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REVIEW ARTICLE

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An overview of the assessment metrics of the concept of resilience in electrical grids

Arash Dehghani | **Mostafa Sedighizadeh** | **Farhad Haghjoo**

Department of Electrical Engineering, Shahid Beheshti University, Tehran, Iran

Correspondence
Mostafa Sedighizadeh, Department of Electrical Engineering, Shahid Beheshti University, Tehran, Iran.
Email: m_sedighi@sbu.ac.ir

Abstract

The subject of resilience in electrical grids has become more popular among researchers in recent decades due to the rise of worldwide natural disasters such as floods, severe storms, snow, and hailstorms as well as the imposition of high costs resulted from widespread outages. Various methods have been proposed to improve the resilience of electrical grids under different conditions. In each work, the authors have validated their proposed method based on a function or metric they have defined to clarify its effect on improving the resilience of electrical grid. However, to date, there is no standardized metric for assessing the resilience of an electrical grid and providing the possibility to compare the many strategies discussed in different papers. This paper tries to explain the metrics that have been presented in various researches in this regard so far, and it compares these metrics from different aspects in order to determine the most comprehensive metric.

KEYWORDS

assessment, electrical grid, high impact low-probability events, metric, resilience

1 | INTRODUCTION

1.1 | Motivation and incitement

With global warming and climate change in recent years, natural disasters such as floods, hurricanes, and hailstorms have increased significantly across the globe. These catastrophes have led to frequent power outages, resulting in socio-economic losses and more importantly, irreparable loss of life in various countries.[1-3] Thus, since 2002, the concept of

List of Symbols and Abbreviations: $d(n_i, n_j)$, number of branch between node n_i, n_j; t_0, moment of start of the event; t_{oe}, moment of decline in network performance; t_{ee}, moment of end of the event; t_r, moment of start of network recovery; t_{r_a}, moment of start of network recovery in condition a; t_{r_b}, moment of start of network recovery in condition b; t_{pr}, end of restoration state of network; t_{ir}, moment of start of infrastructure recovery; $|E|$, total number of branch; $F(t)$, system performance in actual state; $\widehat{F}(t)$, system performance in normal state; $|N|$, total number of node; T, total time of consideration; T^o, estimated system outage duration; T_r, moment of end of network recovery; σ_{st}, total number of shortest paths between nodes s and t; $\sigma_{st}(k)$, number of shortest paths between nodes s and t that pass through node k; R_0, pre-disturbance resilience level; R_{pd}, post disturbance resilience level; S_a, area of trapezoid while the network is in condition a; S_b, area of trapezoid while the network is in condition b; E, time of grid decline retention; Λ, amount of decline; Π, speed of recovery; Φ, rate of decline; AHP, analytical hierarchical process; CAIDI, customer average interruption duration index; CI, choquet integral; CL, critical load; CVaR, conditional value at risk; DOE, Department of Energy; EENS, expected energy not supplied; EIU, energy index of unreliability; EOD, expected outage duration; EPI, expected probability of interruption; GFA, grid friendly appliance; HILP, high impact low probability; LOLF, loss of load frequency; PN, possible network; SAIDI, system average interruption duration index; SAIFI, system average interruption frequency index.

resilience, first introduced by Holling in 1973,[4] has drawn the attention of many researchers and there has been a lot of research around the world over the last two decades.

Given that a standard definition has not yet been defined for the concept of resilience, with the increasing importance of this issue in the last two decades, several definitions of this concept have been proposed in various papers, some of which are mentioned in the following. The concept of resilience in a power system may be defined as "the ability of the system to withstand low-probability high-impact events, so that the least number of outages occur in providing power to grid loads as well as its capability to quickly recover and return to normal status."[5,6] Moreover, resilience can be defined as "readiness or adaptability to change conditions as well as tolerance and rapid recovery of interruption."[7] In general, several definitions are proposed but all of them focus on the ability to *anticipate*, *absorb*, and *quick recovery of the system* in dealing with external, high-impact, and low-probability shocks.[8,9]

Current power systems are designed to be efficiently resistant and protected against events with low-impact intensity and high-probability of occurrence which occur due to various incidents such as equipment failure, human errors, or external disturbances. However, necessary measures have not been taken yet to protect against events with low probability but extensive destructive effects on the grid and many studies and researches are done in this regard every year.[10-12]

According to a study by the U.S. DOE, resilience to major disasters, such as severe storms or earthquakes, is the most important feature that smart distribution grids must possess in the future.[7,13] It should also be noted that more than half of cyber-attacks the confronting measures of which are also a part of the resilience parameter of a grid, resides in the responsibilities of the energy sector.[14]

1.2 | Importance of presented work

In order to explain the importance of the review conducted in this paper, it is first necessary to point out the reasons for the need to provide a standard metric for the issue of resilience in electrical networks:

- Ability to express the status of a network to a planner or policy maker from a resilience perspective; If policies or investments are aimed at improving the resilience of an electrical network, it is first necessary to measure the resilience parameter with a standard method and metric. However, a clear trend and a standard metric for measuring the resilience of a network have not been defined yet,[9,15-17] and individual researchers who are doing research in this field, depending on their perception of this concept, have provided a metric for it.
- Another issue that will emphasize the need to define a standard metric is the possibility of comparing different methods of improving resilience. In other words, if a standard metric is not specified for this issue, it is not possible to show the superiority of different methods of improving resilience over each other.

The first step in determining and defining a standard metric is to review and compare the metrics for this parameter. Therefore, in Section 2 of this study, the metrics presented in many papers, some of which are mentioned in an initial category, in Table 1, are described and compared in terms of various parameters.

In explaining the importance of this study, it can be pointed out that in one study, a suitable method or solution may be proposed to improve the resilience while the applied evaluation metric is not appropriate with many drawbacks. For instance, a study may provide a solution for organizing and managing microgrids to optimize the grid resilience level. However, to show and evaluate the proposed method, the cost parameter has been considered as a metric. As it will be discussed later in this paper, considering the cost as a metric will not be very interesting. This is because in critical conditions, which is the subject of resilience and usually involves a short period of time, the cost metric is insignificant and not desirable.

1.3 | Extent of the presented work

Given that the term "resilience" is conceptually general, a lot of researches have been performed in various fields including health, economics, transportation, earthquakes, environmental issues, agriculture, communications, energy supply, and so on[41-44]; however, all of which are beyond the scope of the present paper. Besides, some of these researches are only for the system or grid in question and do not carry the required efficiency and analysis capability

TABLE 1 Classification of resilience metrics presented in scientific papers from different aspects

	Level of metric			Time-line of metric					Spectrum of metric		Time dependence of metric		Probabilities of the metric		Number of event in metric		Network tested by metric		Load priority in the metric
Publication	Transmission	Distribution	General	Pre-event	During fault	Downtime part	Recovery part	Post restoration	Planning (passive)	Operational (active)	Dynamic	Static	Deterministic	Stochastic	Single event	Several events	Real network	Simulated network	
Farzin[5]		√				√	√			√	√		√		√			√	
Bie[18]		√					√			√		√	√		√		√	√	√
Bian[19]		√				√	√			√	√		√		√			√	
Darestani[20]		√					√		√					√		√	√		
Mousavizadeh[21]		√				√	√			√	√			√	√		√	√	
Chanda[22]		√		√	√	√	√	√		√	√	√	√			√		√	√
Saini[23]		√			√	√	√			√	√			√	√		√		√
Chen[24]		√			√		√	√		√	√		√		√			√	√
Amirioun[25]		√		√					√		√		√		√			√	√
Balasubramaniam[6]		√		√	√	√	√			√	√			√	√			√	√
Xu[7]		√			√	√	√			√	√		√		√			√	√
Wang[26]		√					√			√	√		√		√			√	√
Lei[27]		√		√			√		√	√	√			√	√			√	√
Bajpai[28]		√			√		√		√	√		√	√		√			√	√
Ouyang[29]	√	√		√	√	√	√		√	√	√			√		√	√		
Najafi[30]		√		√					√			√		√	√			√	√
Zhang[31]		√		√	√	√	√			√	√			√	√			√	√
Amirioun[10]		√		√	√	√	√		√		√			√	√			√	√
Ouyang[32]	√			√	√	√	√		√		√			√		√	√	√	
Ouyang[33]	√			√			√		√	√	√			√	√	√	√		√
Liu[34]			√	√	√		√		√	√	√			√	√			√	
Ouyang[35]	√	√					√			√	√			√	√		√		
Panteli[36]	√			√	√	√	√			√	√			√		√	√		
Panteli[37]	√			√	√	√	√			√	√			√	√		√		
Ashrafi[38]		√		√	√	√	√		√	√	√			√	√			√	
Espinoza[39]	√				√	√	√			√	√		√	√	√		√		√
Panteli[40]	√				√	√	√		√	√	√			√	√		√		

for other systems or grids. Therefore, in this study, it has been tried to introduce and compare only the metrics used in evaluating the resilience of electrical grids.

It should be noted that the objective of this paper is not to review the various methods presented to improve the resilience of a system or grid, as this has been done in several studies,[11,13,15,18,45-50] rather it aims to compare the various metrics employed to evaluate the resilience of electrical grids.

Despite the importance of resilience and the need to define a standard metric for this issue, little research has summarized the proposed metrics on measuring resilience in electrical networks. Table 2 contains review papers that somehow address the issue of resilience metrics.

In most of the papers in Table 2, only a minor part of the study and during the review of methods to improve resilience or other topics, some resilience metrics are mentioned. Another problem in the review papers on the subject of resilience metrics is the lack of classification. In other words, in most of these reviews, the proposed metric in each paper is described and analyzed separately, while the basis and performance principles of many metrics presented in different papers are the same. And this makes it impossible to summarize to provide the most appropriate metric to measure resilience in electrical networks.

In this study, more than 40 resilience metrics presented in various researches, based on their performance principles, in the form of six groups of categories, are described and compared from different aspects. Therefore, this research can help technical-scientific committees to define a standard metric and thus enable the comparison of resilience improvement methods with a common criterion and prevents further scattering of this issue in future research.

1.4 | Contributions and organization

With respect to the growing importance of resilience in infrastructure systems and above all, the "electricity supply network" as well as the lack of scientific commissions to define the standard metric so far, in this paper, different metrics have been reviewed and examined which have been presented in various researches in electrical grids. The main contributions of this paper are as follows:

- Investigating a wide range of research and extraction papers that express new ideas and relationships for measuring resilience in electrical grids;
- Categorizing the presented ideas and expressing some of the main drawbacks of the introduced metrics;
- Presenting and describing the basic features that a resilience metric is necessary to have until it can accurately measure this parameter in electrical grids; and,
- Comparison and evaluation of different metrics and proposing the most appropriate metric to modify and standardize the process of measuring this parameter in electrical grids.

While implementing resiliency strategies for different levels of a network might have their own specific realizations, many metrics of resiliency are independent of the voltage level in which they are being considered. With this regard, bulk, transmission levels, microgrid, and distribution levels in an electrical system may share the same metric with little modifications or may obtain ideas from each other. Therefore, it is essential that in this paper, ideas in all those levels are studied. Thus, the whole electrical network from high voltage to low voltage has been examined together.

This paper is organized in different sections as follows: Section 2 presents common metrics introduced in previous researches used to evaluate the resilience in electrical grids. Section 3 investigates the papers which consider only the parameter of resilience as a metric. Section 4 describes the important factors in comparing different metrics, Section 5 provides a comparison between the introduced metrics where their advantages and disadvantages are described. Finally, the paper is summarized in Section 6.

2 | INTRODUCTION OF COMMON METRICS IN RESILIENCE ASSESSMENT

In this section, more than 40 metrics of measuring resilience in electrical networks proposed in papers published in scientific journals have been divided into six groups, described, studied, and compared. Also, the metrics mentioned in only one paper and are less used in other studies are in the seventh row of this grouping. Table 3 shows the groups of resilience assessment metrics.

TABLE 2 Characteristics of previous review papers on resilience metrics in power systems

Publication	Year	Characteristic review
Kandaperumal[51]	2019	• Expression of resilience definitions and division of HILP events into physical-manmade, physical-natural, cyber • Classification of distribution network resilience assessment and improvement methods from different aspects including: temporally (before, during, and after the event), passive (pre-event designs and planning), active (methods used during and after the event) • Classification of distribution network resilience metrics into two parts: attribute-based metrics and performance-based metrics
Das[52]	2020	• Express various definitions of resilience and its differences with the concepts of reliability and robustness • Expression of analysis methods as well as metrics of resilience measurement in engineering systems • Classification of resilience metrics for smart grids into two groups: qualitative and quantitative
Mahzarnia[53]	2020	• Classification of measures to manage resilience in power systems in terms of time into three groups including planning, response, restoration • An overview of resilience measurement metrics and their classification into two categories: qualitative and quantitative • Planning power systems to improve resilience and classify it into two parts: distribution and transmission • Review resilience-based power system responses including unit commitment, transmission line switching, using microgrid as a resilience resource, and defensive islanding • Review the advantages and disadvantages of using renewable resources on the resilience of a network
Bhusal[54]	2020	• Classification resilience metrics into attribute base and performance base • Express resilience assessment criteria such as minimizing lost load, recovery rate, or energy served. • Express the methods of improving resilience and dividing these methods into two general categories: planning base and operational base. • Express resilience evaluation methods (such as methods that are based on machine learning, contingency, Bayesian network) • Review optimization methods.
Hossain[55]	2021	• Definitions and differences of reliability and resilience parameters • Methods and metrics for measuring reliability and resilience • Ways to improve and measuring reliability and resilience for the US grid
Umunnakwe[56]	2021	• Classification of resilience metrics using Axiomatic Design Process method. • Classification of metrics based on system connectivity parameters, failure/recovery parameters, active power, energy cost, voltage magnitude, and line thermal limits. • Review of resilience metrics at three levels of distribution, transmission, and Generic.

2.1 | Metric 1: The load recovered or the energy not supplied

One of the common metrics used in various studies in order to investigate the resilience of electrical grid is the amount of load recovered or supplied after an event. For instance, in Reference 18, which has reviewed the resilience improvement and assessment methods in various researches to evaluate their proposed method, the recovered load rate has been considered as a metric of resilience evaluation. In Reference 19, which schedules the electrical grids to improve resilience, minimizing the lost load has been considered as a resilience assessment metric. Reference 20 has combined the probabilistic model of wind and the fragility model of electric poles to measure the resilience of an electrical energy distribution network by measuring the percentage of loads supplied relative to the time period under study.

In other studies, the ratio of supplied loads to the total load in the studied grid has been considered as a resilience metric. Considering that the difference between the values of numerator and denominator in this ratio is related to the amount of recovered loads, it can be said that in practice, the resilience metric is the same as the amount of recovered load.[21] Reference 22 has introduced and used the amount of lost load with emphasis on the time period of the event as a metric of resilience.

Moreover, considering that the speed of recovering lost loads is one of the basic parameters and features of the concept of resilience in the electrical energy grid, in some studies, taking into account the time interval of unsupplied grid loads, the amount of energy not supplied has been considered as a metric to evaluate the resilience of a grid against an event. For instance in Reference 5, the average of total energy lost in a set of microgrids in the electrical energy distribution grid is defined as the resilience metric and has been used to demonstrate the efficiency of the proposed method. In Reference 23, which suggests improving resilience by optimizing reinforcement strategies, using energy storage units, underground cables on the grid-side, and using home battery inverters and communication infrastructure on the demand-side, Has used the ratio of energy served to the expected energy demand, in other words, the amount of unsupplied energy in the grid has been used as an indicator of resilience.

2.2 | Metric 2: The supplied critical loads

The amount of critical loads supplied after an event has been used in various studies as a metric for the resilience assessment of electrical grids. As mentioned before, basically the concept of resilience was presented to address the occurrence of unusual disasters, namely severe storms, floods, earthquakes, etc, which lead to widespread outages and make feeding critical electrical grid loads impossible for a considerable period of time and disrupts the management and operation. Therefore, the definition of this metric as a tool to evaluate the resilience of an electrical grid seems to be logical. Following are a number of studies using this metric to assess resilience.

In Reference 24, which investigates the scheduling of electrical grid at the time of terrible events, the maximum supply of critical electrical grid loads has been used as a metric of resilience assessment. Simultaneous scheduling of electricity and gas energy carriers for storage as well as reduction of unnecessary loads before an event occurrence to improve the resilience of electrical grid, has been performed in Reference 25 where the supplied critical load has been considered as the resilience metric.

Reference 6 has proposed prioritizing energy storage over supplying non-critical loads to improve resilience and the objective function to be maximized is the supply of critical loads in the studied electrical grid. Another study, which generally examines the issue of electrical grid resilience from the perspective of dynamic discussions and maintenance of the electrical grids stability, has considered the maximization of the supplied critical loads as the objective function.[7] Maximum supply of critical loads in an electrical grid, as a metric with an emphasis on the correlation and connection of the components as much as possible in order to provide the possibility of using the capacity of the resources available in the grid, has been proposed and scheduled in Reference 26. The use of portable emergency generators has been investigated in Reference 27 considering the traffic status on the roads before and after the occurrence of an event, with the aim of providing maximum critical loads in the electrical grid.

One of the main drawbacks of this metric is the lack of a clear definition for critical loads, in other words, the lack of a clear standard for prioritizing the supply of loads in electrical grid. Therefore, critical loads have been considered in different ways in the scheduling performed in different papers. For example, in Reference 25, 30% of the load of each bus is considered as the critical load. In References 7,28,68, the power required to perform basic social activities, such as the power of hospitals and street lighting is considered as a critical burden. In References 29,30,51, hospitals, water pumps and gas pressure stations have been included as critical loads in their calculations.

TABLE 3 Resilience assessment metrics

No.	Applied metrics	References
1	The load recovered or the energy not supplied	5,18-23
2	The supplied critical loads	6,7,24-27
3	Resilience assessment with curve analysis	10,15,29,31-38,57-60
4	Modified reliability metrics	37,39,40
5	Assessment using graph theory	28,55,56,61,62
6	Assessment by examining cost (Operating cost / investment cost / power supply interruption cost)	14,30,63,64
7	Other metrics	65-67

2.3 | Metric 3: Resilience assessment with curve analysis

Resilience assessment using curves has been considered as a metric in a number of researches. In order to explain the assessment methods of resilience using a curve, it is necessary to first describe the curve used in this regard and its variation trend. The issue of resilience, before being considered as one of the infrastructures in electrical grids, was generally raised in many large structures such as health, economics, transportation, and so on. The concept of resilience using a curve was first proposed by Bruneau in 2003 to measure and increase seismic resilience.[57] The general format of this curve, entitled "resilience triangle," has been shown in Figure 1.

The vertical axis in the curve represents the characteristics or performance of an electrical grid, which significantly loses its efficiency at moment t_{oe} due to the occurrence of an event and it is recovered in the period t_r to T_r and the system returns to its initial working state. In examining the impact of a catastrophic event on a structure or system, two parameters are important: The first parameter is the amount of the decline that the structure is affected by and the second parameter is the time required to recover the system and return it to the pre-event state. The first parameter has been considered on the vertical axis while the second parameter on the horizontal axis. Strategies proposed to improve the resilience of an electrical grid, either by improving electrical grid performance in the case of events (reducing the decline in system performance on the vertical axis) or by reducing the system recovery time (reducing the horizontal axis), ultimately reduce the area of the resilience triangle. Thus, the resilience of an electrical grid can be discussed by examining the area of this curve.[31,58,59]

Evaluation of resilience according to the curve, shown in Figure 1, is the most basic way to use this curve for evaluating the resilience of an electrical grid. It has drawbacks such as "not considering the endurance of the grid from the moment of occurrence to the beginning of the decline in system performance," "not considering the decline rate of the system efficiency," "not considering the decline time of the system," etc. Subsequent research, which has used the same curve to assess the resilience of a grid, has considered more details about the situations created for a structure in the face of an event.

In a number of studies, such as,[10,29,32-35,60] the resilience assessment of a grid has been performed in more details using the resilience curve in which according to Figure 2, it has been tried to resolve the problems attributed to the initial curve by dividing the system performance curve into five parts including "endurance period before system performance reduction," "system performance reduction period," "system longevity interval in decline status," "recovery period," and "post-recovery system status."

In these studies and in order to evaluate the resilience, the interval is considered equal to a time period T starting from the moment of event occurrence t_0 and the ratio of area C to area B shown in Figure 2, has been used as the resilience assessment metric. In this way, if there is no reduction in the performance level in the grid due to the occurrence of the event, areas B and C will have the same values and the resilience will be equal to one. The higher the reduction in the system's performance level, the lower the value of this ratio. Therefore, this metric has a value between 0 and 1 depending on the resilience of the grid under study.

By defining the resilience metric in this way, the grid endurance interval will be considered in the metric from the moment an event starts until the time before the system declines. Furthermore, with this method, if several disasters occur between t_0 and T, the impact of all these events will be seen in this metric.

There are other suggestions presented in some papers for using this curve. For example in Reference 15, with closer look at this curve and its linear approximation by determining eight time points, the same area ratio shown in Figure 2 has been finally used to evaluate the resilience of the electrical grid.

Moreover, Panteli et al in 2017 examined the various parts of this curve in more detail and have used the term "resilience trapezoid" instead of "resilience triangle" to define the resilience metric.[36,37] In this study, in order to introduce an accurate metric for resilience assessment, the curve is divided into three parts according to Figure 3, and a total of five mathematical factors have been defined for different parts of this curve. The defined mathematical factors for each of the curved sections have been given in Table 4.

In References 36-38, each of the factors provided in rows one to four of Table 4 has been introduced as a metric for resilience assessment and their aggregation has been considered in the fifth factor that calculates the trapezoidal area. It can be said that the study is relatively comprehensive considering that it includes all related items including "speed and rate of decline," "time of grid decline retention," and "speed of recovery" in the resilience assessment. However, there are some drawbacks to this metric, as mentioned below.

According to what has been described, one of the drawbacks of this method—whether using the curve shown in Figure 2, which uses the ratio of area C to area B, or the curve shown in Figure 3 and using the factors given in

Table 4—is the "lack of providing an appropriate view for the scheduler." This drawback has been further described using the curves shown in Figure 4.

The resilience metric in both methods of "assessment by curve analysis" will be the same for the two curves *a* and *b* shown in Figure 4. However, these two curves are fundamentally very different. If we assume that the vertical axis represents the supplied load of the grid in the case of an unwanted event, the lost load in curve 4-a is low and the retention period under the decline state is long, while the opposite is the case in curve 4-b. It is also possible for the case in curve 4-a that the critical loads in the grid are not interrupted at all; from this point of view the two curves are indistinguishable. Therefore, representing the resilience metric of a grid by a single numerical value in this technique may not provide sufficient information to the scheduler.

It may be assumed that considering the presence of other factors, this objection does not exist in the method of "resilience trapezoid" which was described in accordance with Figure 3 and Table 4. But, the factors introduced in this method cannot help to solve this problem because the mentioned factors may contradict each other. For example, in Figure 4, the first factor, that is, the rate of decline in the system performance, implies that curve 4-a has the higher preference in terms of resilience while the third factor, which represents the decline retention period, recommends curve 4-b. This disagreement is in spite of the fact that the trapezoidal area, which includes the aggregation of these factors, is the same for the two curves *a* and *b*. So the planner cannot use these factors to determine the priority of network performance in terms of resilience in the face of a catastrophic event between modes "a" and "b." Likewise, many other contradictory states between the first four factors in Table 4 can be presented, while the fifth factor may not have affect the decision making.

2.4 | Metric 4: Modified reliability metrics

Given the similarity between the concepts of "reliability" and "resilience" in various respects, a number of researchers have used the metrics defined under the topic of reliability by applying minor changes and modifications to measure and evaluate the resilience in an electrical grid. The following are examples of such researches.

Reference 39, introduced a four-step procedure for resilience assessment and without any changes used the parameters "EENS" as well as "EIU," which are among the metrics employed in assessing the reliability of an electrical grid. In References 37,40 using reliability metrics such as EENS and LOLF, a metric was defined to find the most effective component of the power grid in resilience improving and the impact of measures such as "redundancy," "increasing robustness," and "improving system responsiveness" has been examined and compared by this method.

In Reference 69, which provides solutions to model probabilistic extreme event, equipment failure, and optimal restoration, a set of metrics is defined including *EENS*, *E0D* and *EPI*, which are inspired by reliability indices, to measure the resilience of electricity distribution networks. Reference 70 defines a large number of scenarios that may occur for a network by applying random conditions such as various events, equipment failure and equipment repair process, then, using the CVaR, it extracts only the scenarios that impose the worst conditions on the network and are the subject of the resilience, and calculates the EENS value for those scenarios to measure the resilience.

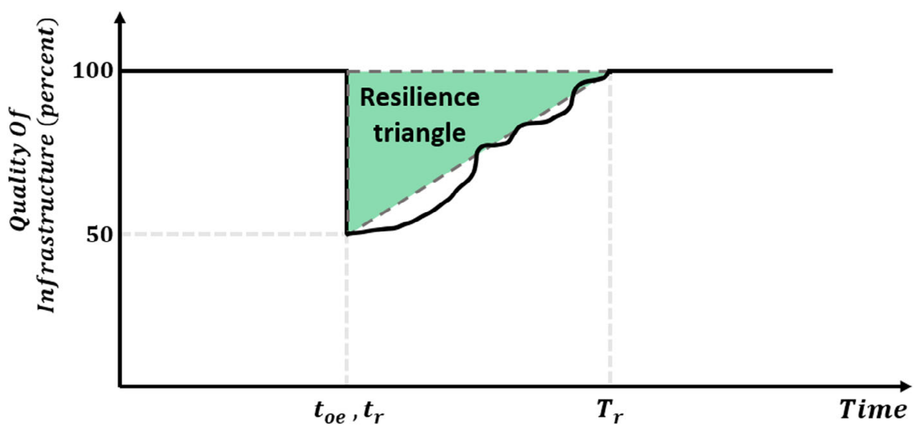

FIGURE 1 Initial curve of resilience assessment of an infrastructure[57]

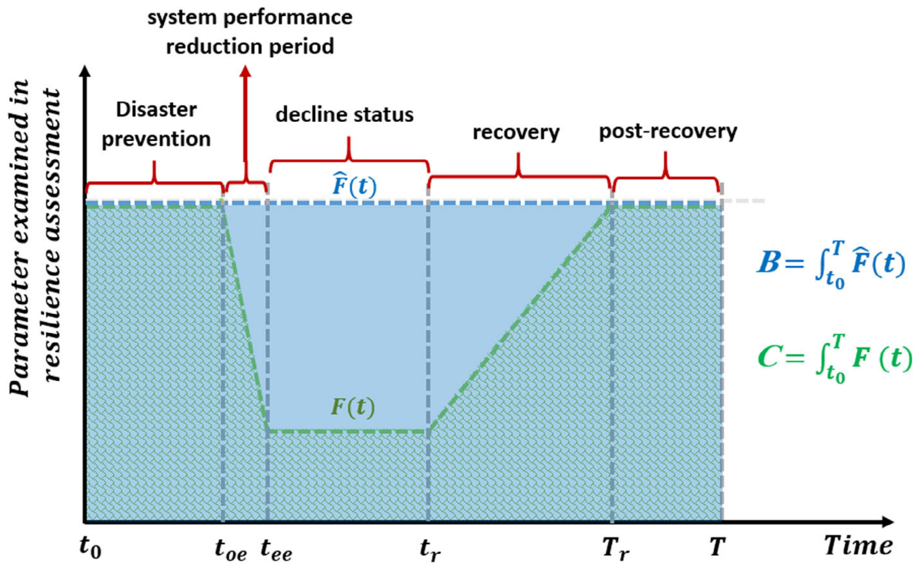

FIGURE 2 Categorization of different parts of a system's performance curve in the face of an event

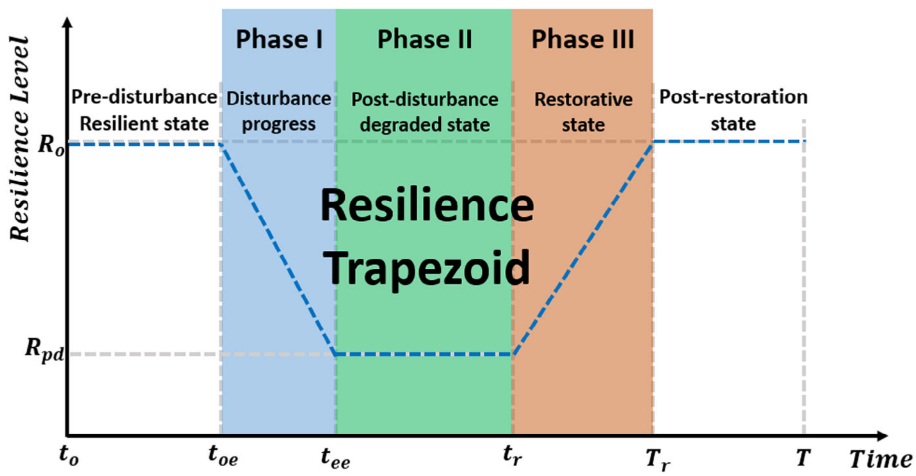

FIGURE 3 Multi-segment resilience assessment curve[36]

TABLE 4 Mathematical assessment factors using resilience trapezoid[36]

No.	Factor	Phase	Description
1	$\Phi=\frac{R_o-R_{pd}}{t_{ee}-t_{oe}}$	I	Rate of decline
2	$\Lambda=R_o-R_{pd}$	I	Amount of decline
3	$E=t_r-t_{ee}$	II	time of grid decline retention
4	$\Pi=\frac{R_o-R_{pd}}{T_r-t_r}$	III	Speed of recovery
5	Area of Trapezoid	I, II, III	Aggregation of all parameters

The use of reliability metrics to assess the resilience is not desirable due to the following and thus, it is less commonly used:

- In general, reliability measurement metrics used in the study of common interruptions in an electrical grid usually measure EENS and emphasize on time intervals and repetition of interruptions. Therefore, they are not effective and

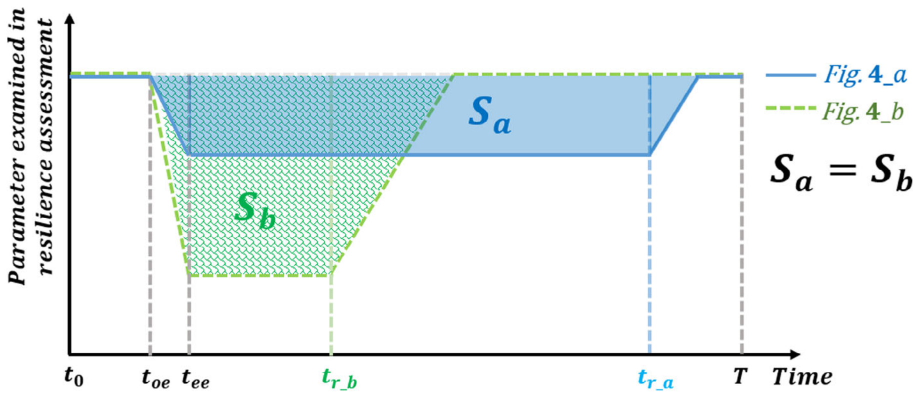

FIGURE 4 Representation of the problem of resilience assessment metric with curve analysis

suitable for use in rare events and resilience assessments.[9,10,38,62] Basically, resilience focuses on the failure results and further examines the performance of the system before, during, and after an event.[68]

- Moreover, reliability metrics, such as SAIDI, SAIFI, and CAIDI, due to their average-taking nature, cannot have the required efficiency in assessing the resilience associated with events with low repetition rates but large effects.[15,18]
- Reliability metrics do not have the ability to indicate the desired resilience parameters such as "robustness," "redundancy," "availability of resources or speed of recovery," etc.
- In general, reliability focuses on random errors that occur due to internal faults in a system, while resilience emphasizes on errors due to shocks and external events.[43]

2.5 | Metric 5: Assessment using graph theory

Another method proposed in several studies to evaluate the resilience of electrical networks is the use of "graph theory" and parameters related to electrical network topology. To explain the evaluation metric of electrical network resilience using graph theory, it is necessary to first briefly explain this theory and some of its most widely used parameters.

In this method, the electrical network is considered as a graph in which the bases of the network represent the nodes of this graph, and the lines of the network represent its edges. Many properties and parameters are defined in a graph, each of which shows the degree of importance, participation, and relationships between the components of a graph.

Given that in examining the resilience of an electrical network, the supply of network loads, in other words, the establishment of communication between load nodes and source nodes during catastrophic events, is considered, in some studies, the aggregation of some graph parameters that indicate the degree of relationship between nodes, has been used to define the resilience metric. A number of widely used parameters of graph theory and a brief explanation of their application to the subject of resilience are given in Table 5.

It should be noted that graph theory has been used in evaluating most complex networks such as natural gas supply, water supply, roads, and public transportation in various researches.

Given that each of the parameters listed in Table 5 expresses a specific feature of a graph and most of these parameters are not of the same type, in studies that have used these parameters in the definition of a metric to assess the resilience of an electrical network, different solutions has been used to aggregate them, which several papers in this regard described in the following.

In Reference 28, CI was used to aggregate the factors of graph theory. CI is an aggregation operator which can be applied to different criteria which cannot adequately provide an answer to the problem, when considered one at a time. It uses the concept of measure and is able to account multiple interdependent criteria. In this study, seven parameters of graph theory (including rows 5 and rows 9-14 of Table 5) are used based on the following three rules:

- Resiliency of a network depends on number of paths that connect a source node to a load node.
- Increasing ratio of the number of sources to the number of critical load increases the network resiliency.

- Increasing number of switches increases the resiliency, but increasing number of switching operations to connect the source to load decreases the resiliency - as more switches means more chances of their non-functioning during an emergency.

In this study, different network states are determined according to (a) the need to provide critical loads, (b) the possibility of changing the status of switches, (c) observing the operating conditions and maintaining the radial state of the network. Then, for each of these cases, seven parameters of graph theory are determined (each of which expresses some kind of network connections and communication between load nodes and source nodes in the network). Then, according to the CI method, these parameters are combined, and for each possible network, a value is specified as the resilience value of that structure from the network and is arranged in descending order. Finally, based on this information, the operator can determine the status of the switches for maximum resiliency. The algorithm presented in this paper emphasizes the recovery of critical loads with minimum switching. The same seven parameters are also mentioned in the review paper[55] as influential factors in the resilience of an electrical network.

Another example of the application of graph theory is provided by Kim et al[61] in assessing the resilience of the South Korean power grid over a wide range of voltages (from 765 to 3.3 kV). In this study, network damage modeling was performed by removing several network nodes by randomly deleting nodes (using normal distribution) and also removing nodes of higher importance (by ranking nodes with the help of two parameters, “degree” and “betweenness”). Nodes are removed randomly to model natural events or human errors, and nodes of higher importance are removed to model intentional errors (terrorist attacks).

In this study, the resilience of the South Korean network has been evaluated by three methods of *error and fault tolerance*, *cascading failure robustness*, and *recovery analysis*. In this evaluation, graph theory parameters (such as *diameter*, *path length*, *clustering coefficient*, *efficiency*) are used to analyze the network performance, and the South Korean network is compared with two random and scale-free reference networks.

Another example of the application of graph theory in evaluating the resilience of an electrical network is given in Reference 53. In this study, four parameters, including “topological resiliency,” “load flow feasibility,” “Failure rate of distribution system equipment,” and “intensity of the unfavorable event” are considered as effective parameters on the resilience of a network. In order to apply the effect of all these parameters in expressing the resilience of an electrical network, the AHP method has been used.

This study presents the “topological resiliency” as a vector consisting of six graph theory parameters (including rows 2-5 and 7-8 of Table 5). Since not all parameters are equally effective in the resilience of network topology, in this study, a relative weighting is used to apply the effect of each parameter and calculate the resilience of the entire network topology.

In Reference 56, a review paper, five graph theory parameters, including rows one to five of Table 5, have been used to evaluate the degree of connectivity in an electrical network and classify resilience metrics. In general, the number of parameters considered in the graph theory method varies in different studies, and usually, the method that considers more parameters in its research will be more accurate.

As can be seen from the sample papers described, there is still no clear trend in assessing the resilience of an electrical network using graph theory, and each of the studies conducted in this regard, have presented their parameters and methods in combining these parameters. Given the definition of various parameters in graph theory, it can be said that this method still has many latent capabilities in defining the resilience assessment metric of an electrical network, and more studies are needed in this regard.

One of the disadvantages of using graph theory in evaluating the resilience of an electrical network is the heavy calculations for medium and large networks. It should be noted that with increasing the number of nodes, the complexity and the time required for calculations will increase exponentially.

2.6 | Metric 6: Assessment by examining cost

Given that it is never possible to ensure a grid is absolutely resilient in confronting various events and it may be damaged by highly severe events and also considering that any action taken to improve the resilience of a grid will be costly, a number of papers have presented the cost spent or imposed as a metric of resilience assessment.

By defining an exponential function to assess the resilience, Reference 14 has used the increased cost of operation imposed on the system in the case of interruption due to an event. In this study, the occurrence of power failure in the

TABLE 5 The most widely used parameters of graph theory and their application in the subject of electrical network resilience

No.	Title	Description	Application in resilience
1	Node degree or node degree distribution	The number of links connected to a node	Measures the structural importance of nodes
2	Graph diameter	$\frac{2\|E\|}{\|N\|(\|N\|-1)}$	Shows the number of nodes must be traveled through to connect a source node to a load node when considering the whole network
3	Average path length of the graph	$\frac{\sum_{i \neq j} d(ni,nj)}{\|N\|(\|N\|-1)}$	
4	clustering coefficient	Relates a node's connectivity to its neighbors	Useful for describing network redundancy
5	Betweenness of node K or aggregated central point dominance	$\sum_s \sum_t \frac{\sigma_{st}(k)}{\sigma_{st}}$	Measures the functional importance of nodes by relating a node's structural position to the efficient flow paths throughout the network. In other words, it characterizes network flow contribution of every node
6	Network efficiency	Inverse of the harmonic mean of the shortest paths between all possible pairs of nodes	Measure the response of networks to the deletion of nodes (vulnerability) or cascading failures and recovery
7	Algebraic connectivity	Eigenvalue of Laplacian matrix of the network	Represents the algebraic connectivity of the network and higher the value of second smallest eigenvalue of Laplacian matrix of the network, the network is more resilient
8	Critical fraction of network	A fraction of nodes is determined by percolation theory, which is deemed resilient enough to supply CLs after nodes have been randomly damaged.	To determine the resilience of the network even after damage to several nodes
9	Branch count effect	Ratio of the total number of connected branches for each path combination in a PN[a] to the number of all CLs	Measure length between CL node and source node
10	Overlapping branches	Total number of common branches in each path combination in a PN	Measure the importance of branches in the network
11	Switching operations	Total number of changes in state of the switches	The importance of not changing the status of the switches
12	Repetition of sources	The ratio of the number of available sources used to supply all CLs to the number of all CLs in each PN	Examine the resources available to supply CLs
13	Path redundancy	The ratio of total number of paths available for all CLs connecting to all sources to the total number of CLs	Investigate available paths to supply CLs
14	Probability of availability and penalty factor	Probability of availability of the source and impose penalties for prior supply of load from the main network	The importance of providing CLs from a more reliable network in the first place (main network) and a closer source in the second place

[a]PN: A subset of a network graph in which there is a connection between the load node and the source node.

system by a terrorist attack has been investigated and the exponential function shown in (1) has been used as a metric to evaluate the resilience of microgrids.

$$\text{resilience metric} = e^{-(\text{Increased operation cost due to the power outage})}. \tag{1}$$

A low value obtained by (1), indicates the high vulnerability of the grid to the event under consideration. Using this method, the resilience rate relative to its improvement cost can be examined.

Reference 30 have evaluated several investment strategies to improve the resilience of a grid, and in order to select the most appropriate solution, it has employed investment cost metrics and unsupplied electrical load cost. Another study, which provided a resource allocation model for repairing and recovering potential storm damage, used the costs imposed by load loss, recovery, and power generation as the best strategy selection metric.[63] Cost function has also been used as a metric for resilience assessment in Reference 64, which has provided the of impact of using mobile energy storage resources and compared it with fixed energy storage resources in order to improve the system resilience level.

Regarding the use of cost as a metric for evaluating the resilience of an electrical grid, it is necessary to consider the following points:

In the first step, it should be noted that the "cost spent" is not a metric for the resilience assessment of a grid, but a metric for comparing different methods that are proposed to improve resilience.

- It is also important to note that in difficult conditions namely severe storms, earthquakes, etc, which give rise to studying resilience, supplying critical loads is crucially necessary for the continuation of human activities and hence, the inclusion of economic factors in such periods (which are usually within a few tens of hours) is not much interesting. Thus, considering such a metric is not acceptable for evaluating the improvement of the resilience of a grid.[25]

2.7 | Metric 7: Other metrics

As mentioned earlier, a standard metric for evaluating the concept of resilience has not been defined so far. Therefore, a number of researches have presented their own solutions and methods for resilience measuring and given that these methods are not common and have been used in less researches, the followings point to some of them which are used for resilience assessment of electrical grids.

Reference 65 has proposed the assessment of resilience based on the ratio of performance level variation of the system according to (2). S_p represents the recovery rate factor, F_o indicates the initial system performance level, F_d indicates the system performance level exactly after the event, and F_r indicates the system performance level after recovery procedures.

$$r_i(S_p, F_r, F_d, F_o) = S_p \frac{F_r}{F_o} \frac{F_d}{F_o}. \tag{2}$$

In the electrical grid investigated in this study, the number of customers whose required electric power has not been supplied is used as the level of performance of the system that is, functions F in (2).

Reference 66 has provided equations for assessing the resilience of a grid according to the definition presented in the US Presidential Policy, which emphasizes on the four concepts of "withstanding capacity," "recovery rate," "preparation capacity," and "adaptation capability" regarding resilience. Examples of relationships used in this study to assess the resilience include (3) and (4):

$$R_I = \frac{\text{withstanding time}}{\text{withstanding time} + \text{recovery time}}, \tag{3}$$

$$\theta = \frac{\text{Number of customers with interruption}}{\text{customers under study}}. \tag{4}$$

It should be noted that R_I is derived from the definition of "accessibility" in the subject of reliability and θ is the same as SAIFI mentioned in IEEE-1366 standard with some modifications. Reference 67 first defined relationships for the resilience parameters such as robustness, redundancy, resourcefulness, and rapidity plus the adaptation capacity and then, it presented a weighted average of these definitions as the resilience metric.

3 | PARAMETRIC ASSESSMENT OF RESILIENCE AND ACCEPTANCE RATE OF METRICS

3.1 | Parametric assessment of resilience

In a number of researches, considering that their proposed schedules or techniques address a single component related to the concept of resilience, including robustness, recovery, or rapidity of the evaluation and hence, the formulations are only performed for that single part and the whole issue of resilience has not been considered and calculated in the objective function. Some examples of such researches have been mentioned here.

In Reference 71, which examines how to locate the repair team to improve the resilience of a grid in the event of storms, a new metric called "Restored Consumers Index" has been used to assess the improvement of the recovery parameter within the concept of resilience. In this metric, the ratio of "the number of restored customers to the length of the operation period" has been used. In Reference 21, in addition to defining a general metric for resilience, the recovery parameter is also defined separately as "the ratio of the energy of recovered loads to total energy of interrupted loads" and it is evaluated in an electrical grid.

In a number of studies, a part of the curve introduced in Section 2.3 has been used as a measure to assess the resilience. For example, the area of the recovery curve in the mentioned curve in References 72,73 has been considered as the metric of a grid resilience. This has been shown in Figure 5 and (5). In these studies, function F or the vertical axis of the resilience curve has been considered as the critical loads supplied.

$$R = \int_{t_r}^{t_r+T^O} F(t)dt. \tag{5}$$

Reference 74, which has introduced the optimal repair time and the resilience reduction worth, has used the ratio of S_1 to S_2 areas described in Figure 6 and (6), to evaluate the restoration section of the resilience of an electrical network. The "optimal repair time" quantifies the priority with a failed component that should be repaired and the authors compute "resilience reduction worth," which quantifies the potential loss in optimal system resilience due to a delay in the repair time.

$$R(t) = \frac{\int_{t_r}^{t} [F(\tau) - F(t_r)]d\tau}{\int_{t_r}^{t} \left[\widehat{F}(\tau) - F(t_r)\right]d\tau} \quad , t \geq t_r. \tag{6}$$

It is noteworthy that in some researches and studies, the side problems of measures taken to resilience improvement are examined, and therefore in these works, a metric is not presented clearly to evaluate the improvement of a grid resilience. For example, in Reference 75, *GFA Controllers* have been proposed to reduce transient voltage and frequency modes due to switching performed to improve system resilience.

3.2 | The acceptance rate of metrics

This paper aimed to classify and introduce all the metrics used in the field of resilience in electrical networks, so to extract all the metrics introduced in various researches, many papers were studied and reviewed. Due to the limitations of presenting a paper and deviating from the main structure of the research, it was not possible to express the details of each of them, and in each group of the category given in Section 2, only a limited number of these papers were mentioned. However, to express the general acceptance of each of the presented metrics, the approximate percentage of the use of each of these metrics in various studies and research is given in Figure 7.

In order to present the percentages given in Figure 7, more than 200 papers presented in scientific journals in the last two decades have been reviewed. Of course, over time and the elimination of the shortcomings of each of the proposed metrics and standardization of the definition of resilience, these percentages will change.

4 | IMPORTANT PARAMETERS IN COMPARING METRICS

In the previous section, we tried to describe the types of methods and metrics used in various studies to evaluate the resilience of the power grid. It was also tried to point out the shortcomings of these methods in their following definition. But which of these methods or metrics are more efficient and which factors should be considered to make these comparisons? In the following, the factors which need to be evaluated in these metrics are briefly described.

4.1 | The time required to calculate a metric

One of the important parameters in the evaluation of a metric is the time required to calculate it since the structure of the electrical grid, and especially the distribution grid, is changing continuously with the change in the amount of generation and consumption and the change in the status of the switches due to the control decisions of the operators. Therefore, calculating the metric should not be too time consuming so that in case the structure of the grid changes, it is possible to re-examine it at an acceptable speed and announce the necessary warnings to the operator.

4.2 | Applicability for all electrical grids

Given that the presentation of a “metric” is intended for the concept of “resilience in electrical networks,” and when the word “standard metric” is used for a theme, the proposed definition must be well comprehensive. If this concept is defined separately for different networks such as transmission network, distribution network, networks containing microgrids, or networks containing distributed generation sources, etc, there will be a lot of scattering and rupture in the definition of concepts and no standard format can be provided for it. Therefore, some of the features that the resilience metric should have are the independence of the network voltage level, structure, equipment, and capabilities. In other words, the definition of a metric should be such that it can be used for any network in question or examined, and the network structure does not disrupt the computational process. Indeed, the definition of the metric does not depend on the structure of the network.

It should be noted that the separation of networks in terms of structural capabilities is used more in the concept of proposed solutions for improving resilience. For example, much research has been done on the ability to use and program microgrids to improve the resilience of electrical networks. However, in this research, the metric used to show the

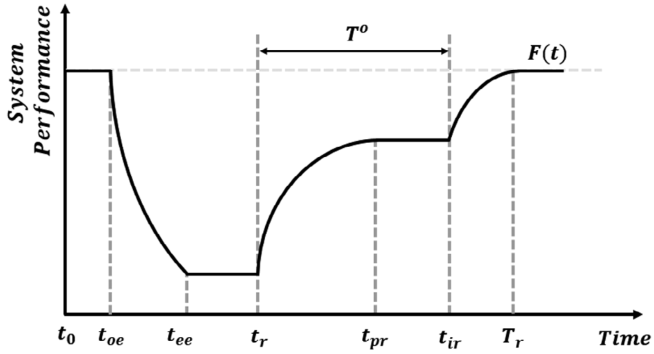

FIGURE 5 Resilience assessment by examining a part of the resilience curve[72]

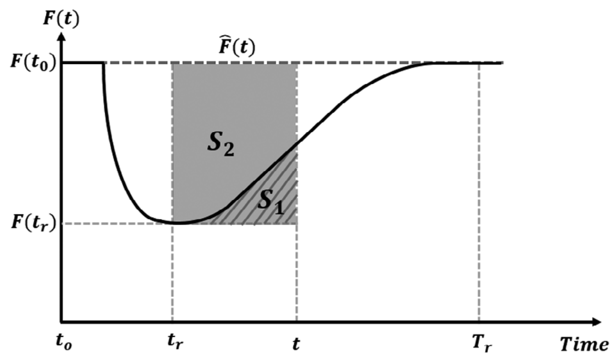

FIGURE 6 Resilience assessment by using the ratio of S_1 to S_2 areas[74]

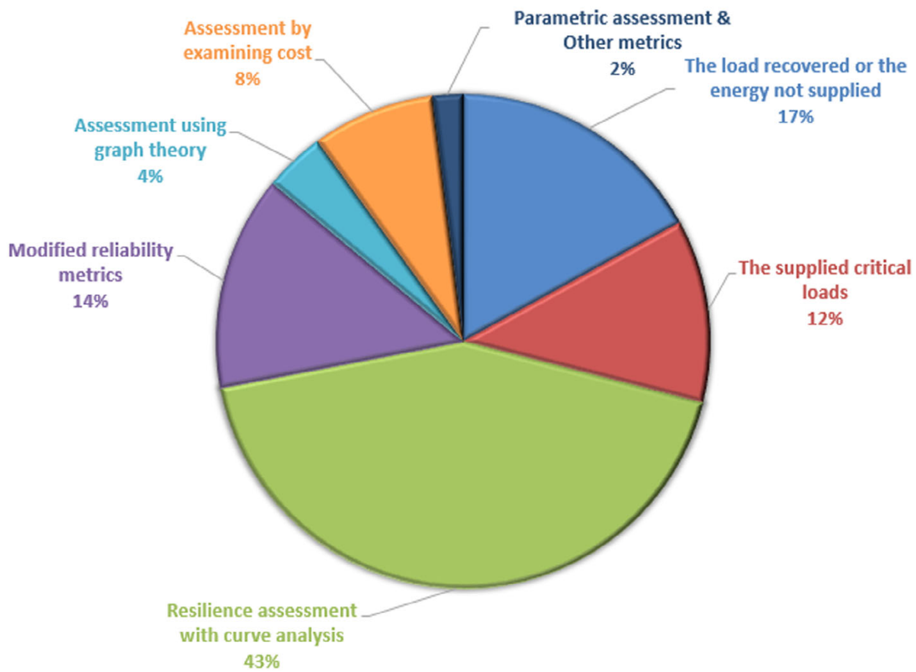

FIGURE 7 Statistical representation of the use of resilience metrics in papers published in the last two decades

effectiveness of the proposed solution is separate from the proposed program and the structural features of the network, and for example, the parameter "critical load provided in the network" is used as an indicator.

It is important to underline that an electrical grid should always be compared with itself and not with other grids, since comparing an electrical grid having its own different sources, loads, and conditions with other grids is not systematic and logical. Indeed, what are compared and examined include the different structures of a grid in terms of resilience, and the best metric is the one that can make the best comparison.

4.3 | Inclusion of all resilience parameters

Quantitative measurement of resilience is not a straightforward process as the resilience is a multi-dimensional and dynamic concept with intrinsic complexities. Many resilience measurements have included only one or two dimensions of the concept, such as "robustness in initial shock" or "post-event recovery period." However, it is necessary to quantify the resilience in such a way that all of its parameters such as robustness, rate of decline, time interval until the beginning of recovery, recovery speed, etc are considered in a way that the concept of resilience is properly quantified. Another point that highlights the importance of this feature is the fact that one of the resilience parameters may be improved by performing a corrective action on the grid structure, but the resilience of the entire structure may be reduced. For example, if overhead lines are replaced with cable lines, initial resistance to events such as storms may increase. However, if the cable is damaged by an event such as a flood, it will take longer than overhead lines to repair. Therefore, it is necessary to define the resilience metric in such a way that all the resilience sections from the initial robustness to the time required for recovery, etc are considered.

4.4 | Independent on the type of event

In order to have a comprehensive metric defined for an electrical network and the possibility of standardizing it, the proposed metric must be independent of the event type. In other words, it should be possible to define the introduced metric for each of the natural events (including storms, floods, earthquakes, etc) or intentional injuries (such as terrorist attacks).

Indeed, the resilience metric should be defined in terms of network equipment failures, and the cause of the failure should not interfere with the metric calculation process. In this regard, the generality of most of the metrics presented in Table 3, since they are related to the supply of network loads, will not be a problem and will be appropriate in this regard.

In resilience studies, event characteristics (including its type and severity) are usually used to find equipment from the network that goes out of service during the event. A clear example of this is the use of the probability of failure of power poles relative to wind speed, which has been used in several papers.

4.5 | The amount of information required

One of the main problems in providing a solution or metric for resilience measuring is the issue of "lack of information." Lack of information can be referred in two ways: first, it refers to the issue of resilience itself as it has been basically defined for rare events, and as mentioned before, this issue has been examined due to the repetition of these events in recent years. Thus, not much information will be available about the occurring events and the impact they will have on the grid under review. The second case is that due to security issues, governments and companies are reluctant to provide complete information about a grid. In other words, identifying the weaknesses of a grid is part of the confidential information. Therefore, it should be considered that only a part of the experience and information gathered from past events is accurate and acceptable. Therefore, the more it is possible for a definition of a resilience metric assessment to be presented separately from the information about previous events, the higher validity it will be able to examine it. For example, the modified reliability metrics that rely on previous information of a grid, and also the graph-theory-based metric described in Reference 28, require a great deal of information from the grid under consideration and will not be very appropriate from this perspective.

4.6 | Ability to present the result appropriately

The resilience of a grid is measured by the investor or policy maker either before an event occurrence to investigate the status of its resilience or after the occurrence of an event to evaluate the performance of the grid. They do not necessarily master all the parameters of this subject, so a metric is good if the output data can provide an appropriate understanding of the status of the grid for decision makers. For example, in Reference 31, the resilience of the study network is presented as a number in terms of Watt-hour, hence the decision maker or planner cannot have a proper understanding of the resilience of the study network with only one number. If a metric can provide the output value in percent, in other words, between values 0 and 1, it will certainly be possible for the scheduler to better compare the resilience of a system in the case of various events.

5 | COMPARISON OF METRICS

Up to this part of the study, it was tried to briefly describe the common methods used to measure the resilience of power systems and some of their shortcomings. Moreover, the important parameters that a metric must have in order to better present the concept of resilience to provide a proper understanding of this concept for the scheduler, were introduced in Section 4.

In this section, a relative comparison has been presented in Table 6 among the common metrics of resilience assessment, in order to examine each of the parameters given in Section 4. The evaluation and comparison given in Table 6 is based on the research related to these metrics in different papers and is therefore relative. It should be noted that researches that have only examined one parameter of resilience, or papers that have investigated the subject of resilience without the use of a specific metric, are one step behind in this field and has no place in this comparison.

In completing the explanations given in the last row of Table 6 and the reason for assigning the appropriate or inappropriate title for the metrics given in this table, some points are mentioned below. As it can be seen from the comprehensive and accepted definitions of resilience in various studies, the issue of resilience precedes the occurrence of an event and will be evaluated with features such as “increased robustness” to a period after the end of an event and features such as “increased recovery speed.” Therefore, the more a metric can have all these features in its calculations, the more comprehensive it will be. As it is clear from the third column of the parameters studied in Table 6, from this perspective, most of the introduced metrics are deficient and have not been able to have all the dimensions of the issue of resilience. Thus, except for the metric of “curve analysis,” in which almost different parts of the subject of resilience are mentioned, in other metrics and despite the efforts made, the inclusion of features such as “rate of decline or speed of recovery,” “time of grid decline retention,” or “increased robustness before the event” have failed in their calculations.

Regarding the parameter of “Independent on the type of event” it can be said that only the metrics that are based on reliability indicators will face some problems in this regard due to the nature of averaging these metrics and the need for information from previous events. In defining other metrics, each of them is based on the possibility of providing

TABLE 6 Relative comparison of common metrics

	Parameter under consideration					
Metric	**The time required to calculate a metric**	**Applicability for all electrical grids**	**Inclusion of all resilience parameters**	**Independent on the type of event**	**The amount of information required**	**Ability to present the result appropriately**
1. The load recovered or the energy not supplied	Appropriate	Appropriate	Inappropriate[a]	Appropriate	Inappropriate[b]	Appropriate
2. The supplied critical load	Appropriate	Appropriate	Inappropriate[a]	Appropriate	Appropriate[c]	Appropriate
3. Resilience assessment with curve analysis	Inappropriate[d]	Appropriate	Appropriate	Appropriate	Inappropriate[e]	Appropriate
4. Application of reliability corrected metrics	Appropriate	Appropriate	Inappropriate	Inappropriate[f]	Inappropriate	Inappropriate
5. Assessment using graph theory	Inappropriate[g]	Appropriate	Inappropriate[a]	Appropriate	Inappropriate	Appropriate
6. Operation cost or non-supply cost	Inappropriate[g]	Inappropriate[h]	Inappropriate	Appropriate	Appropriate	Inappropriate[i]

[a]Failure to check resilience parameters such as “initial robustness,” “decline rate,” “speed of recovery,” etc.
[b]Requires information of all network loads.
[c]Only critical load information is required.
[d]Due to the calculation of different parts of the resilience parameter requires more time for calculations.
[e]Considering that the time intervals in this analysis are examined separately, a large amount of information is required.
[f]Sufficient information needs to be available on the impact of event on the grid under study, as this metric is based on review and aggregation of previous information.
[g]Many factors need to be calculated.
[h]Turning all parameters into cost may not be done properly, in other words, it may not be possible to find the right conversion.
[i]The result is provided in monetary terms.

network loads, regardless of the reason for its interruption, so they have abandoned their dependence on the type of event.

Except for the second and sixth metrics, which examine only the information related to "CLs" and "the amount of cost imposed on the network," respectively, other metrics need a significant amount of network information to perform their calculations. For example, in calculating the "graph theory" metric, it is necessary to calculate several factors, each of which requires a significant amount of network information, so that the output of these factors can be used in calculating the defined metric. Therefore, metrics are usually not very suitable for this feature.

Due to the fact that in most of the described metrics, the output can be presented as a percentage, the result is tangible for the planner, and therefore, most of the metrics are suitable in terms of the parameter "ability to present the result appropriately." This is not true for the fourth and sixth metrics. Given that the fourth metric is based on averaging, while the issue of resilience is related to low-frequency events, this metric cannot have a good output from this perspective. Furthermore in the sixth metric, it cannot provide a proper insight to the planner due to the fact that the output is provided as a cost.

Given that some of the features listed in Table 6 are somewhat contradictory, having a metric with all the introduced features together will not be practical. For example, the third feature entitled "Inclusion of all resilience parameters" will increase the accuracy and necessity of considering the impact of all resilience parts in a metric and this matter requires more time and amount of calculations, in other words, it reduces the "calculability at acceptable time" feature.

Consequently, in order to introduce a suitable metric, it is necessary to examine it in different aspects. The characteristics of some aspects have been compared in Table 6. However, there are many parameters to consider in this regard which need to be investigated in future research. From the perspective of this paper, the third metric, entitled "Resilience Assessment with Curve Analysis," as well as its various parts in more details than other metrics has been considered as the subject of resilience and is therefore preferable. It should be noted that the disadvantage of this method is its time consuming or requiring high calculations, which can be reduced by using mathematical optimization methods or advanced computing equipment.

6 | CONCLUSION AND FUTURE RESEARCH DIRECTIONS

This paper provided an overview of the metrics used to assess the resilience of power systems and attempts were made to evaluate the advantages and disadvantages of these metrics. This research may be able to help researchers and scientific communities to determine a standard metric for evaluating the resilience of electrical grids. According to the studies of several papers on the subject of resilience, to define a suitable metric for measuring this parameter in electrical networks, it is necessary to perform the following steps in future research, respectively:

- *A standard definition of resilience*: Due to the lack of a well-established definition of the resilience subject, new descriptions of this issue are still offered in various papers, and this issue will lead to the application of a researcher's personal opinion in this field and as a result, more disintegration.
- *Provide important resilience characteristics and their impact ratio*: After defining the resilience parameter, it is necessary to determine the features and their importance in this parameter in relative terms. For example, suppose the two characteristics "network performance decline rate" and "network downtime" are among the properties of the resilience parameter. What should be the ratio of the effect of these two properties on the resilience parameter? This paper tries to present some of these features albeit briefly.
- *Definition of a comprehensive* metric *for resilience*: By performing the previous steps in a standard way, it is possible to compare the various metrics presented on the subject of resilience so that finally, the scientific-technical committees can provide a standard metric in this regard.
- Given that having "comprehensiveness" is one of the fundamental features in defining a standard metric for a parameter, among the metrics defined in various studies, which are divided into seven categories in this paper, the metric of "curve analysis" can be superior to other metrics. However, as noted, the metric "curve analysis" still has bugs and further investigations can be applied to resolve and its eventually standardization. By determining a certain and standardized metric, it is possible to compare different strategies, which are proposed to improve the resiliency of a system. It can also explain why one structure has higher resilience compared to another or why the resilience of a system is diminished over time.

CONFLICT OF 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.

DATA SHARING AND DATA AVAILABILITY

Data sharing not applicable - no new data generatedData sharing is not applicable to this article as no new data were created or analyzed in this study.

PEER REVIEW

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ORCID

Mostafa Sedighizadeh https://orcid.org/0000-0003-3160-5435

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