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ORIGINAL RESEARCH

Defining a new index to compare the resilience of different structures of an electrical energy network

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Abstract

The issue of resilience in electrical distribution systems has been proposed increasingly with the frequent occurrence of natural disasters in recent years and the imposition of high costs due to widespread power outages. To date, various resilience indices have been proposed, some of which have been improved upon over time by extensive research, leading to more comprehensive indices. However, a standard index has not yet been approved and presented in this regard by international committees, despite the efforts made. The issue of resilience in electrical networks was examined by curve analysis index in more detail compared to other proposed indices, although it is not yet complete and should be investigated from various aspects and its shortcomings be eliminated. The present study aims to evaluate some fundamental obstacles in the "curve analysis" index and correct it in a new index called "Combining Investment and Reform" (CIR) index. Two issues of "costs in terms of investment and repairs imposed by the event" and "need to separate critical and non-critical loads" are considered simultaneously in the proposed index. Finally, the capabilities of the proposed index are evaluated and compared in a sample electrical network in the face of events with different intensities.

1 | INTRODUCTION

1.1 | Motivation and incitement

During the recent years, the occurrence of natural disasters such as floods, severe storms and hailstorms has increased significantly across the globe due to global warming and climate change, leading to frequent power outages and blackouts, as well as socio-economic damages in different countries [1–3]. Thus, the concept of resilience which was first introduced by Holling (1973) [4] gradually attracted the attention of more researchers since 2002. A large number of studies have been conducted around the world during the last two decades, which are still ongoing [5–11].

Despite the scattered consensus in various studies on the definition of resilience parameter and confirmation that this parameter is different from the previously defined concepts such as reliability, but so far, no standard definition has been provided for the concept of resilience in international forums, and this parameter has been defined in different ways in various studies depending on the idea presented. In most studies, the resilience is defined as "the ability of the power system to withstand catastrophic events which occur infrequently and lead to widespread blackouts in the system so that the network has the least interruption in its load power supply, as well as the ability to quickly recover and return to normal status". In addition, it can be acknowledged that the principles of all of the definitions for the resilience parameter are based on the ability of a system to "predict", "absorb", and "quickly recover" in the face of "external", "unlikely", and "high impact" shocks [12–16]. Therefore, further research is needed to provide a standard definition of resilience parameter and requires more studies.

1.2 | Literature review

Generally, the studies which examined the "resilience in electrical networks" can be divided into two general categories.

The first category includes the studies which provide methods, planning, and investments to improve network resilience before catastrophic events and increase its resilience. For example, refs. [17, 18] plan the supply and location of removable generation sources to improve the resilience of an electrical network, or ref. [19] presents a model of pre-event resource allocation for repairing and recovering the possible damages. In addition, ref. [20] plans and organizes the generation and consumption in the electricity distribution network before occurring the storm and its approaching to the electricity network under consideration. The second category includes the studies which design methods and planning to react appropriately during an event, provide more network loads, and improve network resilience. For instance, refs. [21, 22] provide solutions for generation planning and power exchange between microgrids in a network after a catastrophic event, ref. [23] indicates some suggestions for planning controllable loads to improve the resilience parameter during catastrophic events, and refs. [24, 25] propose some ideas and plans to provide critical loads after an event. To compare different methods and strategies, a resilience evaluation index needs to be able to examine both categories simultaneously.

So far, no standard index has been presented to assess the resilience of an electrical network and compare the efficiency of resilience improvement methods proposed in various studies since a standard definition has not yet been adopted and presented by the international community for measuring and assessing the resilience of an electrical network [11, 26–30] and each of the studies which presented the solution and ideas in this regard has defined and used a new index to evaluate its proposed solution depending on what part of the resilience parameter is improved by the proposed solution. The following are some examples of recent research introducing and using different indices to evaluate the resilience parameter in an electrical network.

In [31], 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", as an indicator of resilience. Simultaneous scheduling of electricity and gas energy carriers for storage as well as reduction of unnecessary loads before an event occurs to improve the resilience of electrical grid, has been performed in [32] where "the supplied critical load" has been considered as the resilience metric.

In [33], to measure resilience, network performance curve analysis and the definition of "resilience trapezoid" have been used to evaluate this parameter. In this study, in order to introduce an accurate index for evaluating resilience, the network performance curve is divided into three sections: "disturbance progress", "post-disturbance degraded state" and "restorative state." Also, five mathematical factors have been defined for different parts of this curve. Ref. [34] 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, with using the Conditional Value at Risk-CVaR, it extracts only the scenarios that impose the worst conditions on the network and are the subject of the resilience, and calculates the "Expected Energy Not Supplied-EENS" value for those scenarios to measure the resilience. In other words, one of the reliability indices for measuring the resilience parameter is modelled in this study.

TABLE 1 Resilience assessment indices in electrical networks

No.	Applied metrics	References
1	The load recovered or the energy not supplied	[12, 16, 21, 31, 40–42]
2	The supplied critical loads	[13, 14, 18, 22, 25, 32]
3	Resilience assessment with curve analysis	[20, 29, 33, 43–54]
4	Modified reliability metrics	[11, 34, 54–56]
5	Assessment using graph theory	[30, 35, 57–59]
6	Assessment by examining cost (Operating cost / investment cost / power supply interruption cost)	[17, 19, 36, 60]

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. 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. For example, the review paper [35] introduces parameters such as Branch Count Effect (BCE), Overlapping Branches (OB), Aggregated Central Point Dominance (ACPD) etc. as influential factors in measuring the resilience of an electrical network.

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. For instance, ref. [36] has evaluated several investment strategies to improve the resilience of a grid, and in order to select the most appropriate solution, it has used investment cost metrics and unsupplied electrical load cost.

More than 40 indices proposed in evaluating the resilience of an electrical network in [37] have been introduced by the authors of this paper and have been examined and compared in more detail. As shown in Table 1, the indices introduced in various studies for assessing the resilience of electrical networks can be classified into six general groups [30, 37–39].

The variety of indices and methods of measuring resilience, some of which were mentioned, indicate the lack of a standard and specific index for measuring this parameter in electrical networks and point to the need for further studies to integrate the issue.

1.3 | Importance of presented work

The issues of "pre-event planning" and "actions during and after the event" are not considered simultaneously in none of the previously defined resilience assessment indices. In other words, none of these indices can be used to compare the methods which address the issues of investment or costs imposed before the decline in network performance and planning to improve resilience during and after an event [61]. The present study seeks to present and define an index which can cover this gap and consider the above-mentioned parameters simultaneously in order to compare and select the optimal method from the planner's perspective.

As mentioned earlier, resilience assessment index using system performance curve analysis is among the common indices in assessing the resilience of electrical networks, which were utilized in various studies [47–50]. Among the studies proposed so far regarding this index, Panteli et al. have examined this index in more detail and modified and improved it through several studies [53, 54]. However, assessing resilience using curve analysis has its drawbacks and shortcomings, which can lead to wrong decisions by the planner. In this study, this index has been studied more carefully, and its efficiency has been improved by providing solutions.

1.4 | Contributions and organization

The proposed index in this study is based on the curve analysis with the purpose of eliminating its related obstacles by adding the following issues.

- The effect of "investment before the event or costs incurred before the decline in network performance" and "planning during and after the event" has been regarded simultaneously in the proposed index.
- The need to supply critical loads compared to normal network loads has been applied in the proposed index due to the necessity to supply critical loads in an electrical network during the catastrophic events.

In order to explain the advantages of the proposed index over the resilience indices presented before, the impact of events with different damage intensities on the index is investigated in a sample electrical network. In addition, the efficiency of common strategies in improving the resilience of an electrical network is compared with the help of the proposed index.

In Section 2, the resilience index with curve analysis is described and its drawbacks are indicated. The proposed index and the method of its calculation are described in Section 3. The capabilities of the proposed index in measuring and comparing conventional methods of improving the resilience of an electrical network are described in Section 4. Finally, the conclusion is given.

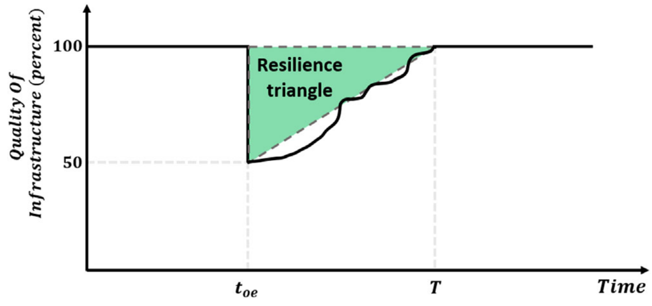

FIGURE 1 The initial resilience assessment curve of an infrastructure [44]

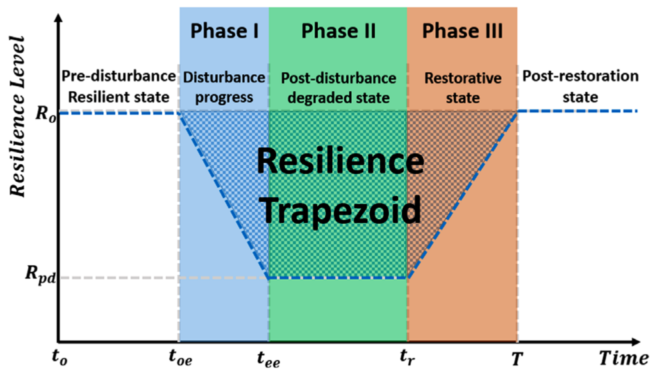

FIGURE 2 Resilience index using resilience trapezoid [53, 54]

2 | ASSESSING RESILIENCE BY CURVE ANALYSIS AND ITS SHORTCOMINGS

Considering that the basis of the proposed index in this study is based on the curve analysis index, in this section, the generality and operation of this index, the trend of its changes in various researches over time, and its functional defects are described in more detail. Applying the resilience curve and using the difference between the performance in the actual and normal state of the network during the adverse event is among the common methods in assessing the resilience of a network.

Bruneau (2003) introduced the concept of resilience using the curve analysis to measure and increase earthquake resilience [44]. Figure 1 illustrates the general format of the curve known as "Resilience triangle".

Assessing resilience using the curve analysis has been corrected and improved by various researchers over the years, especially during the last two decades, when the issue of resilience has attracted a lot of attention among the politicians and top executives due to the increasing incidence of adverse events [47–52].

Panteli et al. (2017) examined the various parts of the aforementioned curve in more detail and used the term "Resilience trapezoid" instead of "Resilience triangle" to define the resilience index. In order to introduce an accurate index for resilience assessment, the curve is divided into three parts (Figure 2) and a total of five mathematical factors are defined for different parts of the curve. Table 2 indicates the defined

TABLE 2 Factors of resilience assessment using resilience trapezoid method [53]

No.	Metric	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	$\Pi = \frac{R_o - R_{pd}}{T - t_r}$	III	speed of recovery
5	Area of Trapezoid	I, II, III	Aggregation of all parameters

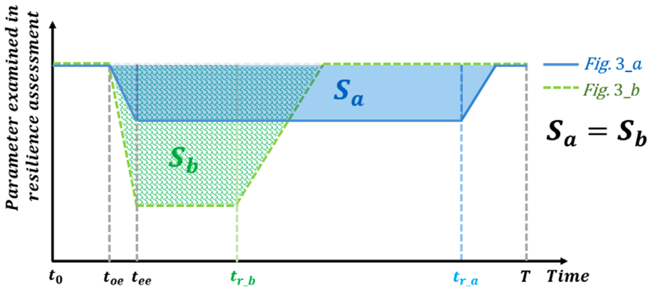

FIGURE 3 Displaying two different functions of the network with the same outputs in the resilience index and not providing the correct understanding to the planner (a: Low failure rate–long failure duration, b: High failure rate–low failure duration)

mathematical factors for each part of the curve [33, 53, 54].

The above-mentioned method has drawbacks which can be corrected and become an ideal one for assessing the resilience of an electrical network, despite a closer look at the performance curve of an electrical network and examining the various parts of the resilience parameter in ref. [53]. Some of the major drawbacks of the aforementioned method are as follows.

2.1 | Lack of proper vision to the planner

Providing a planner with an understanding of the state of the entire network in the face of an adverse event is among the important features which should be present in the resilience assessment index of an electrical network. However, assessing resilience using the curve analysis discussed in previous studies can lead to a misunderstanding of the resilience of an electrical network, the reason of which is described in Figure 3.

In describing the deficit of the curve analysis method, it is worth noting that efforts are made during planning for dealing with adverse events to ensure that the critical loads of the network are not interrupted until repairing the damages since the adverse events usually cause widespread blackouts. The need to supply critical loads of an electrical network in the face of adverse events is such that the amount of critical loads supplied is regarded as the criterion for assessing the resilience of a network in a large number of studies [25, 32].

During assessing the resilience of an electrical network by the curve analysis, the curves a and b in Figure 3, give the same answers to the planner in terms of area parameter (fifth

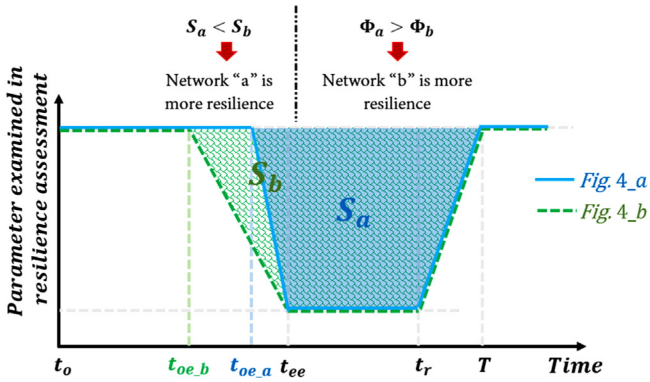

FIGURE 4 Inefficiency of applying only one parameter in the curve analysis method

parameter of Table 2) which includes the aggregation of other parameters. In other words, the resilience of two electrical networks with the performance curves a and b against an event is considered as the same from the perspective of above-mentioned method. However, the performance of the electrical networks related to the aforementioned curves is fundamentally different from each other.

In curve a, fewer loads are affected by power outage due to the event, while the time for repairs and network correction is longer. However, in curve b, the number of loads which are affected by power outage is higher, while the repair time is shorter. In curve a, the critical loads of the electrical network, which are the subject of the resilience of an electrical network more than other loads, may not be affected by power outages at all, while the probability of power outage at critical loads in the electrical network related to curve b is considerably high. However, this method regards two electrical networks with performance curves a and b as the same in terms of resilience and provides the planner with the same amount of resilience, which can lead to his/her wrong decisions.

Even in Figure 3, it can be imagined that the resilience trapezoid area of the a curve (S_a) is greater than the b curve (S_b), in which the resilience assessment index with curve analysis indicates the electrical network related to the a curve as a network with less resilience than the electrical network related to the b curve, while maybe the critical loads in the electrical network related to the a curve have not been interrupted at all.

2.2 | Inefficiency of applying only one parameter

Presenting different parameters to examine all of the parts of the network performance curve during the event may be regarded as one of the features of this method at first glance, while it is not considered as an advantage and can cause the planner to make mistakes during decision-making.

Based on Figure 4, the inefficiency of using only one of the parameters listed in Table 2 to decide on the degree of resilience of an electrical network can be explained. According to the first parameter in Table 2, the high slope of the performance

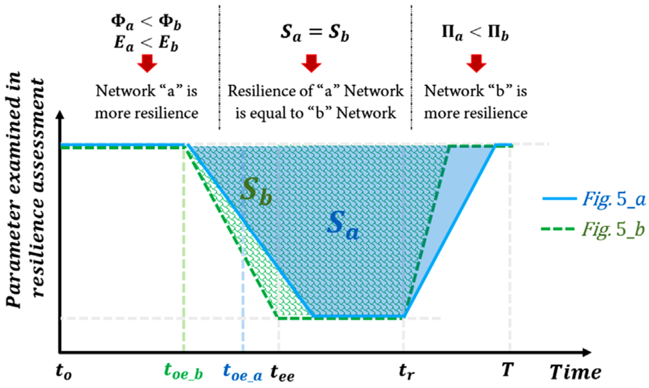

FIGURE 5 Contradiction of the parameters indicated in Table 1 in an electrical network

decline of an electrical network in the face of an adverse event means the weakness of the network. In addition, the slope of the performance decline of the electrical network related to the curve Figure 4a is more than that of Figure 4b, meaning that the electrical network related to the curve Figure 4a is weaker than that of curve Figure 4b in terms of resilience, while the area of the resilience trapezoid or the fifth parameter expresses the opposite. Indeed, the electrical network attributed to the curve Figure 4a is regarded as superior because the area of the resilience trapezoid related to curve Figure 4a is less than that of the Figure 4b, indicating the inefficiency applying only one of the parameters listed in Table 2.

2.3 | The contradiction of parameters despite resilience trapezoids equality

In this method, the area of the resilience trapezoid or the fifth parameter of Table 2 may be introduced as a comprehensive parameter containing other parameters, which is free from previous obstacles. However, in some situations, the area of the resilience trapezoid is considered as the same for both network conditions, while other parameters provide conflicting data to the planner (Figures 3 and 5).

As shown in Figure 3, the area of the resilience trapezoid is regarded as the same in Figure 3a and b, while the first parameter of Table 2 (system performance decline slope) indicates the superiority of the electrical network attributed to the curve Figure 3a and the third parameter considers the electrical network attributed to the curve Figure 3b as superior due to its shorter downtime.

In addition, the two curves demonstrated in Figure 5 can be investigated. The electrical network related to the performance curve of Figure 5a is superior to that of the curve Figure 5b in the perspective of the first and third parameters of Table 2 (Φ, E), while the electrical network attributed to the curve Figure 5b is proposed from the perspective of the fourth parameter of Table 2 (recovery speed-Π). However, the area of the resilience trapezoid including the aggregation of the factors is regarded as the same in the curves displayed in Figure 5.

It is noteworthy that several situations of contradiction between the factors listed in rows 1–4 listed in Table 2 can occur in an electrical network, making decision making difficult for the planner, despite the lack of influence of the fifth factor in decision making.

The above-mentioned shortcomings which can lead to wrong decisions by the planner indicates the need for further studies to modify the method of curve analysis to assess the resilience of an electrical network.

3 | MEASURING RESILIENCE USING "COMBINING INVESTMENT AND REFORM (CIR (INDEX" AND ITS BENEFITS

Assessing resilience using the curve analysis has a large number of advantages over the indices presented in this field and is among the most widely used methods in measuring resilience in most systems including electrical networks, earthquake, health, environment, and the like, despite its drawbacks. Therefore, the proposed method in the present study entitled "CIR index" is based on the aforementioned method and offers some suggestions for its modification and improvement.

From the authors' point of view and based on the studies, the resilience assessment index of an electrical network should have the following capabilities.

- Ability to provide a good understanding to the planner about the state of an electrical network in the face of a catastrophic event: It is worth noting that the planner may be an economist or a politician not necessarily familiar with electrical issues. Thus, the output of the resilience index should be able to describe the state of the network concretely.
- Ability to compare solutions and methods to improve resilience regarding an electrical network: The ability to compare and determine the most effective method to improve the resilience of an electrical network is among the most basic applications of an index after determining the inappropriate state of an electrical network in terms of resilience due to various solutions and methods proposed to improve the resilience of the network.

To define an index which can have the aforementioned capabilities, all the effects of adverse events, as well as the methods which are proposed to improve resilience in an electrical network cab be divided into two categories. The first category includes solutions and planning which improve network robustness to supply all of its loads during a catastrophic event, despite damage to a part of the network equipment, and the second category includes solutions and methods which are planned after the failure of network performance and failure to supply part of the network loads. An index should be able to combine the effects of these two categories in order to provide the correct result to the planner. The totality of this classification is illustrated in Figure 6.

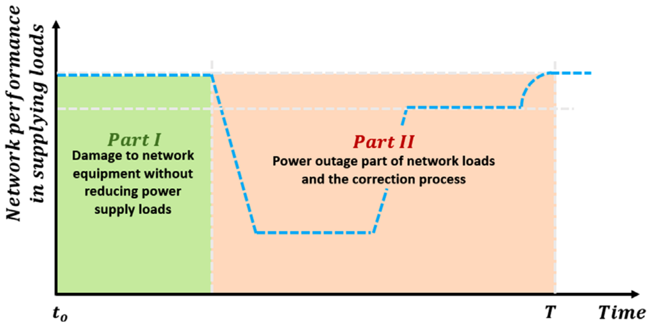

FIGURE 6 General classification related to the effect of adverse events, as well as methods and plans for improving resilience (t_0: The moment the event begins, T: The time window under consideration)

An index provides the best output when it can provide the percentage of the load supplied since all of the efforts and planning in an electrical network are conducted to supply its loads in different conditions including the occurrence of adverse events. However, two faults occur during the planning with the definition of "percentage of load supplied" as an index of resilience.

- First, using this method makes it impossible to compare the plans and strategies which increase the robustness of the electrical network and improve the first part of the curve shown in Figure 6. In other words, suppose an electrical network can be made resistant against an event by two completely different solutions so that all of the loads of the network are supplied and no deficiency occurs during supplying its loads with the implementation of each of the solutions, in which case the index presented cannot determine the optimal method in this regard.
- The second fault is related to resilience. Supplying the critical loads is considered as a priority in this situation because the issue of resilience is related to the performance of a network in the face of catastrophic events. In addition, the proposed index should be able to distinguish between critical and non-critical loads supply and the output of the index should not be the same in two different structures of a network or two different methods in supplying critical loads.

Based on the features and capabilities which an index needs to have, as well as the need to address the issues raised in Section 2, the proposed index for measuring the resilience of an electrical network is described as follows.

3.1 | Definition of "combining investment and reform index"

In this part, the basis of the proposed index is described as "Combining Investment and Reform Index" with the acronym CIR. As shown in Figure 6 and as the name implies, the two performance parts of an electrical network are combined into one computational expression in the face of an adverse event. Part 1 of the curve deals with "costs imposed on the network before the decline in its performance in supplying loads" and "plans and investments made to increase the robustness of the electrical network", while part 2 covers "amount of load lost" and "plans and methods of repairs". The proposed index includes a combination of the above-mentioned parts and is presented in the form indicated in Equation (1).

$$CIR = \frac{TEN}{(TEN + C_1 \times VENS + C_2 \times WRENS)} \tag{1}$$

The parameters mentioned in Equation (1), including TEN, VENS and WRENS, all have energy dimension, and the definition, application, and calculation method will be described below.

Total Energy of Network (TEN): This parameter represents "amount of energy required by the entire network during the time window under consideration". In other words, TEN in Equation (1) plays the role of the baseline, and the large amount of VENS and WRENS parameters means more effect of event on the electrical network and its lack of resilience. To calculate the amount of TEN, the network load in the time window under consideration can be integrated according to Equation (2).

$$TEN = \int_{t_0}^{T} F_L(t)\, dt \tag{2}$$

where t_0 to T indicates the time interval of assessing the resilience of the network, which includes the moment the event starts (t_0) until the moment the network returns to normal condition (T) in terms of supplying the network loads. In addition, $F_L(t)$ represents the aggregation of network loads at the moment t.

Virtual Energy Not Supplied (VENS): In the first part of the network performance curve, network load supply is not defective, and the network provides all of its loads by conducting actions such as robustness before the event, redundancy, adding the resource for producing and saving energy, applying Tie-switches and the like, despite the damage to a part of the equipment. This section of the network performance curve is related to the cost, whether of the type of damage to the network equipment and the effort for their reforming, or whether of the type of investment to increase the robustness of the equipment against catastrophic events.

In order to apply the impact of the cost in the proposed index, this section of the curve is matched with other ones and converted from cost to energy format. To this aim, the term "virtual energy not supplied" is defined. In other words, the cost used in this section of the curve is similar to the cost imposed on the system due to failure to supply of a part of the network load or energy. Therefore, the cost spent in this section has become "assumed energy not supplied" using a coefficient called K_{CE} in order to integrate this part of the cost with the second part of the network performance curve and provide an integrated index

(Equation (3)).

$$VENS = K_{CE} \times Cost_{I\&R} \tag{3}$$

where K_{CE} is considered as the cost to energy conversion factor and $Cost_{I\&R}$ represents the amount of cost imposed on the network due to the event. It is noteworthy that K_{CE} is the reverse of "cost of electricity production" [62]. In other words, "cost spent in order to enhance network robustness" or "cost imposed in order to correct damage to the network" failed to supply more loads than the usual network load, and the cost could be spent for increasing the generation capacity in the network and more energy sales.

Including VENS parameter in the resiliency assessment index of an electric network creates two basic features for the introduced index. With the existence of VENS parameter in resilience assessment index, comparing methods and planning which deal with network robustness before the event becomes possible and the two electrical networks reinforced by various methods can be separated, even if no deficiency is created during supplying the network loads.

Weighted Real Energy Not Supplied (WRENS): In the second part of the network performance curve, the failure of the equipment due to event reaches a degree which leads to the power outage in some parts of network loads. The phrase WRENS is included in the proposed index similar to indices of resilience triangle or trapezoid and calculated by measuring the area of not-supplied load trapezoid or triangle. However, separating the impact of not supplying critical and non-critical loads in calculating the aforementioned parameter is regarded in the proposed index. Regarding the relevance of the resilience issue which relates to the need for supplying the critical loads in an electric network, the impact of critical loads lost in the proposed resiliency assessment index is considered K_{Cr} times more than that of non-critical loads. This issue is included in the WRENS parameter of Equation (1) and detailed in Equations (4)–(7).

$$WRENS = K_{Cr} \times S_{CENS} + S_{NCENS} \tag{4}$$

$$F_L(t) = F_{L_{cr}}(t) + F_{L_{ncr}}(t) \tag{5}$$

$$S_{CENS} = \int_{t_0}^{T} \left[F_{L_{cr}}(t) - F'_{L_{cr}}(t)\right] dt \tag{6}$$

$$S_{NCENS} = \int_{t_0}^{T} \left[F_{L_{ncr}}(t) - F'_{L_{ncr}}(t)\right] dt \tag{7}$$

where $F_{L_{cr}}(t)$ and $F_{L_{ncr}}(t)$ represent the aggregation of critical and non-critical loads at the moment t and in the normal operation mode of the network, respectively. Also, the parameters $F'_{L_{cr}}(t)$ and $F'_{L_{ncr}}(t)$ represent the aggregation of critical and non-critical loads supplied at moment t and in the interval of event and damage to the network, respectively. Accordingly, S_{CENS} and S_{NCENS} show the amount of not-supplied energy due to failure to supply critical and non-critical loads, respectively. By applying the WRENS parameter in the resiliency assessment index in accordance with the Equation (4), the deficiency in Section 2.1 is resolved and the value of this index for two curves brought in Figure 3 is differentiated, despite equal areas, and can provide the planner a certain understanding of network resilience status.

It is worth noting that there is still no clear consensus on the method of determining critical and non-critical loads, which can vary depending on the type of event and network conditions. For example, in [32], 30% of the load of each bus is considered as a critical load, in [57, 63], the power required to perform basic social activities such as the power of hospitals and street lighting is regarded as a critical load, or in [47, 61], hospitals, water pumps, and gas pressure stations are considered as critical loads in their calculations.

Impact factors C1 and C2: Given that the VENS and WRENS parameters in the proposed index represent "costs imposed" and "Unsupplied network load," respectively, Therefore, by changing the coefficients of C1 and C2 in Equation (1), it is possible to modify the impact of these parameters in the resilience assessment index, depending on the planner's opinion. For instance, if in a study, the comparison of investment strategies to improve the resilience of a network is not desired, due to the importance of supplying network loads to the costs imposed during the catastrophic events, the amount of C1 can be less than C2. In this way, it is possible to reduce the impact of imposed costs on the resilience index. But if the purpose of planning is to compare two investment methods to improve the resilience of an electrical network, both of which have the same function in supplying network loads, the parameter "imposed costs" is effective in decision making, and in this study, the coefficient C1 can be applied even more than C2.

The abstract concept of the parameters indicated in the proposed resilience assessment index is shown in Figure 7.

As shown in Figure 7, the two essential criteria for measuring the resilience of an electrical network, including "Costs imposed on the network (derived from investment or repairs)" and "Amount of unsupplied energy of the network (with separation of critical and non-critical load)," respectively, using the VENS and WRENS parameters, are combined in the proposed CIR index and examined simultaneously.

3.2 | Basis for calculating the resilience of a network according to the proposed index

The issues related to resilience and probability are always mixed and expressing the degree of resilience for a network cannot be limited to just a specific case since the parameters such as the type and severity of the event, equipment failure, amount of load during the event, and the like cannot be discussed with certainty.

To calculate the degree of resilience for a network using the proposed index, the results for a large number of scenarios which may occur for an electrical network during a catastrophic

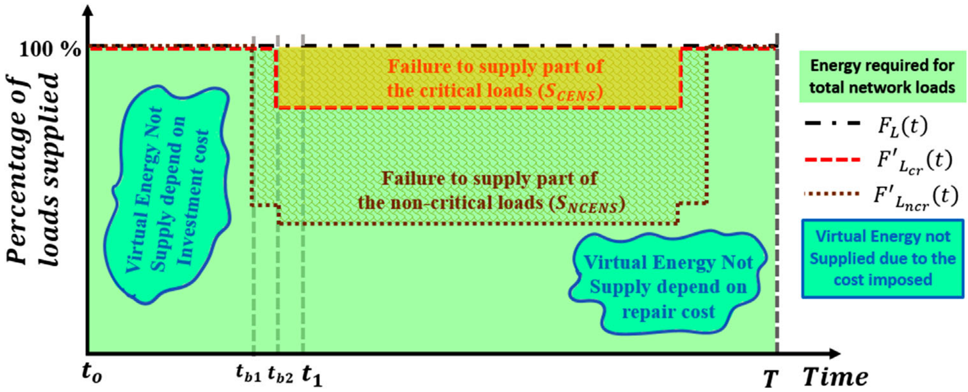

FIGURE 7 An abstract outline of the concept of CIR index (t_0: The moment the event begins, t_{bi}: The moment a part of the network destructs, t_1: The moment the event ends, T: The moment repair ends)

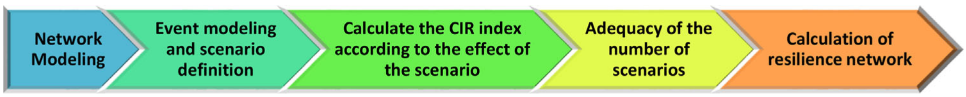

FIGURE 8 General structure of the process of calculating the resilience index for an electrical network

event is synthesized based on the Monte Carlo method and the process shown in Figure 8 and Equation (8), and amount of resilience index is accordingly calculated.

$$\text{Resilience system} = \sum_{s=1}^{N_s} CIR\,(s)\,/N_s \tag{8}$$

Where N_s represents the number of scenarios evaluated and $CIR(s)$ indicates the value of CIR for the s scenario. It should be noted, given that in the matter of resilience, catastrophic events are considered, scenarios with high impact intensity and the possibility of damage to several components of the network are considered in the modelling, and the effect of these scenarios is examined according to the network conditions and the type of event.

An example of how different scenarios are defined, also how probabilities affect the definition of these scenarios, including the probabilities of the severity of the event or the vulnerable network components, is described in Section 4. It is worth mentioning that Equation (8) has a general format, and an example of the calculation process in facing an electrical network with a severe storm using "Gumbel distribution" and "Fragility curves of lines" is examined in Section 4, and the same method can be generalized to other events.

4 | EXAMINING THE CIR INDEX IN A SAMPLE NETWORK

In this section, the calculation method and the capabilities of the index presented in a sample network are examined. It is noteworthy that fundamentally two different electrical networks cannot be compared due to differences in structure, sources, loads, and equipment life. Thus, the degree of resilience is always examined for an electrical network in different conditions which are created by the occurrence of different events, as well as the proposed methods and planning for that network.

Basically, the resilience assessment index is used to assess the resilience of an electrical network in the face of a catastrophic event and compare the proposed methods and plans to improve the resilience of that network. To this aim, the degree of resilience of the sample network is investigated using the proposed index without applying any modifications or planning to improve resilience, along with assuming the possibility of damage to a part of the network due to an event. Then, various common strategies are applied to improve resilience in the network under consideration, while describing the capabilities of the proposed index in demonstrating the impact of the strategies.

4.1 | Sample network

In the present study, IEEE modified 33-bus radial network, the single-line view and basic information of which are given in Figure 9 and Table 3, respectively, is investigated as a sample network. The IEEE modified 33-bus radial network has been used in a large number of network resilience assessment studies with minor modifications depending on the proposed method [64, 65]. Basic information of the above-mentioned network including line specifications and amount of loads is taken from MATPOWER v7.3 MATLAB code [66].

As demonstrated in Figure 9, the dotted lines represent tie-lines which are not in the circuit in the normal position in order to maintain the radius of the network, and are applied by the operators depending on the necessity to supply

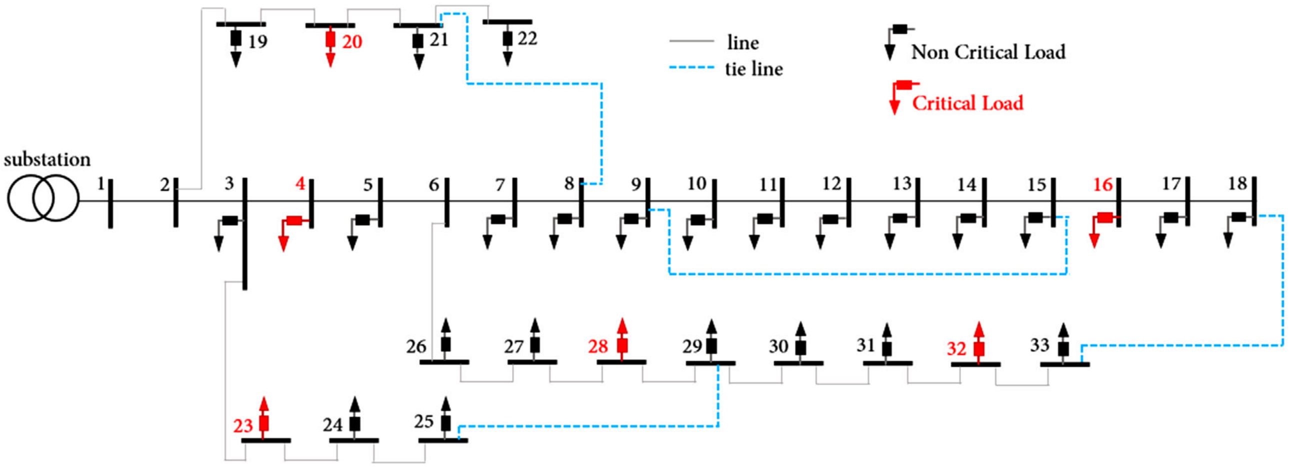

FIGURE 9 IEEE modified 33-bus radial network

TABLE 3 IEEE 33-bus modified circuit specifications

						Load at node *i*								Load at node i	
Line #	Node *i*	Node *j*	*R* (Ω)	*X* (Ω)	Length (m)	*P* (kW)	*Q* (kVAR)	Line #	Node *i*	Node j	R (Ω)	X (Ω)	Length (m)	P (kw)	Q (kVAR)
1	1	2	0.092	0.047	100	–	–	22	3	23	0.451	0.308	450	90	40
2	2	3	0.493	0.251	500	100	60	23	24	25	0.898	0.709	900	90	50
3	3	4	0.366	0.186	350	90	40	24	24	25	0.898	0.707	900	420	200
4	4	5	0.381	0.194	350	120	80	25	6	26	0.203	0.103	200	420	200
5	5	6	0.819	0.707	800	60	30	26	26	27	0.284	0.147	300	60	25
6	6	7	0.187	0.619	200	60	20	27	27	28	1.059	0.934	1000	60	25
7	7	8	0.712	0.235	700	200	100	28	28	29	0.804	0.701	800	60	20
8	8	9	1.03	0.74	1000	200	100	29	29	30	0.507	0.259	500	120	70
9	9	10	1.044	0.74	1000	60	20	30	30	31	0.975	0.963	950	200	100
10	10	11	0.197	0.065	200	60	20	31	31	32	0.311	0.362	300	150	70
11	11	12	0.374	0.13	350	45	30	32	32	33	0.341	0.53	350	210	100
12	12	13	1.468	1.155	1500	60	35	33	25	29	0.5	0.5	250	60	40
13	13	14	0.542	0.713	550	60	35	34	8	21	2	2	2000	–	–
14	14	15	0.591	0.526	600	120	80	35	12	22	2	2	2000	–	–
15	15	16	0.746	0.545	750	60	10	36	9	15	2	2	2000	–	–
16	16	17	1.289	1.721	1300	60	20	37	18	33	0.5	0.5	500	–	–
17	17	18	0.732	0.574	700	60	20								
18	2	19	0.164	0.157	150	90	40	**Aggregate Statistics of Network Loads**						***P* (kW)**	***Q* (kVAR)**
19	19	20	1.504	1.356	1500	90	40	Total non-critical network loads						3085	1490
20	20	21	0.41	0.478	400	90	40	Total critical network loads						630	310
21	21	22	0.709	0.937	700	90	40	Total network loads						3715	1800

maximum network loads. The nominal voltage of the network under consideration and its apparent power are equal to 12.66 kV and 10 MVA, respectively. In addition, the loads displayed in red are assumed to be critical network loads with a higher supply need than other ones.

4.2 | Event modelling

The effect of events such as earthquakes, storms, floods, and the like on an electrical network is investigated to examine the issue of resilience in various studies. Certainly, the

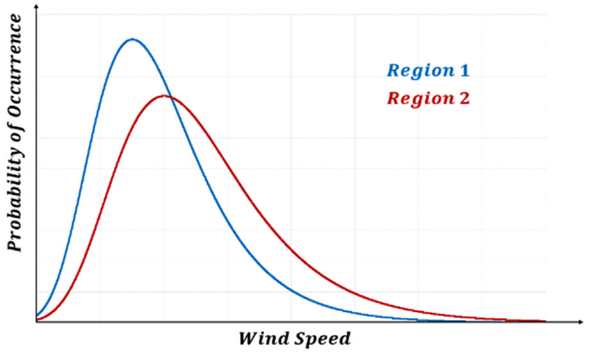

FIGURE 10 Sample of probability distribution for hurricane occurrence according to probability density function of Gumbel distribution

occurrence of severe hurricanes and storms is considered as the most harmful type of natural disasters for electrical networks, which has increased significantly and imposed high costs on electrical networks during the last two decades due to climate change and global warming. Therefore, the present study aims to assess the above-mentioned phenomenon without reducing the comprehensiveness of the proposed index.

Different probability distributions are used in different studies to model severe hurricanes and storms. The Gumbel distribution which is called 'Extreme Value Distribution' was utilized to model severe storms since the subject of resilience is mainly related to events with high-intensity and low probability of occurrence. Generally, the random variable and Gumbel distribution are utilized to describe the behaviour of the maximum values in a number of random samples. In other words, the aforementioned function models the worst cases of the event occurrence according to its type and history in the studied geographical region. Probability Density Function and Cumulative Distribution Function related to the Gumbel distribution are represented in Equations (9) and (10), respectively.

$$f(x) = \frac{1}{\beta} e^{-\left(z + e^{-z}\right)}, z = \frac{x-\mu}{\beta} \tag{9}$$

$$F(x, \mu, \beta) = e^{-e^{\frac{(x-\mu)}{\beta}}} \tag{10}$$

where μ and β indicate the location and scale parameters of the Gamble distribution, respectively, and $\beta > 0$. The possibility of modelling the worst cases of a natural phenomenon is among the features of Gamble distribution, which corresponds exactly to the subject of resilience.

In order to model the probability of severe storms using the Gamble distribution, the study region is first divided into several regions and the features related to the probability distribution are determined for each region according to the history of the most severe storms when the geographical region is regarded as vast. The dividing process is applied for transmission networks, which usually cover a large region. Figure 10 illustrates a sample of the distribution curves.

The μ and β parameters are determined according to the data related to the history of events in a region and using the *evfit* command in MATLAB. With the parameters μ and β, Gumbel's cumulative distribution function related to the desired geographical area will be obtained according to Equation (10), Therefore, it is possible to define the samples of wind speed and the definition of an event scenario from the inverse transform of (10) using MATLAB function *evinv*. The whole network is assumed to locate in a geographical region and a Gumbel distribution feature is utilized for location and scale parameters with values of 55 and 8, respectively, since the sample network examined in this study is considered as a distribution network. The location parameter indicates the storm's intensity with the highest probability of occurrence, and the scale parameter indicates the change in the likelihood of the occurrence of strong winds with different intensities.

4.3 | Equipment failure modelling

In general, the degree of failure for the equipment of an electrical network during catastrophic events depends on the "intensity of the event" and the "fragility of the equipment structure". Failure of electrical network equipment is modelled by various methods such as "applying experimental equations" [21, 66] or "using fragility curves" [39, 42]. It is worth noting that any of the devices in a network may fail during an event. However, in order to facilitate calculations, only network lines are assumed to fail by the event without reducing the totality of the issue and fragility curve method is utilized to model line failure.

In order to make the modelling more realistic, network lines are divided into four categories with poor, medium, proper, and complete endurance, and a different fragility curve is regarded for each category based on Figure 11 and the circuit displayed in Figure 12 since all of the devices in an electrical network including its lines do not have the same condition and structural endurance. In this study, experimental results similar to the study [67] were used to define the fragility curve for lines with different structures.

Among 37 existing lines in the sample network, lines 6 and 14, 10 and 28, as well as 8, 25, and 31 are assumed to have a poor, medium, and proper structure, respectively, and other lines have a complete structure. In other words, the probability of line failure with complete structural status is extremely low and 7 lines of the network in the aforementioned order have a higher failure probability.

In order to determine the failure of a line due to the occurrence of an event, its failure probability is compared with the random number generated by the uniform probability distribution, and the assumption of its failure is considered during modelling when the failure probability is regarded as higher. In the present study, the performance of the protective parts of the circuit is assumed to be flawless and the failed parts can be separated from the network quickly. In addition, the assumptions given in Table 4 regarding the time and cost of repairing the lines are considered based on their structural condition.

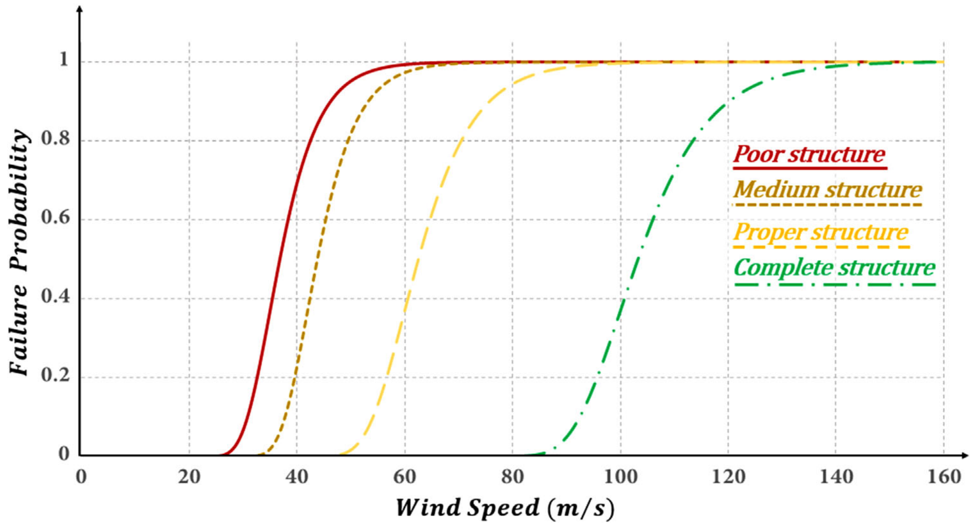

FIGURE 11 Fragility curves for four types of lines in the electrical network

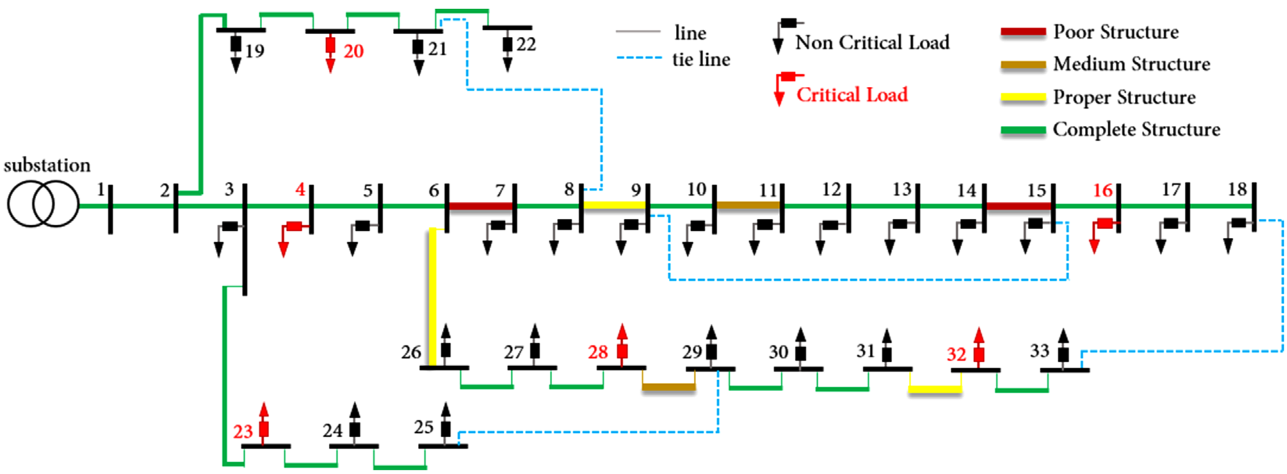

FIGURE 12 Modified IEEE 33-bus circuit with assumptions related to four types of lines in terms of failure

TABLE 4 Hypotheses regarding the behaviour of lines damaged by the event

Line number	Endurance rate against the event (h)	The cost of repair For each line ($)	Time required for repair (h)
6, 14	1	10,000	48
10, 28	4	20,000	96
8, 25, 31	7	40,000	144
Other lines	15	80,000	192

4.4 | The resilience of a network before reform or investment

In order to calculate the resilience of an electrical network based on Equation (8) and apply the Monte Carlo method, a large number of scenarios should be defined, along with evaluating their results. To define a scenario, the process described in Section 4.2 is utilized, and the failed parts of the circuit are identified and separated from the circuit by assuming the proper operation of the protective equipment according to what was elaborated in Section 4.3.

The power flow is performed for the remaining parts of the network which are connected to a power source by examining the failed lines and the possibility of connecting the isolated parts of the network using the existing tie lines. Then, the required planning is conducted and the value of the CIR parameter is determined for the above-mentioned scenario by considering power flow constraints including observing bus voltage limits, observing the line capacity limits, maintaining the radial state in networks with this constraint, as well as supplying the maximum load with the priority for critical loads. Details of the process for calculating the resilience of an electrical network for each scenario are shown in in Figure 13.

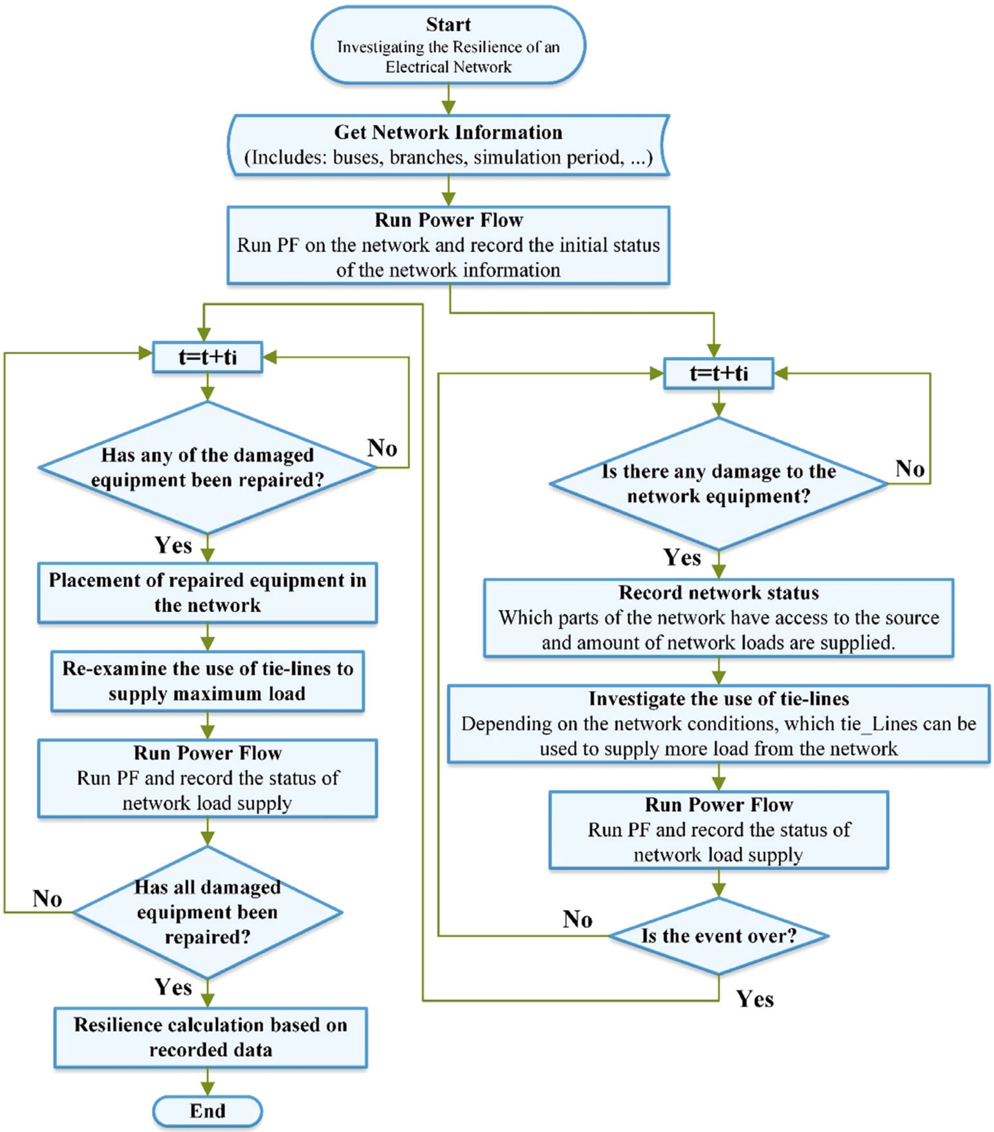

FIGURE 13 Flowchart of program for extracting the information needed to calculate the proposed index

In order to calculate the CIR parameter in a specific scenario according to the algorithm in Figure 13, it is necessary to examine at each time step the impact of network changes, such as the removal of damaged network equipment or the repair and operation of damaged equipment, on the network's supplied load.

In the algorithm shown in Figure 13, due to the necessity of observing the radial state of the network in order to enable proper protection in the distribution network, As well as the need to use the fewest tie lines in order to reduce network losses, the optimal method of using tie lines has been modelled in the case of a change in the network due to an exit of a line or an entry in the circuit of a line after a repair.

For example, the details of calculating the CIR parameter for a scenario in which seven fragile lines of the network including 6 and 14, 10 and 28, as well as 8, 25, and 31 fail to operate are represented in Equations (11)–(13) by regarding the assumptions indicated in Table 4. The state of the network and changes in the supply of normal and critical loads in this case are shown in Figures 14 and 15, respectively. In the programming, the selection of the optimal tie-lines status is made under two conditions: maintaining the radial structure of the network and achieving the highest value of the CIR.

$$
\begin{aligned}
VENS &= K_{CE} \times \mathrm{Cost}_{I\&R} = K_{CE} \times (\text{Investment Cost} \\
&\quad + \text{Repair Cost}) = K_{CE} \times \left(0 + \text{Repair Cost}\right) \\
&= 10\ \mathrm{kWh}/\$ \times 180000\$ = 1800000\ \mathrm{kWh} \\
&\quad \text{Investment Cost} = 0 \\
\text{Repair Cost} &= \text{Repair Cost}_{Line\_6,14} \\
&\quad + \text{Repair Cost}_{Line\_10,28} + \text{Repair Cost}_{line\_8,25,31} \\
&= 20000\$ + 40000\$ + 120000\$ = 180000\$
\end{aligned} \tag{11}
$$

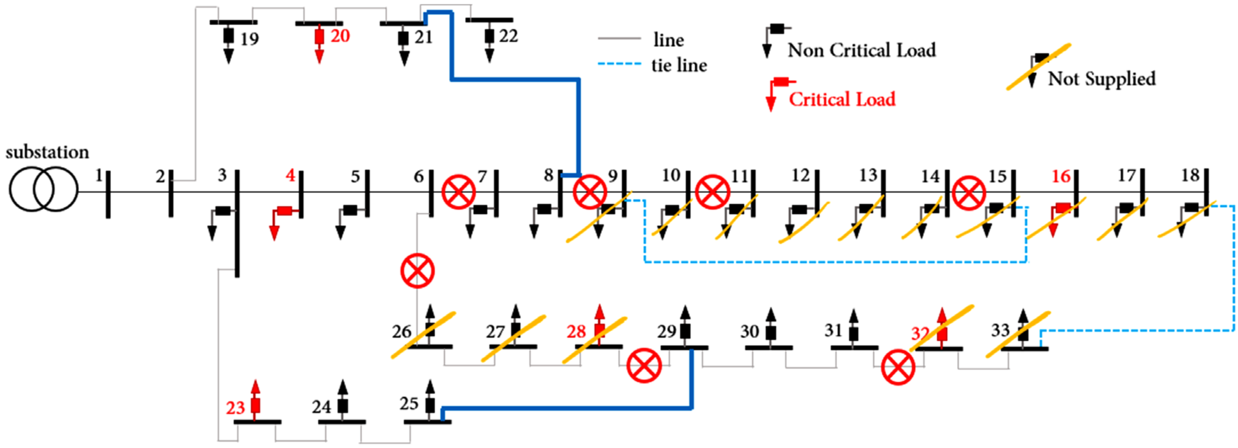

FIGURE 14 Network status in case of damage to seven lines of it

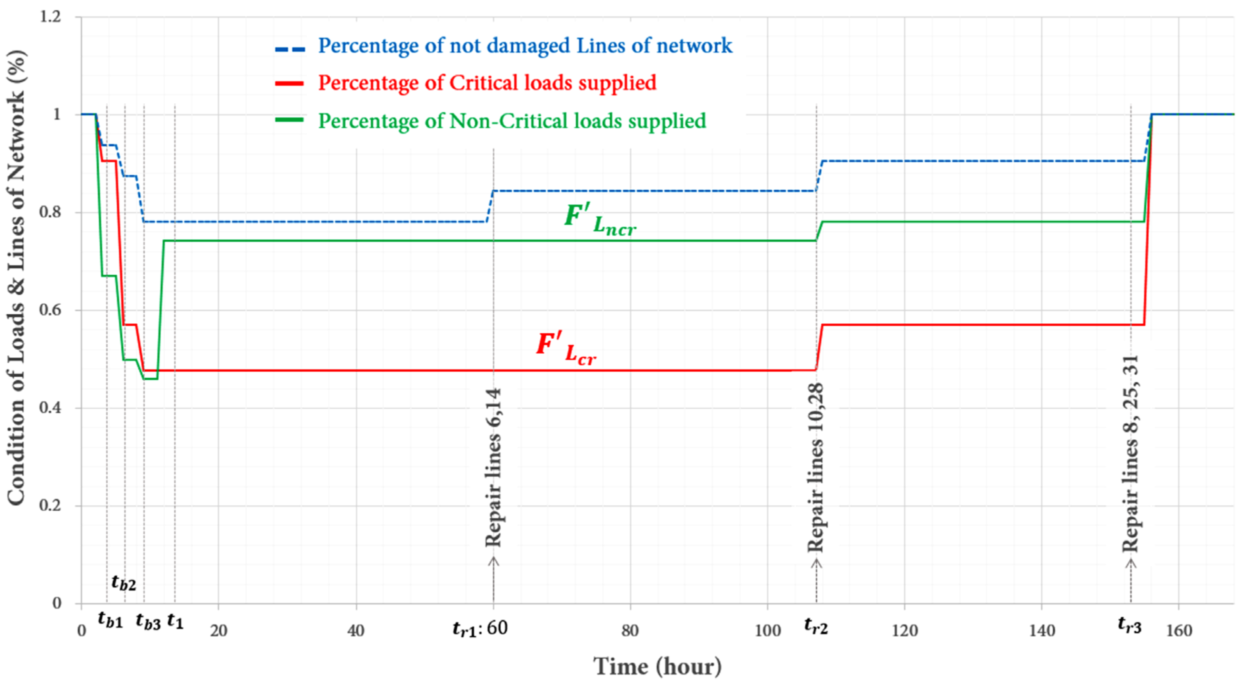

FIGURE 15 Load supply diagram and status of network lines in a scenario with damage to seven lines of the network (t_{b1}: The moment lines 6 and 14 fail, t_{b2}: The moment lines 10 and 28 fail, t_{b3}: The moment lines 9, 18, 26–28 fail, t_1: The moment the event ends and repair start, t_{ri}: The moment repair of i lines ends)

$$K_{cr} = 5$$

$$S_{NCENS} = \int_{t_0}^{T} \left[F_{L_{ncr}}(t) - F'_{L_{ncr}}(t)\right] dt$$

$$= 3085\,\text{kW} \times \left(\int_{0}^{168} \left[1 - F'_{L_{ncr}}(t)\right] dt\right)$$

$$= 121395\ \text{kWh} S_{CENS} = \int_{t_0}^{T} \left[F_{L_{cr}}(t) - F'_{L_{cr}}(t)\right] dt$$

$$= 630\text{kW} \times \left(\int_{0}^{168} \left[1 - F'_{L_{cr}}(t)\right] dt\right)$$

$$= 46620\ \text{kWh}\ WRENS = K_{Cr} \times S_{CENS} + S_{NCENS}$$

$$= 5 \times 46620 + 121395 = 354495\ \text{kWh} \tag{12}$$

$$CIR = \frac{TEN}{(TEN + C1 \times VENS + C2 \times WRENS)}$$

$$= \frac{624120}{624120 + 0.2 \times 1800000 + 0.8 \times 354495} = 0.49 \tag{13}$$

To determine the network's resilience by considering the probability of different event modes, it is necessary to repeat the preceding process, calculate the CIR parameter for many scenarios, and aggregate the results according to Equation (8). The process of generating the scenario and calculating the

TABLE 5 Comparison values of CIR parameter and curve analysis index for four scenarios with different intensities

Network status		Scenario 1: Full robustness and no damage to the network	Scenario 2: Damage to part of the network while supplying the entire load	Scenario 3: Damage to the network while supplying all of the critical loads	Scenario 4: Damage to a large part of the network and failure to supply a part of the critical and non-critical loads
Damaged lines		–	L6, L14	L6, L14, L10, L28	L6, L14, L10, L28, L8, L25, L31
Normal load not supplied		0	0	285 kW	745 kW
Critical load not supplied		0	0	0	330 kW
Resilience trapezoid metrics [53]	Φ (MW/h)	–	–	–	−0.377
	Λ (MW)	0	0	0.285	2.64
	E (Hours)	0	0	96	48
	Π (MW/hours)	–	–	–	0.0275
	Area of trapezoid (MW × hours)	0	0	27.36	262.68
CIR index		1	0.94	0.82	0.49

CIR parameter continues until achieving the appropriate accuracy and stopping the criterion because the accuracy of the index obtained using the Monte Carlo method improves with increasing the number of samples. In addition, a minimum limit is maintained for the number of scenarios examined to ensure the completeness of the data. Similar to studies [11] and [68], the ratio of "standard deviation to the expected value of the evaluated index" with a value of 3% was utilized as a stopping criterion. The value of the resilience index for the 33-bus IEEE sample network reaches 0.621 by performing the aforementioned steps, modelling 1050 scenarios, and applying Equation (8).

4.5 | Comparing the performance of the CIR index with the curve analysis index in different intensity scenarios

To demonstrate the effectiveness of the CIR parameter from events of varying intensities, as well as comparing this index to the curve analysis index, Table 5 shows the values of these indices for four scenarios with different intensities. Following are some of the improvements of the proposed index over the curve analysis index are outlined according to the results given in Table 5.

- In the second scenario, the value of the CIR parameter is not 1% or 100% due to the cost imposed to repair the failed lines from the event, despite the supply of all of the network loads including non-critical and critical by using tie-lines in the network, which results in informing the planner about the incompleteness of the network under study, despite supplying all of its loads. While in the curve analysis index, the first and second scenarios are not separated from the viewpoint of resilience, informing the planner incorrectly of the identical network structure status.
- The large difference between the third and fourth scenarios in the value of the CIR parameter stems only from failing to supply a part of the critical loads during the fourth scenario, meaning that the CIR parameter is affected by failing to supply the critical loads, which can affect the proposed index and make the planner informed concerning non-resilience of the network and the need for reform. While changing the status of each of the unsupplied loads in the investigated network from critical to non-critical and vice versa does not affect the value of the curve analysis index and does not create a difference in the output value of this index.
- The proposed index provides a better understanding of the network status for the planner by displaying the results as a percentage.

4.6 | Comparing the performance of common resilience assessment indices

To ensure the accuracy of the performance of the proposed index and in accordance with the various resilience indices expressed in numerous articles, the results obtained from the measurement of the common indices of resilience evaluation, in the IEEE-118 bus radial network, according to the parameters given in Figure 16 are briefly compared in Table 6.

In resilience studies, various indices have been proposed and used in different ways. Table 6 shows some common indices for evaluating resilience in electrical networks. It is noteworthy that each of the parameters listed in Table 6 has been employed as a resilience evaluation index in different studies, both singly and in various combinations. For example, different combinations of a graph's parameters have been proposed and used in evaluating a network's resilience under the "Graph Theory" title.

Based on the specifications given in Figure 16, the second column of Table 6 represents the output of each index in

TABLE 6 The resiliency of IEEE 118-bus network from the viewpoint of common resilience evaluation indices

			Capabilities of resilience evaluation indices					
Resilience index		**Index value in the defined scenario**	**Investigation of pre-event investments**	**Separation of the effect of critical and non-critical loads**	**Investigating the costs imposed on the network due to the event (Such as the cost of repairs, planning reforms, etc.)**	**Examining all parts of the resilience parameter, including the rate of decline, retention time in the state of decline, recovery speed, etc.**	**Examining multiple scenarios and possibilities**	**Calculation time and information volume needed**
Assessment based on network load	Unsupplied network load (MW)	3.519	✗	✓	✗	✗	✗	✓
	Percentage of supplied load	0.845						
	Percentage of supplied energy	0.956						
Assessment based on critical load	Unsupplied critical load (MW)	1.515	✗	✓	✗	✗	✗	✓
	Percentage of supplied critical load	0.659						
Graph theory index	Graph diameter	0.019	✓	✗	✗	✗	✗	✗
	Average path length of the graph	9.372						
	Clustering coefficient	0.636						
	Network efficiency	0.152						
Curve analysis index	Area of trapezoid (MWh)	168.925	✗	✗	✗	✓	✗	✗
Proposed index	CIR	0.751	✓	✓	✓	✓	✓	✗

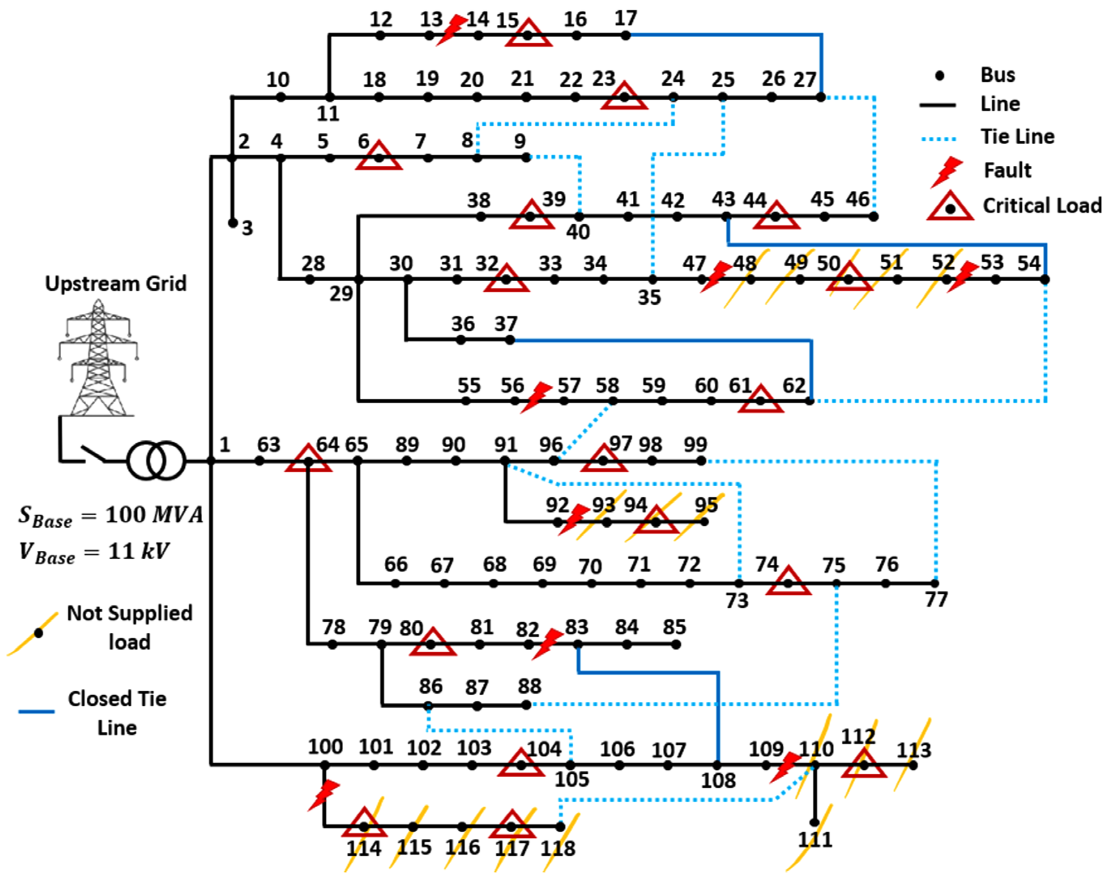

FIGURE 16 IEEE modified 118-bus radial network

expressing the resilience of the IEEE 118-bus network, which shows the dispersion of the results from the "quantity" and "dimension" points of view. And it confirms the necessity of developing a standard index to unify the results and evaluate different strategies.

The third to eighth columns of Table 6 compares each index's comprehensiveness from the perspective of different criteria. Also, it has been examined whether different parts of the resilience parameter, such as "Costs imposed on the network before and after the event", "Prioritizing the supply of loads in critical conditions of catastrophic events", "Considering possibilities and examining multiple scenarios" have been applied to the calculations of each index.

As compared to other indices presented so far, the curve analysis index covers more details of the resilience parameter in its definition and has been used in many studies and research projects in the field. The CIR index in this study was defined based on the curve analysis index, and its comprehensiveness has been improved by adding features listed in Table 6 and fixing shortcomings.

The resilience of the network was assessed without corrective measures or investment up to this part. Now, the method of selecting a strategy to improve resilience using the proposed index is evaluated.

4.7 | Selecting the optimal strategy based on the proposed index

In order to explain the capability of the proposed index in distinguishing and selecting the optimal strategy among the ones proposed for improving resilience of an electrical network, several strategies which are commonly proposed to improve resilience in electrical networks are compared in the sample network.

Assume that four strategies are presented to improve the resilience of the 33-bus IEEE network indicated in Figure 12, and the planner should comment on selecting the optimal strategy among the proposed ones represented below and symbolically shown in Figure 17.

- Strategy 1: Adding tie-line between buses 22 and 12; A tie line with a length of 2.5 km and resistance and reactance of 2 ohms has been modelled.
- Strategy 2: Adding generation source; Installation of a power source on Bus 18 with a power production capacity equal to 1.5 megawatt.
- Strategy 3: Adding energy storage source; Installation of an energy storage source on bus 32 to supply the critical loads of this bus with a capacity of 230 kW.

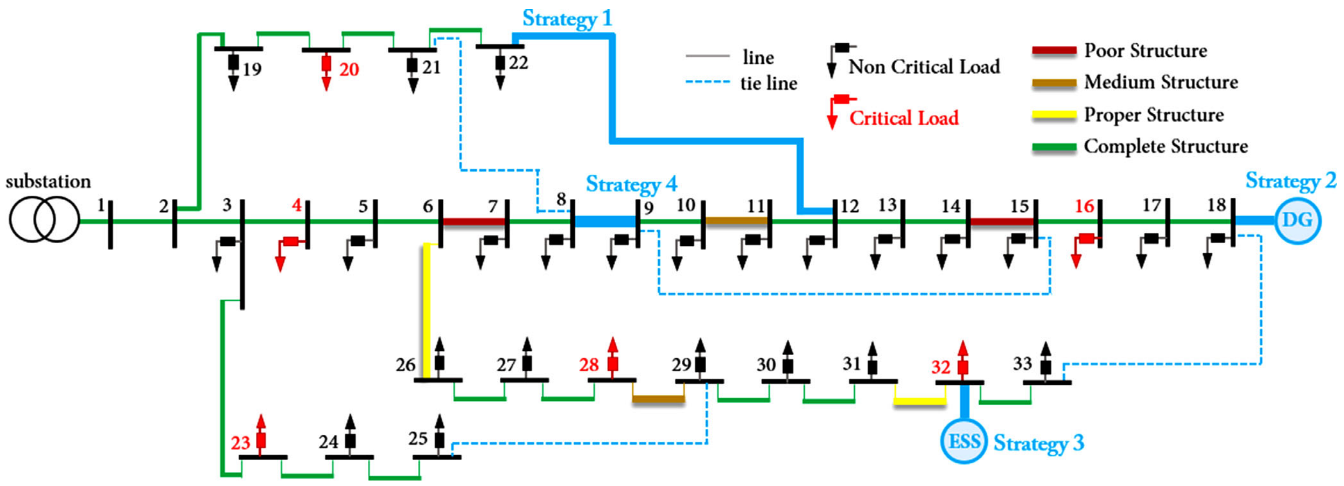

FIGURE 17 Demonstrating proposed strategies to improve resilience in IEEE 33 bus network

TABLE 7 Effect of the indicated strategies on the proposed index

No.	Strategy	Cost of investment	Resilience of network before investment	Resilience of network after investment	Change in resilience (%)
1	Install a tie-switch between node 22 and 12	200 k$	0.621	0.523	−15.65%
2	Install a DG at bus 18	125 k$		0.609	−1.82%
3	Install an energy storage system at bus 32	25 k$		0.661	+6.50%
4	Increase the robustness of L8	50 k$		0.687	+10.77%

- Strategy 4: Line reinforcement; Increasing the endurance of line 8 by making corrections to the poles along the route and transforming the line structure from a weak to a complete state in the modelling process.

A part of the network loads which were previously more likely to confront outage due to the failure of fragile lines are supplied with a higher probability by applying any of the above-mentioned strategies. Now, the planner should comment regarding selecting the optimal strategy among the proposed approaches. To this aim, each of the four raised strategies was simulated separately in the sample network, and the measurement of network resilience was performed for them using the proposed Index. Calculation results and the effectiveness of each of the aforementioned strategies in improving the resilience of the studied network are shown in Table 7, and the analysis related to these results is presented in the following. It is noteworthy that similar to Section 4.4, the K_{CE} coefficient is equal to 10 kWh/$ and the importance of critical load supply compared to non-critical network loads is five times.

As shown in Section 4.4 and the fourth column of the Table 7, the resilience of the investigated network will be 0.621 before applying any investment or corrections. The fifth column of the Table 7 presents the resilience value of the IEEE 33-bus network based on each of the proposed strategies. Also, to clarify the effectiveness of each strategy in improving the network resilience parameter, a percentage of changes in network resilience is presented in the last column of Table 7.

Based on the last column of Table 7, the fourth strategy is regarded as superior to other solutions introduced from the perspective of proposed resilience index by improving resilience by 10.77%. Table 7 is analysed briefly in order to select the appropriate strategy.

- The first strategy is not appropriate from an investment perspective because its cost is high due to the need to build a new line between buses 12 and 22. In terms of the amount of load provided, this solution does not have a high impact on the supply of network loads due to the possibility of using network tie-lines in similar routes and only increases the probability of supplying some non-critical loads in some scenarios. Therefore, it cannot cover the negative impact of high investment costs, and as a result, it will not only not improve the resilience index but will reduce it by 15.65%.
- The second strategy is considered appropriate in supplying critical and non-critical loads and increases the probability of providing a significant part of the lost loads. However, like the first method, it imposes high costs on the network, eliminates

the appropriate effect of supplying the network loads, and fails to improve the resilience index due to the need to build a source of production.

- The third strategy plays a significant role in supplying the critical loads of the network at a low cost by using the energy storage source in bus 32, which contains a large critical load and increase the amount of resilience up to 6.5%. In addition, it affects the resilience index better and is regarded as superior to the first and second ones since supplying critical loads during catastrophic events is considered as highly important.
- The fourth strategy proposes the plan to improve the robustness of line 8 considering the network structure and plays a significant role in increasing the probability of supplying the network loads and improving resilience at a low cost by providing conditions for using the existing tie-lines. Therefore, it is regarded as the most effective solution in improving the resilience of the network. The fourth strategy meets approximately the probability of supplying the same load provided in the second one and plays a more influential role in improving resilience because it imposes less cost on the network than the construction of a generation unit. Comparing the results of the fourth and second strategies proves the efficiency of the proposed index in simultaneously examining the issues of "cost" and "amount of load supplied", indicating that the solution does not necessarily require more load or higher cost to be optimal. Rather, it is necessary to examine these two parameters simultaneously and according to the conditions.

4.8 | Analysing the effect of cost on priority of a strategy

Drawing the curve "percentage of improvement of resilience index to the cost" is considered as another analysis, which facilitates to the selection of the optimal strategy for the planner. For example, the question related to the previous study is that how much the superiority of the fourth strategy over other strategies last. In other words, it should be clarified that how much cost is necessary for the aforementioned strategy to be superior over other ones when more cost is needed for increasing the robustness of line 8. The curve of changes in the resilience index to the cost used for the fourth strategy is shown in Figure 18 to display the effect of cost on the superiority of a strategy.

Based on the Figure 18 and assuming that the cost used for the third strategy is constant, the fourth strategy is still superior to the third one with its cost increasing to $72,500. However, using the third strategy to improve the resilience of the network under consideration takes precedence by increasing the cost to more than this amount.

Expressing the maximum amount of acceptable investment in a strategy is regarded as another point, which can be indicated by analysing the curve "changes in the resilience index to the cost" for each strategy. For instance, the fourth strategy can affect the network resilience index significantly up to

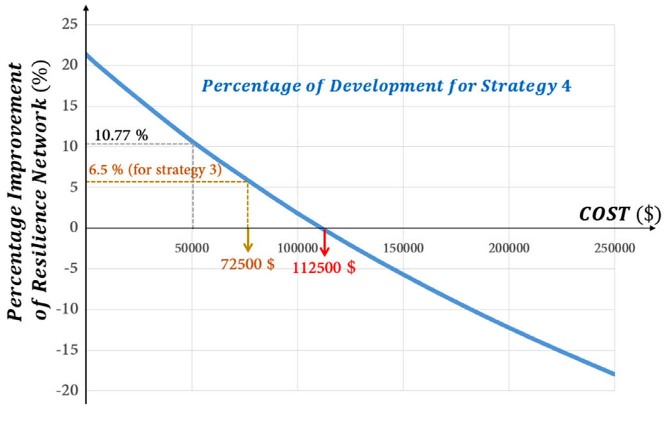

FIGURE 18 Percentage of improving network resilience by changing the investment cost required in the fourth strategy

$112,500, regardless of comparing to other strategies. However, it can no longer be justified and cannot affect the resilience index significantly when more investment is needed due to the possibility of building a generation source at a lower cost.

The results indicated the ability of the CIR index to combine the factors of "amount of investment or the cost imposed" and "efficiency of strategies in supplying network loads with priority of supplying critical loads" in order to select the optimal strategy. This feature is among the main reasons for the need to define a new index in the subject of resilience, which was not done in the indices presented so far [69] and an attempt was made to include it in the proposed index.

The possibility of determining the K_{CE} and K_{cr} parameters depending on the planner's opinion and the conditions of the network under consideration is among the practical advantages of the proposed index. The K_{cr} parameter is determined based on the importance of supplying critical loads compared to non-critical loads. In addition, the K_{CE} parameter depends on the amount of cost required for energy generation in that network, which differs in different places and can be changed in the proposed index.

5 | CONCLUSION

Power systems (electricity supply network) are considered as a main part of a modern network, the resilience of which against natural hazards should be improved. The measurement of resilience should be standardized and the same index should be defined before proceeding in this regard.

So far, a large number of indices have been proposed in various studies, among which the "system performance curve analysis" is regarded as more efficient compared to others due to the study of different parts of the subject of resilience. It has been used in more studies although it has some shortcomings. The present study examined the shortcomings and problems which can be created for the planner and introduced the CIR index based on the above-mentioned index for their solving. The salient features of the proposed CIR index are as follows.

- Applying two types of costs including "investment cost" and "repair cost" in the proposed index. However, all of the network loads may have been supplied, despite the damage to the network.
- Creating a balance between "amount of investment" and "benefit from increasing resilience"; Maximum investment is not necessarily the best solution. This index can provide a balance point between the cost used and the degree of resilience improvement in compliance with the systematic decisions of the planner since the cost used has been considered in the proposed index in addition to the amount of load supplied.
- The strategies which considered a specific part of the resilience in their examination and fundamentally have a different function can be compared in the proposed index. For example, the strategy of increasing the robustness of a line before the event can be compared with that of planning the generation change after the event by using the proposed index.
- There is the possibility to change the impact of critical loads supply in the proposed index. The impact of critical loads supply in the proposed index compared to normal loads can be altered depending on the planner's opinion and by changing the K_{cr} coefficient according to the importance of critical loads supply.
- There is the possibility of determining the cost to energy conversion factor by the planner. The cost to energy conversion factor in different countries and even in different cities of a country can vary according to its geographical and political conditions. In the proposed index, the conditions for determining this parameter are provided by the planner.

Finally, the capabilities of the proposed index in a sample network for events with different intensities and common strategies to improve resilience were examined and described.

AUTHOR CONTRIBUTIONS

Arash Dehghani: Conceptualization; Data curation; Formal analysis; Investigation; Software. Mostafa Sedighizadeh: Conceptualization; Data curation; Formal analysis; Investigation; Methodology. Farhad Haghjoo: Supervision; Validation; Visualization; Writing - original draft.

CONFLICT OF INTEREST

The authors certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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The data that support the findings of this study are available from the corresponding author upon reasonable request.

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