the SFC (please see Fig. 8). In addition, voltage deviation index (MVI) and amount of lost load (LLI), in which they are achieved through the system's instantaneous parameters, (e.g.,voltage and lost loads), are also considered in the numerical simulations. The IEEE 33-bus test system is evaluated in this paper to validate the short-term resilience metrics (i.e. FI, REI, MVI, LLI) with the data extracted from [61].

In [61], a two-stage stochastic scheduling model is employed to improve the short-term resilience of a microgrid in a 24-hour time horizon while reducing operating costs. In this paper, the percentage of supplied load is considered as SFC as shown in Fig. 16. We can see from the figure that integrating the resilience measures in the proposed scheduling method can significantly improve the SFC, resulting in an advanced enhancement for the resilience metrics. Resilience metrics can be calculated by the following formulation.

$$FI = \sum_{s=1}^{N_s} v_s \frac{\int_{t_d}^{t_{pe}} (M_p - M(t))dt}{M_p(t_{pe} - t_d)} \tag{5}$$

$$REI = \sum_{s=1}^{N_s} v_s \frac{\int_{t_r}^{t_{pr}} (M(t) - M_{pe})dt}{(M_p - M_{pe})(t_{pr} - t_r)} \tag{6}$$

$$MVI = \sum_{n=1}^{N_{bus}} \sum_{s=1}^{N_s} v_s \left(\sum_{t=1}^{N_t} (|V_n^* - V_{nts}|) \right) \tag{7}$$

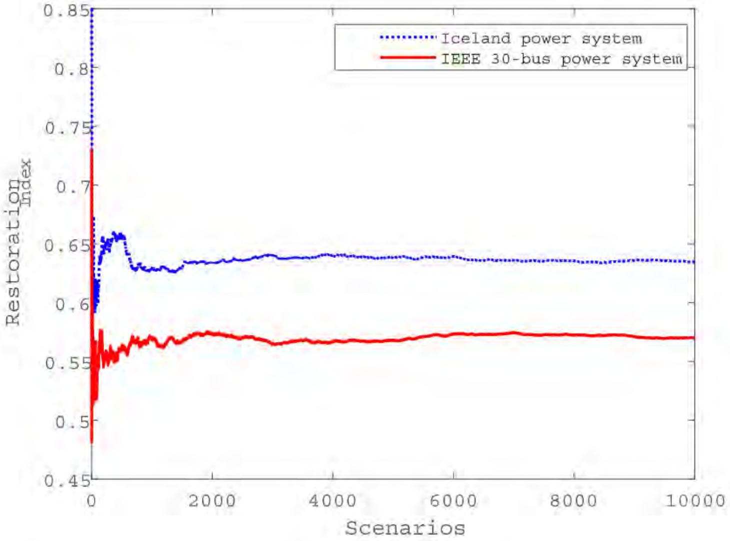


Fig. 15. The convergence of the restoration index through the Monte-Carlo simulation.

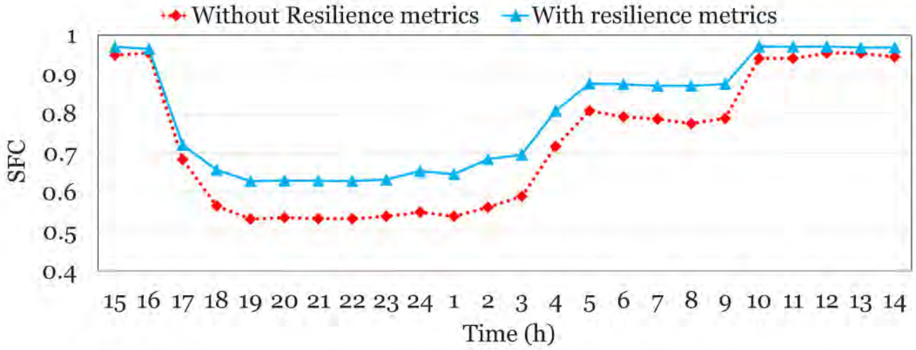


Fig. 16. The system functionality curve for the IEEE 33-bus test system during an extreme event.

$$LLI=\sum_{n=1}^{N_{bus}}\sum_{s=1}^{N_s}v_s\left(\sum_{t=1}^{N_t}\left(\frac{P_{nts}^{shed}\Delta t}{P_{nts}^{L}}\right)\right)\tag{8}$$

The simulations are carried out in two cases. In the first case, it is assumed that the resilience metrics are neglected in the scheduling process, with the operating cost targeted as the main goal during the planning. The resilience metrics are then calculated for the assessment. In the second case, it is assumed that resilience metrics are considered in the formulations as an independent objective function. The results are illustrated and shown in Fig. 17 with different resilience measures. We can see that, integrating the resilience criteria in the planning program results in a tremendous and quick improvement in the short-term resilience or operation resilience of a power system with a significant reduction in costs and computational time.

In all, this section has graphically shown how numerical criteria can be used to evaluate and improve resilience of the power system in the short-term and long-term time horizons.

5. Applications of smart grids for enabling resilience

The attention for applying microgrids to improve resilience of the power system has been continuously increasing [94]. The capabilities of a microgrid to improve the power network resilience can be examined in five main categories i.e. (i) converting power systems into microgrids, (ii) deployment of dynamic microgrids, (iii) networked microgrids, iv) multiple-microgrids, (v) other methods. Numerous studies have been widely developed under each category, with some of which are summarized in Table 3. By validating the information presented in Table 3 and Fig. 11, we can clearly understand the key roles of smart microgrids in different phases of resilience in the face of destructive events. From the moment when the event occurs, the sensitive loads of the system can be satisfied by creating dynamic microgrids. This feature improves the ability of the system to withstand the event. In the second step, the fast recovery process starts from reconfiguration and forming networked microgrids [95]. Furthermore, the use of smart microgrids as resilience sources decreases the lost load and economic losses [96] and rises social welfare in the meanwhile.

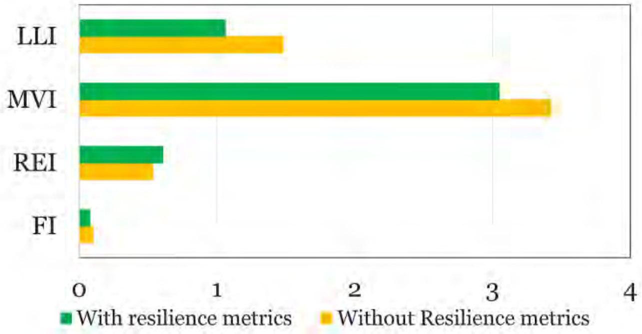


Fig. 17. The short-term resilience metrics of the power system.

Table 3
Review on diverse uses of microgrids in the resilience of the power system context.

Category	Ref.	Description
Converting power systems into microgrids	[97]	Determining the capacity and optimal location of power switches
	[98]	Fast division of distribution systems into microgrids
	[99]	Creating independent microgrids
	[100]	Distribution systems reconfiguration
	[101]	Assessing the effect of adding microgrids on the resilience of an interdependent gas-power network using Graph and network theories
Deployment of dynamic microgrids	[102]	A load shedding method for creating dynamic microgrids
	[71]	Dividing healthy parts of the system into microgrids
	[103]	Instant management of distributed resources
	[104]	A recovery scheme using the master–slave method through microgrids
	[105]	Instant reconfiguration
Networked-microgrids	[106]	Possible islanding in normal condition for saving critical loads in an emergency
	[107]	An operational method for coordinating neighboring microgrids to improve resilience
	[108]	Optimal planning of networked microgrids considering resilience constraints
	[109]	Energy management of networked microgrids for resilience optimization
	[110]	Flexible strategies for disconnecting/reconnecting networked microgrids
	[111]	Power-sharing methods in networked microgrids to improve resilience
	[112]	Physically interconnection of isolated microgrids through common bus for sharing energy during emergencies
Multiple-microgrids	[113]	Development of a set of independent microgrids
	[114]	The resilience of multiple interdependent energy systems
	[115]	Evaluation of CHP generation units based on pollution and resilience
	[27]	A hierarchical output management method in multiple microgrids
	[116]	Identifying vulnerable equipment to improve the resilience
	[117]	Autonomous set of microgrids through the deployment of energy hubs
	[118]	Stochastic programming to minimize the investment cost of resilience enhancement schemes through multi-microgrids for power and water systems
	[119]	Resilience-oriented stochastic modeling of distribution systems based on disaster effect on infrastructures considering multi-microgrids
	[120]	Proposing an integrated mechanism to enhance the distribution systems resilience through a three-level method in terms of decreasing lost load
Other methods	[37]	Reduce load shedding using a robust method through microgrid scheduling
	[121]	Stability analysis of microgrid when feeding sensitive loads in the island mode
	[122]	Economic analysis of microgrid when feeding sensitive loads in the island mode
	[57]	Calculation of microgrid performance curve in the face of destructive events
	[123]	Investigating the resilience of communication systems and grid dynamics
	[124]	Bi-level reserve scheduling and providing reliable power in connected microgrids
	[65]	Evaluation of microgrid capabilities to improve resilience
	[125]	Planning urban residential microgrids using hybrid renewable resources
	[126]	Integration of distributed energy resources in microgrids
	[127]	Cascade AC failures model for power grid resilience analysis
	[67]	A comprehensive mathematical model for improving microgrid resilience
	[61]	Developing a tow-objective resilience-economic model for microgrid scheduling
	[84]	A comprehensive mathematical model for resilience evaluation considering microgrids
	[128]	A two-stage model for improving the resilience of islanded microgrids through battery swapping stations
	[129]	Developing a two-stage optimization model to guarantee the resilience of microgrid during an event

As a direction and guidance to future research, Table 4 summarizes some highlighted research on microgrid applicability for resilience of the power system. According to Table 4, although various research has been developed on the applications of smart microgrids in the context of resilience of the power system, the gaps are still there and await to be addressed. With the data provided in Table 4, the following research gaps can be concluded:

- Lack of comprehensive resilience measures in microgrids-based power systems.
- Lack of a mathematical model for integrating resilience metrics in the planning stage and optimization process.
- Huge computational burden of the proposed strategies for calculating resilience of large-scale power systems.
- Limited research on studying the behavior of extreme events on power systems.
- Lack of a coordinated relationship between assessing the resilience and decision making against extreme events.
- Lack of identifying the potentials of multiple microgrids for defining self-healing strategies for improving resilience of the power system.

Table 4
Analysis of the research on the use of microgrids for resilience.

Ref.	Test case	Main contribution	Defects
[37]	A small sample microgrid	Robust microgrid scheduling	Ignoring resilience metrics
[57]	IEEE 30-bus	Resilience evaluation using SFC	Only overhead lines considered
[61]	Modified IEEE 33-bus	Two-objective bi-level microgrid scheduling	Applied to one microgrid
[67]	IEEE 33-bus	Bi-level microgrid scheduling	Ignoring resilience metrics in the objective function
[84]	Iceland real power system	Resilience evaluation considering microgrids	Large computational burden
[113]	IEEE 14-bus	Evaluating the resilience	Ignoring the economic aspects
[114]	A 33-bus feeder	Hierarchical outage management of microgrids	Ignoring AC power flow constraints
[121]	3-feeder 16-bus case	Stability of microgrid in feeding CLs	Ignoring resilience metrics in design
[122]	Low voltage 10-bus case	Economics of a microgrid in feeding CLs	Ignoring resilience metrics in design
[123]	Modified IEEE 123-bus	Communication system resilience	Ignoring the PSR
[124]	A real system in Canada	Ensuring reserve and reliable power in microgrids	Only fed loads are considered as resilience metric

- Lack of efficient models for energy transactions between neighboring microgrids in an emergency condition.

6. Conclusions

The resilience of critical human infrastructures such as power systems, communication systems, transportation systems, and resource availability is closely related to the life of millions of people who are affected by extreme events. In addition, the need for sustainable energy in all infrastructures has highlighted the importance of resilience of the power system in the face of adversities. The need to address resilience of the power system is first described in this paper. Standard definitions established for resilience are then expressed under various conditions. Through the literature review, the benefits of applying smart microgrids to improve resilience of the power system are further extracted. Numerical simulation case studies on various applications of microgrids and their potential use as sources of resilience in power systems have been finally demonstrated with effective and efficient system performance.

6.1. Remarks

The main contributions of this paper can be summarized as follows:

- A comprehensive resilience measure should be considered with different types and severity levels of the event.
- Considering the system and event uncertainties makes the results more realistic.
- Power systems are more vulnerable to adverse weather-related events than other natural disasters.
- Considering microgrids improves resilience of the power system by reducing lost loads.
- Distributed energy resources can reduce system dependence on transmission lines through microgrids and improve resilience.
- The rate of system degradation during the disaster can be reduced by deploying dynamic microgrids.

6.2. Future directions

The following research areas are proposed for future work:

- Utilize distributed control strategies such as reinforcement learning for network management during the event. The reason is that these methods do not require a communication system, they also offer a huge advantage in terms of cyber-attacks and flexibility at the same time.
- Involving the development of self-healing mechanisms in power systems, such as defensive islanding through multiple microgrids, to reduce the effects of severe adversities. The damaged sections of the power system will be immediately separated under this condition to prevent a major outage from occurring.
- Modeling resilience-oriented scheduling for multiple microgrids in critical situations. This will make it possible to improve short-term resilience without consuming much time and cost.
- Employing the concept of blockchain for energy transactions between neighboring microgrids in an emergency condition. Under this circumstance, the generated power of independent producers will be available through smart and quick contracts to save the critical loads.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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