international journal of critical infrastructure protection 35 (2021) 100469

Contents lists available at ScienceDirect

International Journal of Critical Infrastructure Protection

journal homepage: www.elsevier.com/locate/ijcip

A study on resilient and cost-based design in power distribution network against severe hurricane

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ARTICLE INFO

Keywords:
Network planning
Resilience
Distribution network
Disasters
Geospatial map

ABSTRACT

Vulnerability mitigation is the solution for creating resilient distribution networks aims to prevent the uncontrollable outage propagation. This paper presents a new resilience index as a powerful tool to enhance the resilience of distribution systems against extreme hurricane events. The suggested framework provides a comparative study for optimal feeder routing problem and HV substation placement from the cost and resilience viewpoints. Once, the network is planned based on cost minimization, and then the proposed resilience index is calculated for the planned network. Finally, the network is planned based on resilience enhancement and afterward the planned network's cost is calculated. In case of resilient-based planning, the studied area is divided into small sites with different wind speed to evaluate the geospatial characteristics of hurricane and a fragility index is calculated for each distribution network component located at each sites. Both cost- and resilient- based networks are planned using deterministic and probabilistic approaches. In deterministic approach, network planning is done according to the worst prediction, the highest wind speed. But in probabilistic one, some scenarios with specified probability are defined for wind speed. Results show that, fragility index is high when considering worst prediction, so this less probable scenario needs higher investments. In this regards, scenario based planning, can lead to the best compromised solution considering cost and resilience which the obtained results validate the accuracy of the modellings and efficiency of the proposed method.

Abbreviations: VD_{MVF}, Acceptable voltage drop for MV feeder; $P(h)$, Annual occurrence of the hurricane; λ, Average number of hurricane; $AvLoss(S_{HV}^{hv})$, Average annual loss factor of a HV substation; P_{DisTr}^{dt}, Active power of a MV distribution transformer, kW; $AvLd(DT_{dt})$, Average annual load factor of a HV substation; $AvLd(Load_{LB}^{dt})$, Average annual load factor of a MV distribution transformer; $ALSF(S_{DisTr}^{dt})$, Average annual loss factor of a MV substation; P_z, Active power of z-th load, kW; γ_i, Binary decision variable; λ_{dt}, Binary Decision Variable; λ_{Con}, Conductor fragility index; $I(MVF_f)$, Current of f-th MV feeders; $HV_{Load}(S_{HV}^{hv})$, Current of a HV substation; ${CC^{dt}}_{DisTr}$, Cost of construction of new MV transformer; ${CL^{dt}}_{DisTr}$, Cost of resistive and core loss of MV distribution transformer; $TL(S_{DisTr}^{dt})$, Current of a MV substation; CC_{HV}, Cost of construction of new HV substation; ${CC^f}_{MVF}$, Cost of construction of new MV feeder; $CL(S_{HV}^{hv})$, Cost of resistive and core loss of HV substation; Ω_{HV}, Cost function of HV substation; $\Omega_{_{DisTr}}$, Cost function of MV distribution transformer; Ω_{MVF}, Cost function of MV feeders; d_f, Distance of f-th MV feeder, m; pd, Distance between two poles; ELCF, Energy loss cost factor,($/kWh); hv, Indicator of HV substations; dt, Index for distribution transformer; z, Index for load buses; ^{h}, Number of hurricane per year; N_{Feeder}, Number of feeders; N_{MV}, Number of MV transformers; N_{HV}, Number of HV substations; N_{LB}, Number of load buses; N_{DistTr}, Number of distribution transformers; N_{MVF}, Number of MV feeders; F_{Con}, Number of conductors; N_Φ, Number of distribution poles; $P_{NLL}(S_{HV}^{hv})$, No load loss of a HV substation, kW; λ_Φ, Poles fragility index;λ_{Tr}, Transformer fragility index; $P_{NLL}(S_{DisTr}^{dt})$, No load loss of A MV distribution transformer, kW; T_P, Planning period; $\cos\theta_{HV}^{hv}(S_{HV}^{hv})$, Power factor of hv-th HV substation; $\cos\phi_{DisTr}^{dt}$, Power factor of dt-th MV distribution transformer; R_f, Resistance of f-th feeder; $\Psi_{Network}$, Resilience index of whole network; 2, Resilience index for feeder; Ψ_Φ, Resilience index poles; Ψ_{Tr}, Resilience index transformers; Ψ_{Con}, Resilience index conductors; w, Site-specific wind speed; $P_{SCL}(S_{HV}^{hv})$, Short-circuit loss of a HV substation, kW; S_{HV}^{hv}, Supplied load for high voltage substation (KVA); $P_{SCL}(S_{DisTr}^{dt})$, Short-circuit loss of a MV distribution transformer, kW; S_{DisTr}^{dt}, Supplied load for medium voltage distribution transformer (KVA); Ω_F, Total cost function of distribution network.

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https://doi.org/10.1016/j.ijcip.2021.100469
Received 24 February 2020; Received in revised form 12 April 2021; Accepted 29 July 2021
Available online 25 August 2021
1874-5482/

1. Introduction

Security and reliability are the vital parameters of electric power grid operation that must be considered carefully. In recent years, many disasters associated with climate change occurred that causes large blackouts like: 2005 Hurricane Katrina blackouts, 2011 Japan Earthquake blackouts, and 2012 Hurricane Sandy blackouts. During 2003 till 2012, 679 large blackouts occurred which in each blackouts at least 50000 customers were affected by natural disasters in the US [1]. Also, 933 events occurred during 1948 to 2006 has been reviewed in [2]. The first studies of adverse weather event on electric network have been done during 1930s, when a strong storm of New England Hurricane occurred in 1938 [3]. In the last decades, noticeable improvement of assessing techniques of weather condition's effect on power systems have been emerged. In addition, complexity and interdisciplinary feature of this problem speed down the research activities. Irreparable damages as the major result of large power outages due to adverse weather cause financial loss of $80 billion annually in United States. Due to progressive climate change in future, much more resilient critical infrastructure must be developed to maintain the power system more secure and reliable [4]. Existing techniques for measuring power distribution network's reliability are not sufficient for assessing network's resilience. Based on the references [5–7], resilience can be defined as the ability of power system to be strong enough against different hazards and recover quickly from attacks or naturally occurring events. The research about adverse impacts of natural disasters on power system have different aspects. In [7], resilience metrics including all infrastructures of a city is suggested. But, their techniques do not focus on power distribution systems and hence, are not practicable for electrical networks. Several articles such as references [6,8–10], assess resilience of energy infrastructures. Authors in [11] suggests a graph theoretic method based on fuzzy cognitive maps which assess power system as an interconnected system of energy resources and loads. The proposed model, analysis power grid during destructive events that leads to optimal reinforcement techniques for grid infrastructures. In [12], resilience of power system has been analysed regarding customer benefits. Assessing power distribution system resilience, enhances control decisions made by network's operator as corrective actions. Moreover, recently developed technique in distribution automation can be involved in the suggested methods [13]. Mainly, resilience studies of critical infrastructures are based on complex network theory which has been proposed by authors in [14,15]. In [16], analytical hierarchical process (AHP) has been used to evaluate the resilience of a distribution systems. Also, in [17] proper assessment metrics is suggested to evaluate the efficiency of power system after disaster. The method includes the repair process of transmission lines, generators, and the distributed generation. After this stage, components' state and system power flow have been done to analyse the state of the system and effective corresponding metrics are calculated. The extraordinary potential of catastrophic to create opportunities to change and societal enhancement, especially to reduce risk is emphasized in [18]. This paper studies 30 coastal communities following the Great East Japan earthquake, tsunami, and nuclear disaster and as a result, the importance of solar power had been taken into account in disaster-affected communities than the rest of Japan following the introduction of the country's Feed-in-Tariff (FIT) system in 2012. In [19], a technique is applied to evaluate the resilience of distribution networks considering the effect of critical loads under extreme weather events.

Several natural disasters have attracted researchers' attention. For example in case of fire, a stochastic programming technique to increase resilience of a distribution network against wildfire has been proposed in [20]. The vulnerability of the Karachi urban inhabitants against heat stress and the vital role of ecosystem to mitigate futures effects of heatwaves is investigated in [21]. Also, due to increasing urban population which makes flood risk management very difficult, new methods have been proposed to investigate resilience levels to floods considering critical infrastructure networks as risk propagators at different spatial scales [22].

The resilience investigation of power distribution network has been proposed supposing as multi-criteria decision making problem [23].

In case of destructive wind storm and hurricane, as the most probable High impact–low probability (HILP) incidents, resulting in widespread power outages, some researches have been investigated to minimize the damages imposed by the threat.

In [24], a new method is proposed to improve the resilience of distribution network against hurricane. In this paper a method based on the restoration and emergency reaction planning before occurrence of hurricane, as an effective action in reducing time and cost of electricity interruption and improving resilience in overhead distribution networks, is investigated.

In [25], the resilience of power distribution systems against hurricane is discussed considering the effect of protective devices on reconfiguration and restoration of the distribution network.

A bi-level optimization-based model for reconfiguration of the distribution network to enhance the resilience of distribution network against extreme High impact–low probability (HILP) incidents to minimize the cost of load outage is investigated in [26].

In order to assess the impact of hurricane on distribution networks, a two-stage resilience enhancement scheme considering predisaster strengthening and postcatastrophe system reconfiguration is studied [27].

Also, a new methodology is proposed to establish a relation between network component fragility curves, component geographical location and disasters spatial risk index. In this paper, due to adverse impacts of natural disasters on distribution network's component, resilient and cost-based planning of MV distribution network using Greedy algorithm is proposed and discussed. The geographical information for hurricane as a severe disaster is applied to create a spatial risk index map [28–29].

In [30], a resilience index is presented incorporating different strategies such as: upgrading distribution poles, DG placement with different capacities and distribution system automation. The proposed resilience improvement method decreases unserved loads, restores the distribution system rapidly and decreases the dependency of water network operation to power network failures using a stochastic two-stage optimization approach.

Also, a resilient radial distribution networks against severe windstorms is planned using a risk-based technique. The employed framework presents a decision-maker with a means of determining the resilient network plan that decreases the risk of major costs due to destructive windstorms [31].

A probabilistic–proactive distribution network operation model based upon the chaos theory is presented in []. The suggested resilience index considering operational cost and load shedding cost, decreases the destructive effects of hurricane as an extreme events [32].

Additionally, using factors affecting resilience of electrical networks are restricted and have not been applied in published works yet.

On the whole, distribution systems are more vulnerable to hurricane attacks, as a significant type of extreme events.

High wind speeds during hurricanes cause severe consequences to power distribution network resulting in power outages that last for long times, depending on the severity of the storm.

In this regard, there is a great need to a methodology able to optimize the hardening programme investments.

This scheme could potentially save a large amount of money, as well as increase the resilience of the program. So, this paper is organized to provide a comprehensive study on optimal resilient planning of distribution networks aims to find an optimal solution for optimal feeder routing problem, finding cost-effective hardening of the lines considering hurricane, costs and operational parameters in normal and resilient modes of distribution networks.

In other words, the scope of this paper is to improve the resilience of the conventional distribution network by developing proper resilience metric based on the network topology. Both cost- and resilient- based networks are planned using deterministic and probabilistic approaches. In deterministic approach, network planning is done considering worst prediction. But in probabilistic one, some scenarios with specified probability are defined for wind speed. It can be concluded that, scenario based planning, can lead to the best compromised solution considering cost and resilience which the obtained results validate the accuracy of the modellings. As a result, the proposed method shows its superiority to the other similar works done before.

The main contributions of this article are as follows:

1 A framework for assessing the hurricane resilience of power distribution systems considering the impact of hurricane is suggested.
2 A comprehensive study on optimal resilient planning of distribution networks aims to find an optimal solution for optimal feeder routing problem and HV substation placement is presented.
3 Both cost- and resilient- based networks are planned using deterministic and probabilistic approaches.
4 A scenario based approach is applied, in this approach, a specific wind speed is considered resulting in best compromised solution regarding cost and resilience.

The rest of this article is organized as follows. Section 2 investigates related problem formulations. A case study and obtained numerical consequences are presented in Section 3. Finally, Section 4 concludes this article.

2. Distribution network components fragility model

The situation of electric power components encountering weather events are defined as fragility curves. There are different states assumed for modelling power components, but, most of the works suppose two states known as fail or survive. Generation, transmission, and distribution consist three main part of a power grid. Because of high reliability of generation side, it is not needed to incorporate their components in failure assessment this time [33,34].

Here, effective assessment tool known as Federal Emergency Management Agency's Multi-Hazard (HAZUS-MH) (FEMA 2008) is used to anticipate adverse impact of outages as destructive results of natural disasters on vital elements of transmission and distribution systems [35].

In other words, fragility functions describe the electric power components' strength and their collapse limitations facing weather events such as severe winds and flood.

Different type of power system components lead to different classifications of damage models. Distribution poles, spans, Pad-mount device such as transformers and conductors damages are the key equipment that should be modelled from fragility point of view. If there is no sufficient data or proper obtained fragility curves, the following technique can be applied to approximate failures for transmission and distribution system equipment. Based on the suggested formulations, the relations between failure rates of equipment and wind speed can be model by exponential equations. Thus, assuming η_{Tr}, η_{Pole} and η_{Con} as failure rates of components as Eqs. (1) to (3), then, Poisson distributions are used to formulate the modelling failures of distribution equipment.

$$\eta_{Pole} = 10^{-4} \times e^{0.0421w} \tag{1)}$$

$$\eta_{Tr} = 2 \times 10^{-7} e^{0.0834w} \tag{2}$$

$$\eta_{Con} = 8 \times 10^{-12} w^{5.173} \tag{3}$$

Here w is site-specific wind speed.

2.1. Evaluation of hurricane hazard model

Hurricane is a probabilistic event. In this paper, hurricane is modelled probabilistically using Poisson distribution function as below:

$$P(h) = \frac{\exp(\lambda) \times \lambda^h}{h!} \tag{4}$$

Where, annual occurrence of the hurricane is obtained by P. that is defined as Poisson probability distribution function. Also, $\lambda$and h indicate the average number of hurricane and number of hurricane per year respectively. The mentioned problem is solved using deterministic and probabilistic approaches. In deterministic approach, network planning is done according to the worst prediction, means one scenario with 100% probability (NScen = 1, Prob1 = 1) and known wind speed.

In probabilistic one, some scenarios with specified probability (NScen, ProbScen) are defined for wind speed. The summation of scenarios probability must be equal to 1.

These scenarios define future possibilities and probabilities of wind speed which are different for each geographical area.

In this modellings the worst prediction is one of the scenarios but not with probability of 100%.

2.2. Resilient distribution network planning to reduce the hurricane damage

In this section the distribution network's planning model is presented. In case of cost-based planning, the objective of the optimal planning is minimization of network total cost, and at the next step calculation of the resilience index for the optimal cost-based planned case. On the contrary, in case of resilient-based planning the aim of the objective function is maximization of the network total resilience index and at the next step, calculation of the total network cost for the optimal resilient –based planned case.

2.2.1. High voltage (HV) substation modelling

A HV substation's load is defined as the summation of all distribution transformers connected to a HV substation through MV feeders. Eq. (5) describes the load supplied by k-th S_{HV}^{hv} :

$$S_{HV}^{hv} = \sum_{dt=1}^{N_{DistTr}} \frac{P_{DistTr}^{dt}}{\cos\phi_{dt}^{Tr} \cdot \mathrm{AvLd}(\mathrm{DT}_{dt})} \cdot \lambda_{dt} \tag{5}$$

Supposing S_{HV}^{k} as the capacity, the cost of HV substations are obtained as below:

$$\Omega_{HV} = \sum_{hv=1}^{HV^N} \left\{ CC_{HV}\left(S_{HV}^{hv}\right) \cdot S\left(S_{HV}^{hv}\right) + CL\left(S_{HV}^{hv}\right) \cdot T_P \cdot 8760 \right\} \cdot \gamma_i \tag{6}$$

Where

$$CL\left(S_{HV}^{hv}\right) = \left\{ \begin{array}{c} P_{NLL}\left(S_{HV}^{hv}\right) + \\ P_{SCL}\left(S_{HV}^{hv}\right) \cdot HV_{Load}{}^2\left(S_{HV}^{hv}\right) \cdot AvLoss\left(S_{HV}^{hv}\right) \end{array} \right\} \cdot ELCF. \tag{7}$$

$$HV_{Load}\left(S_{HV}^{hv}\right) = \frac{\sum_{dt=1}^{N_{DistTr}} (P_{dt}) \cdot \lambda_{dt}}{S_{HV}^{hv} \cdot \cos\phi_{HV}^{hv}\left(S_{HV}^{hv}\right)}. \tag{8}$$

2.2.2. Medium Voltage (MV) distribution transformer modelling

The load demand supplied by dt-th MV distribution transformer is formulated as the followings:

$$S_{DisTr}^{dt} = \frac{\left(\sum_{z=1}^{N_{LB,dt}} P_z\right)}{\cos\varphi_{DisTr}^{dt} \cdot \mathrm{AvLd}(\mathrm{Load}_{LB}^{dt})} \tag{9}$$

$$\Omega_{DisTr} = \sum_{dt=1}^{N_{DisTr}} \left\{ CC^{dt}{}_{DisTr} \cdot S_{DisTr}^{dt} + CL^{dt}{}_{DisTr} \cdot T_P \cdot 8760 \right\} \cdot \lambda_i. \tag{10}$$

Where,

$$\mathrm{CL}^{dt}{}_{DisTr} = \left\{ \begin{array}{c} \mathrm{P}_{NLL}\left(\mathrm{S}^{dt}_{DisTr}\right) + \\ \mathrm{P}_{SCL}\left(\mathrm{S}^{dt}_{DisTr}\right)\cdot\mathrm{TL}^2\left(\mathrm{S}^{dt}_{DisTr}\right)\cdot\mathrm{ALSF}\left(\mathrm{S}^{dt}_{DisTr}\right) \end{array} \right\}\cdot\mathrm{ELCF}. \tag{11}$$

$$\mathrm{TL}^{dt}{}_{DisTr} = \frac{\sum_{z=1}^{N_{LB}} P_z}{\left(\mathrm{S}^{dt}_{DisTr}\cdot\cos\varphi^{dt}_{DisTr}\right)} \tag{12}$$

2.2.3. Medium voltage feeder modelling

Several important factors such as minimum length, minimum cost, and best cross section affect determining route for a feeder which is known as feeder routing problem. Proper feeder routing can efficiently improve power system's resilience. In this paper a distribution network is represented using node-edge illustration. Graph nodes and graph edges indicate candidate location of distribution transformers and candidate feeder connecting the distribution transformer to HV substation respectively. Minimum spanning tree (MST) is applied to achieve minimum length of the tree and satisfy radially structure constraint. In order to prevent paper length and get more information about (MST), please refer to ref [36].

Cost of medium voltage feeder. The formulation of cost function of selected feeders is shown using Eq. (13):

$$\Omega_{MVF} = \sum_{f=1}^{N_{MVF}} \left\{ \begin{array}{c} \mathrm{CC}^f{}_{\mathrm{MVF}}\cdot d_f + \\ \mathrm{I}^2\left(\mathrm{MVF}_f\right)\cdot R_f\cdot\mathrm{ELCF}\cdot\mathrm{T_P}\cdot 8760 \end{array} \right\}. \tag{13}$$

Regarding the satisfaction of below constraints, we have:

$$I\left(\mathrm{MVF}_f\right) < \mathrm{I_M}\left(\mathrm{MVF}_f\right) \quad \forall f \in S^{hv}_{HV} \tag{14}$$

$$\mathrm{VD_{MVF}} < \mathrm{VD_{MV,max}} \tag{15}$$

Here, $\mathrm{VD_{MV,max}}$ is defined as 2% from Iranian standard.

Finally, total cost function of distribution network can be evaluated as below:

$$\Omega_F = \sum_{hv=1}^{N_{HV}} \Omega^{hv}{}_{HVDist} + \sum_{dist=1}^{N_{MV}} \Omega^{dist}{}_{MVDist} + \sum_{f=1}^{N_{Feeder}} \Omega^f{}_{MVFeeder} \tag{16}$$

2.3. Resilience modelling

The area under study which is demonstrated in Fig. 1 consists of some sites with definite maximum hurricane wind speed. The wind speed probability distribution function for each site and the fragility curve of network components is provided.

In the case of multiple HV substation, the study area is separated into several HV substations with their defined areas. It should be noted that MST algorithm must be applied for each HV substation area.

Branch resistance depends on the distances between MV substations, and between the MV and HV substations which are incorporated in MST evaluations as weighting factors. However, regarding resilient planning of distribution networks, components' failure rate is used instead of distances in MST formulations aiming at minimum damage of MV feeders in front of destructive hurricane speed.

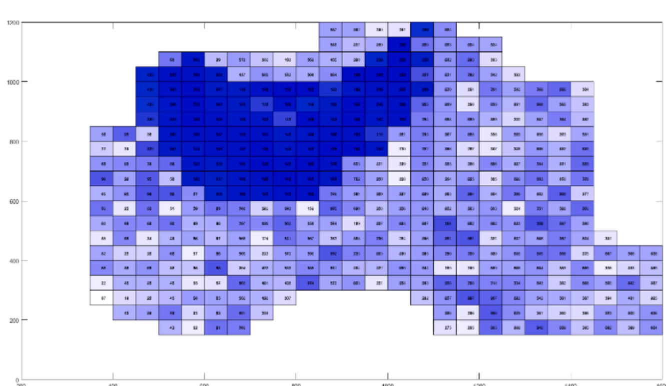

Fig. 1. Geospatial map of wind speed in study area.

Due to adverse impact of hurricane on power systems' components and as a result destructive damages leading to long-term outages of electric networks, it seems essential to map the geographical locations of systems' component with their associated fragility curves. If the line length span between two poles is divided to 30 meter, the number of distribution poles and conductors along a feeder can be obtained. Finally, the resilient-based modelling process of the network component and total network resilience index is evaluated in the followings.

Eq. (17) defines feeder fragility index affected by several terms namely as distribution poles, conductors and transformers as below:

$$\Psi_{Feeder} = \omega_\Phi \Psi_\Phi + \omega_{Tr} \Psi_{Trans} + \omega_{Con} \Psi_{Con} \tag{17}$$

Where $\Psi_\Phi, \Psi_{Trans},$ and Ψ_{Con} are fragility index of feeder, pole, transformer and conductors respectively. Also,ω_Φ, ω_{Tr} and ω_{Con} refers to constant coefficients representing effectiveness degree of each components.

For example, distribution pole's fragility index is evaluated replacing the first term of Eq. (17) to (1) as following:

$$\Psi_\Phi(i) = \eta_{Pole} = 10^{-4} \times e^{0.0421w} \tag{18}$$

Additionally, supposing (19) as distance formulation between substations i and$j$, then, the number of distribution poles and conductors are obtained using Eqs. (20) and (21) as described below:

$$\forall\ [S \in][HV]$$

$$\forall\ [F \in]\ [Feeder]$$

$$F_{Dist}\left(s_i, s_j\right) = \sqrt{\left(x_{s_i} - x_{s_j}\right)^2 + \left(y_{s_i} - y_{s_j}\right)^2} \tag{19}$$

Where, $x_{s_i}, y_{s_i}, x_{s_j}, y_{s_j}$ are the X and Y coordination of substation i and j respectively

$$N_\Phi = round\left(\frac{F_{Dist}\left(s_i, s_j\right)}{pd}\right) \tag{20}$$

$$F_{Con} = N_\Phi - 1 \tag{21}$$

Where pl=30 in this study. Consequently, the fragility index for a feeder can be obtained by replacing Eqs. (19)–(21) to Eq. (17) as described in (22):

$$\Psi_{Feeder} = \omega_\Phi \sum_{p=1}^{N_{pole}} \Psi_\Phi(p) + \omega_{Tr} \sum_{t=1}^{N_{Trans}} \Psi_{Tr}(t) + \omega_{Con} \sum_{c=1}^{N_{Con}} \Psi_{Con}(c) \tag{22}$$

Finally, the total fragility index of whole power system including N_{HV} HV substation and N_{Feeder} for each HV substation is given by (23).

$$\Psi_{Network} = \sum_{Scen=1}^{\mathrm{N}_{Scen}} \mathrm{Prob_{Scen}} \times \sum_{h=1}^{N_{HV}} \sum_{f=1}^{N_{Feeder}} \Psi_{Feeder}(h,f) \tag{23}$$

In order to have resilient network, the total fragility of the network must be lower. So, minimizing (23) leads higher resilience. Hereinafter, resilience index is defined as follows:

$$\mathrm{Res}I_{Network} = \frac{1}{\Psi_{Network}} \tag{24}$$

3. Numerical results analysis

The main goal of this paper is to achieve the optimal comparative resilient-based and cost-based planning of the medium voltage (MV) conventional distribution network. While the same planning process is done for two stages and for each cases, a comprehensive comparison is prepared regarding optimal plan of MV distribution network based on capital cost and the resilient – based design.

3.1. Test case system

The provided test case system with its associated geographical data which is illustrated in Fig. 1, is used to apply suggested effective planning technique. As shown, the Figure consists of several 50 × 50 blocks with definite numbers. Also, the study area is illustrated with colour spectrum from white to dark blue that each colour represents the speed density of each block. To avoid paper prolong, the worst prediction, highest wind speed, data is used in the represented Figure.

In current Figure, dark blue and white colours indicate higher and lower wind speed respectively.

Furthermore, Fig. 2 illustrates dimension plot of the wind speed in the study area.

Fig. 3 depicts counter plot of the study area wind speed amplitude.

The main candidate feeder's routs are shown in Fig. 4 and their associated data are gathered in Table A in appendix. Moreover, 32 MV substation or load points and their associated characteristics are provided in Table B in appendix.

3.2. Simulation results: deterministic modellings

The rest of the paper is focused on the optimal network planning technique in order to plan the best feeder's routes from cost-base and resilient-base planning point of view.

In all cases HV substation and its associated MV substations are indicated by node 33, 34 and nodes 1–32 respectively.

3.2.1. First case: resilient-based planning

In this paper MST method based on prim's algorithm is applied to solve optimal network configuration which aims at finding radial network with minimum feeder length. The satisfaction of voltage drop and feeder power limitations are checked during planning process to be in acceptable ranges.

Optimal power system configuration in terms of resilience planning is depicted in Fig. 5.

In current Figure, the selected feeders connected to MV substations are shown. The number of MV feeders can be obtained from number of MV substations. Regarding resilience index of feeders as optimization function for MST algorithm, fragility index of each component namely distribution poles, conductors and transformers as the first stage of planning process, should be determined from related fragility curves. Then, the number of distribution poles is evaluated using Eq. (21).

Moreover, the location of distribution poles for each feeder and the number of falling poles in a block is determined. Finally, fragility index of each pole and consequently the total feeder section's fragility index are obtained.

In the followings, associated consequences representing the efficiency of proposed method is detailed. For each HV substation, related each feeder section's fragility index obtained by summation of distribution poles' fragilities are illustrated in Figs. 6-7. The overall results of this stage of planning is gathered in Table 1.

3.2.2. Second case: cost-based planning

In this section, the same MST technique using Prim's algorithm is applied to solve the optimal power system planning problem with respect to cost.

The cost-based planning configuration of network is represented in Fig. 8.

Here, cost and resilience index are evaluated as primary and secondary aims regarding resilience index of feeders as optimization function of planning problem.

Like first case, for each HV substation, related each feeder section's fragility index obtained by summation of distribution poles' fragilities are illustrated in Figs. 9-10.

At the end, the final results of this stage are given in Table 2. In addition, the overall results of two stages considering one HV substation is given in Table 3.

Comparing cost- and resilient- based networks shows a substantial difference in their configuration resulting better resilience index with higher costs.

It's clear that, this investment must be reasonable. So, there is a need to consider all possible scenarios and not only the worst one which done and reported in the next part.

3.3. Second stage: scenario based modellings

In this section, the results of cost- and resilient-based modellings in the case of scenario based planning have been obtained and analysed. Furthermore, the features of scenarios considered in the proposed method are given in **Table 4**.

Resilient-based planning

As noted before, in this scheme, some scenarios with specified probability are defined for wind speed. These scenarios define future possibilities and probabilities of wind speed.

According to optimal configuration plotted in Fig. 11, some feeders of each HV substations encounter destructive natural events, however, they are routed in a way that do not meet higher fragility index. Based on current Figure, two optimal radial MV networks are planned with respect to resilience index. For each HV substation, related each feeder section's fragility index obtained by summation of distribution poles'

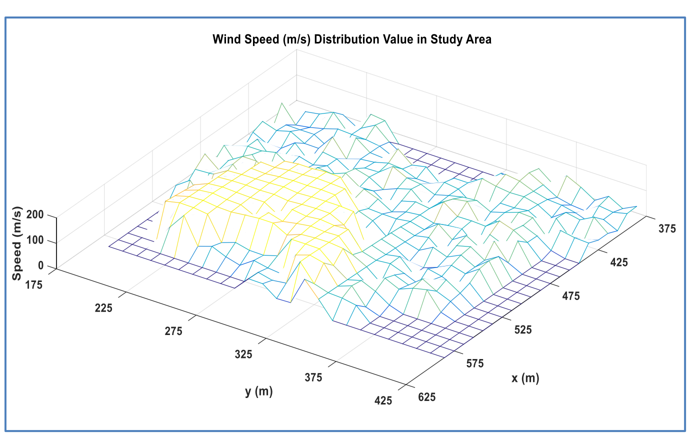

Fig. 2. 3D plan of the wind speed.

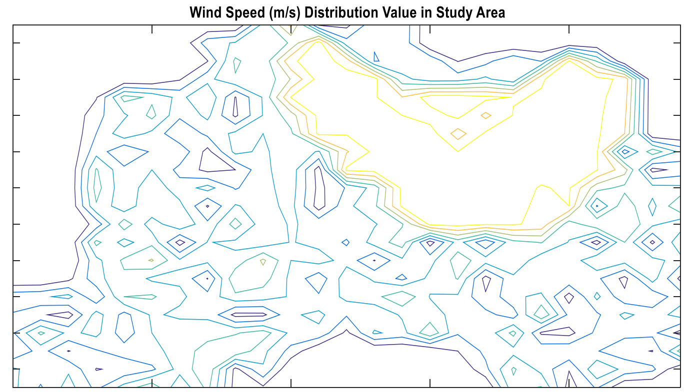

Fig. 3. Counter plot of the study area wind speed amplitude.

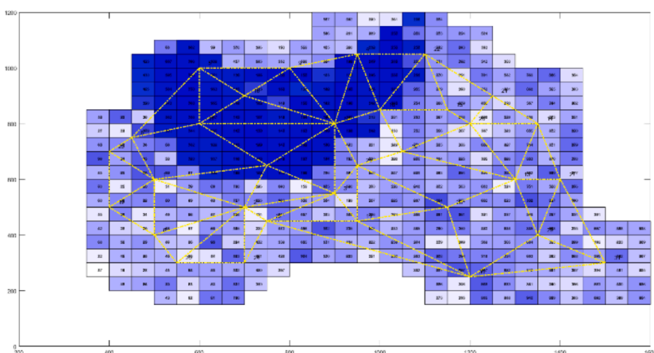

Fig. 4. The scheme of candidate feeder's routes.

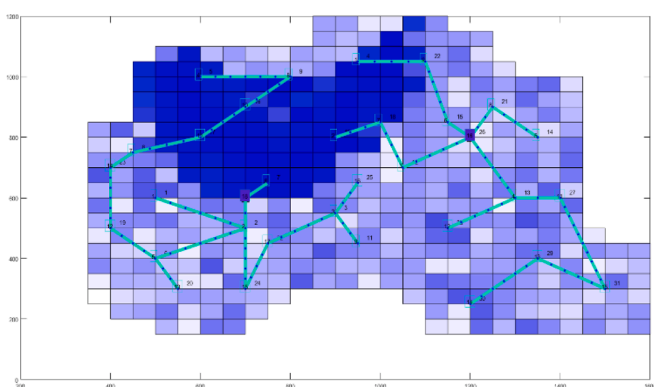

Fig. 5. Optimal power system configuration in terms of resilient-based planning.

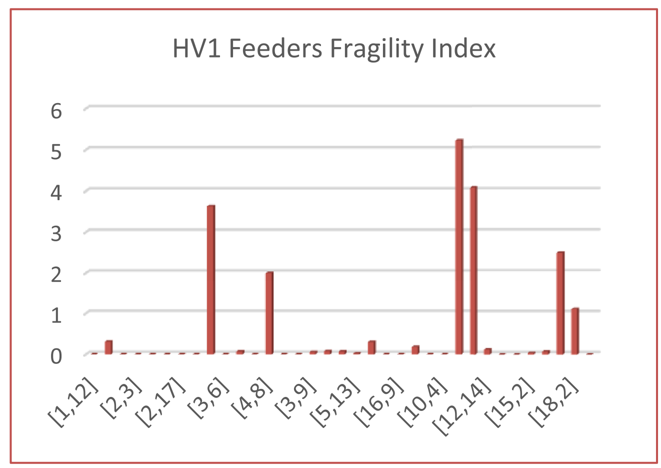

Fig. 6. Diagram of fragility index of all feeders for HV1.

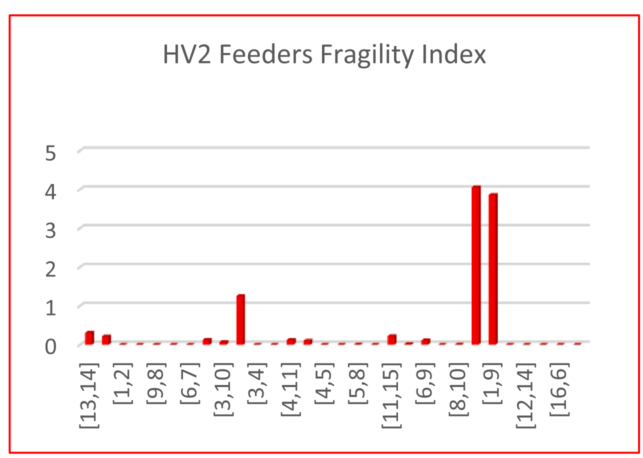

Fig. 7. Diagram of fragility index of all feeders for HV2.

fragilities are illustrated in Figs. (12) and (13). As, explained before, higher value of fragility index indicates higher risk of components to be damaged facing natural disasters.

Based on the comparison between Figs. (12) and (13), it can be seen that the number of feeders with high fragility index differs for each HV substation. In addition, network resilience index of each scenario is given in Table 5. Also, resilience index for each HV substation and as a result total network's resilient index is provided in Table 6.

Comparing Table 3 and 7, the cost index for minimum cost network is as same since in this scheme the HILP modellings is not incorporated into the problem and the optimal network is the one which has the lowest costs.

As seen, similar to that of represented in Table 3, the resilience enhancements needs extra investments.

Table 1
Total result of resilient-based planning with two HV substation.

Planning		Cost index	Resilience index
Resilient-based	HV1	2544.815	0.0504
	HV2	2342.807	0.0953
	Total	**4887.622**	**0.0329**

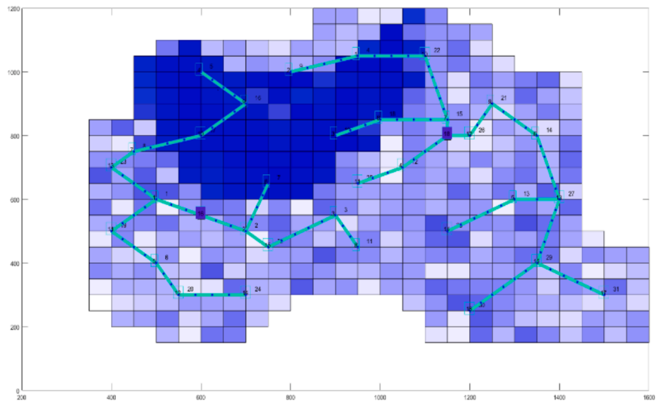

Fig. 8. Optimal power system configuration in terms of cost-based planning.

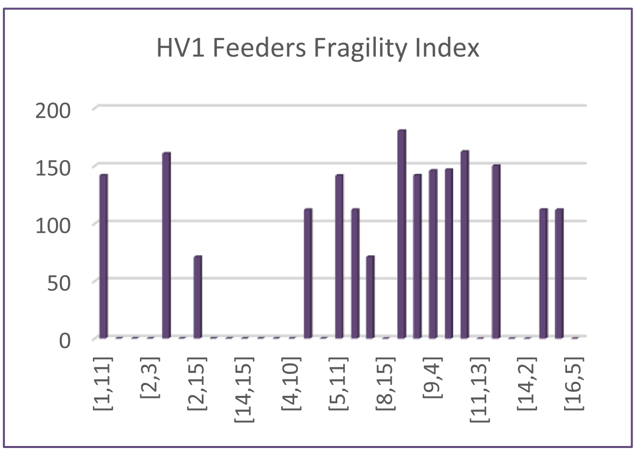

Fig. 9. Diagram of fragility index of all feeders for HV1.

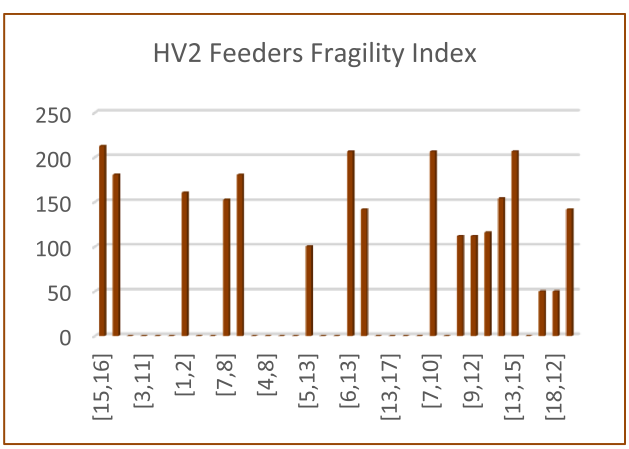

Fig. 10. Diagram of fragility index of all feeders for HV2.

Table 2
Total result of cost-based planning with Two HV substation.

Planning		Cost index	Resilience Index
Cost-based	HV1	1942.247	0.0547
	HV2	2467.52	0.0710
	Total	**4409.767**	**0.0309**

Table 3
Comparison between total network cost and resilience index in stage 1 (two HV substation).

Planning Type	Cost	Resilience Index
A-Minimum Cost Network	4409.767	0.0309
B-Resilient Network	4887.622	0.0329
B/A	**1.1083**	**1.0647**

Table 4
Characteristics of each scenario.

Number of scenario	Probability of each scenario (%)	Max speed of each scenario
1	35	110
2	40	90
3	25	150

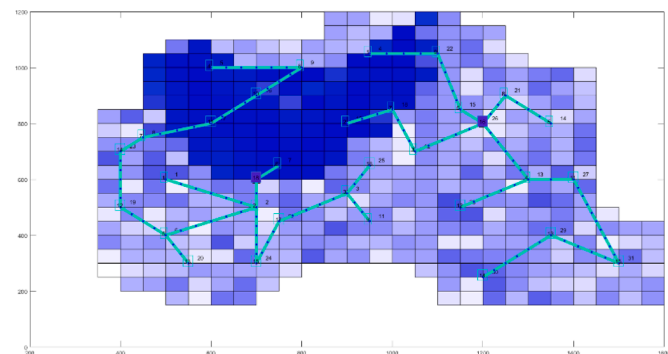

Fig.11. Optimal configuration in terms of resilient-based planning.

So, a comprehensive comparison considering both deterministic- and scenario based- modellings is provided in Table 8.

Based on given results in Table 6, to enhance the resilience of the network against the worst prediction, the investments increases about 10.83% and the resilience enhance about 6.47% compared to that when cost-based planning is aimed, which these numbers are 3.91% and 17.64% for the scenario based- modellings.

Due to the limited budget of Distribution Company, and low probable of worst prediction, it's better to consider the possible and probable wind speeds in future. This leads to the best compromised solution considering cost and res ilience which is reasonable.

In this regards, scenario-based planning seems reasonable.

As noted in Table 6 enhancing resilience forces lower costs than when deterministic one is applied.

4. Conclusion

In this paper, due to adverse impacts of natural disasters on electric network's component, resilient-based and cost-based planning of MV distribution network using MST algorithm is suggested and discussed. The optimal planning was solved with attention to a fitness function based on network cost and component fragility during hurricane. The geographical information for hurricane as a severe disaster is applied to create a spatial risk index map. In this work a new methodology is proposed to establish a relation between network component fragility curves, component geographical location and disasters spatial risk index. Essential data are provided and fragility index of each power component is evaluated. Finally, according to the applicability and possibility of second stage, scenario-based planning seems reasonable.

At the end, the obtained results show that, improving resilience, as significant goal of this paper forces lower costs than when deterministic one is applied.

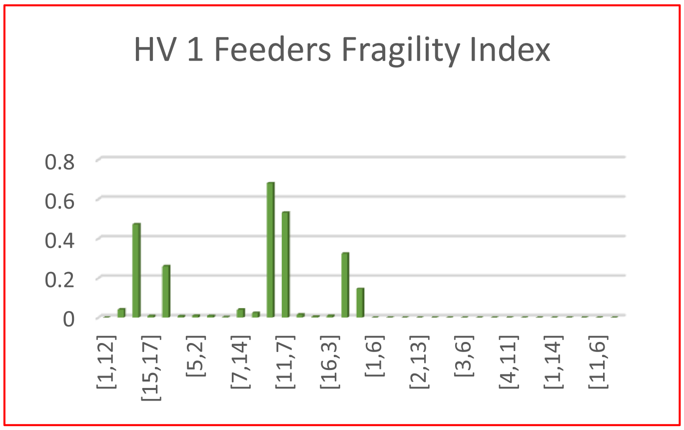

Fig. 12. Diagram of fragility index of all feeders for HV1.

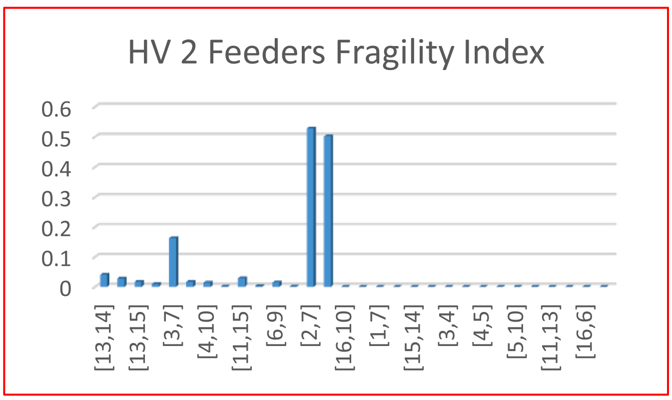

Fig. 13. Diagram of fragility index of all feeders for HV2.

Table 5
Whole network resilience index for each scenario.

Number of scenario	Probability of each scenario (%)	Whole network resilience index for each scenario
1	35	0.7601
2	40	0.9502
3	25	0.6334

Table 6
Final resilience index and cost for resilient-based planning

Planning		Cost	Resilience index
Resilient-based	HV1	2239.416	0.3873
	HV2	2342.807	0.7326
	Total	**4582.223**	**0.2533**

Table 7
Comprehensive comparison between total network cost and resilience index in stage 2, for both, cost-based and resilient-based planning.

Planning Type	Cost index	Resilience Index
A-Minimum Cost Network	4409.767	0.2153
B-Resilient Network	4582.223	0.2533
B/A	**1.0391**	**1.1764**

Table 8
Summary comparison stage 1 and stage 2.

Deterministic Modellings	Cost Ratio	Resilience Index
B/A	**1.1083**	**1.0647**
Scenario based Modellings	Cost Ratio	Resilience Index
B/A	**1.0391**	**1.1764**

Table A
Candidate feeder's route data.

Feeder Number	Feeder From	Feeder To	feeder Number	Feeder From	Feeder To
1	1	19	37	11	28
2	29	30	38	32	3
3	28	13	39	12	26
4	1	2	40	12	18
5	1	7	41	12	13
6	2	3	42	13	29
7	2	7	43	13	27
8	2	20	44	13	26
9	9	10	45	13	14
10	10	25	46	14	27
11	2	32	47	14	21
12	1	8	48	1	23
13	9	16	49	14	26
14	3	7	50	32	30
15	3	10	51	27	31
16	4	10	52	25	28
17	4	18	53	15	26
18	4	9	54	15	22
19	24	32	55	16	5
20	1	6	56	18	22
21	5	9	57	16	17
22	5	8	58	16	10
23	5	17	59	17	8
24	3	11	60	7	10
25	6	2	61	19	23
26	6	19	62	20	24
27	6	20	63	12	25
28	22	21	64	21	26
29	31	30	65	17	7
30	8	23	66	24	2
31	30	11	67	10	18
32	15	18	68	25	3
33	29	31	69	4	22
34	11	32	70	27	29
35	25	11	71	28	30
36	10	17			

Table B
MV substation data.

Substation Number	Substation X	Substation Y	Substation Number	Substation X	Substation Y
1	500	600	17	600	800
2	700	500	18	1000	850
3	900	550	19	400	500
4	950	1050	20	550	300
5	600	1000	21	1250	900
6	500	400	22	1100	1050
7	750	650	23	400	700
8	450	750	24	700	300
9	800	1000	25	950	650
10	900	800	26	1200	800
11	950	450	27	1400	600
12	1050	700	28	1150	500
13	1300	600	29	1350	400
14	1350	800	30	1200	250
15	1150	850	31	1500	300
16	700	900	32	750	450

Declaration of Competing Interest

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

Appendix

5. References

[1] Executive office of the president, economic benefits of increasing electric grid resilience to weather outages, Tech. Rep. (2013).
[2] P. Hines, J. Apt, S. Talukdar, Trends in the history of large blackouts in the United States, Proc. 2008 IEEE Power Energy Soc. General Meeting—Convers. Del. Electr. Energy 21st Century (2008) 1–8. Jul.
[3] T. H. Haines, V Hurricane experiences of power utilities in Boston Area, Electr. Eng. 58:3 (1393) 109–110.
[4] E.D. Vugrin, D.E. Warren, M.A. Ehlen, A resilience assessment framework for infrastructure and economic systems: quantitative and qualitative resilience analysis of petrochemical supply chains to a hurricane, Process Saf. Prog. 30 (3) (2011) 280–290.
[5] D. Gritzalis, M. Theocharidou, and G. Stergiopoulos. "Critical infrastructure security and resilience." January): 0–16 (2019).
[6] J. P. Watson, R. Guttromson, et al, Conceptual framework for developing resilience metrics for the electricity oil and gas sectors in the United States, Sandia national laboratories, albuquerque, nm (united states), tech. rep (2014).
[7] F.D. Petit, R.E. Fisher, S.N. Veselka, Resilience Measurement Index, Argonne National Laboratory, USA, 2013.
[8] S.D. Manshadi, M.E. Khodayar, Expansion of autonomous microgrids in active distribution networks, IEEE Trans. Smart Grid 9 (3) (2016) 1878–1888.
[9] H. Gao, Y. Chen, Y. Xu, C.C. Liu, Resilience-oriented critical load restoration using microgrids in distribution systems, IEEE Trans. Smart Grid. 7 (6) (2016) 2837–2848.
[10] R. Arghandeh, A. von Meier, L. Mehrmanesh, L. Mili, On the definition of cyber-physical resilience in power systems, Renew. Sustain. Energy Rev. 58 (2016) 1060–1069.
[11] Salman. Mohagheghi, Reinforcement of energy delivery network against natural disaster events, Int. J. Dis. Risk Reduct. 10 (2014) 315–326.
[12] A. Kwasinski, Quantitative model and metrics of electrical grids' resilience evaluated at a power distribution level,, Energies 9 (2) (2016) 93.
[13] Y. Xu, C.-C. Liu, K.P. Schneider, D.T. Ton, Toward a resilient distribution system, IEEE Power & Energy Soc. General Meeting (2015) 1–5.
[14] R. Albert, A.-L. Barabási, Statistical mechanics of complex networks, Rev. Mod. Phys. 74 (1) (2002) 47.
[15] X.F. Wang, G. Chen, Complex networks: small-world, scale-free and beyond,, Circuits Syst. Magazine 3 (1) (2003) 6–20.
[16] S. Chanda, A.K. Srivastava, Defining and enabling resilience of electric distribution systems with multiple microgrids, IEEE Trans. Smart Grid. 99 (2016), 1–1.
[17] H. Zhang, Z. Bie, Gengfeng Li, Y. Lin, Assessment method and metrics of power system resilience after disasters, J. Eng. 16 (2019) 880–883.
[18] Junko Mochizuki, Stephanie E. Chang, Disasters as opportunity for change: Tsunami recovery and energy transition in Japan, Int. J. Dis. Risk Reduct. 21 (2017) 331–339.
[19] Diansheng Luo, Yongwei Xia, Yuanyuan Zeng, Canbing Li, Bin Zhou, Hao Yu, Qiuwei Wu, Evaluation method of distribution network resilience focusing on critical loads, Ieee Access 6 (2018) 61633–61639.
[20] Dimitris N. Trakas, Nikos D. Hatziargyriou, Optimal distribution system operation for enhancing resilience against wildfires, IEEE Trans. Power Syst. 33 (2) (2018) 2260–2271.
[21] Adnan Arshad, Muhammad Ashraf, Ristina Siti Sundari, Huma Qamar, Muhammad Wajid, Mahmood ul Hassan, Vulnerability assessment of urban expansion and modelling green spaces to build heat waves risk resiliency in Karachi, Int. J. Dis. Risk Reduct. (2020), 101468.
[22] Damien Serre, Charlotte Heinzlef, Assessing and mapping urban resilience to floods with respect to cascading effects through critical infrastructure networks, Int. J. Dis. Risk Reduct. 30 (2018) 235–243.
[23] S. Chanda, Measuring and Enabling of Resilience Using Multiple Microgrids, Master's thesis, Washington State University, 2015.
[24] Masoud Sadeghi Khomami, Mohammad Sadegh Sepasian, Pre-Hurricane Optimal Placement Model of Repair Teams to Improve Distribution Network Resilience, 165, Electric Power Systems Research, 2018, pp. 1–8.
[25] Rajatha Bhat, Yousef Mohammadi Darestani, Abdollah Shafieezadeh, A. P. Meliopoulos, Reginald DesRoches, Resilience assessment of distribution systems considering the effect of hurricanes, in: 2018 IEEE/PES Transmission and Distribution Conference and Exposition (T&D), IEEE, 2018, pp. 1–5.
[26] Masoud Sadeghi Khomami, Kamran Jalilpoor, Meghdad Tourandaz Kenari, and Mohammad Sadegh Sepasian, Bi-level network reconfiguration model to improve the resilience of distribution systems against extreme weather events, IET Generation, Trans. Distrib. 13 (15) (2019) 3302–3310.
[27] Yichen Shen, Chenghong Gu, Zhibo Ma, Xinhe Yang, Pengfei Zhao, A two-stage resilience enhancement for distribution systems under hurricane attacks, IEEE Syst. J. (2020).
[28] Masoumeh Karimi, Sajad Najafi Ravadanegh, Mahmoud Reza Haghifam, Resiliency enhancement with vulnerability mitigation and redundancy improvement of distribution network against severe hurricane, J. Energy Manage.Technol. 5 (1) (2021) 8–16.
[29] Karimi, Masoumeh, Sajad Najafi Ravadanegh, and Mahmoodreza Haghifam, A Planning Framework for Resilient Distribution Networks against Natural Disasters, Journal of Iranian Association of Electrical and Electronics Engineers.
[30] Javad Najafi, Ali Peiravi, Josep M. Guerrero, Power distribution system improvement planning under hurricanes based on a new resilience index, Sustain. Cities Soc. 39 (2018) 592–604.
[31] Željko N. Popović, Neven V. Kovački, Dragan S. Popović, Resilient distribution network planning under the severe windstorms using a risk-based approach, Reliab. Eng. Syst. Saf. 204 (2020), 107114.
[32] Amirhossein Nasri, Amir Abdollahi, Masoud Rashidinejad, Probabilistic–proactive distribution network scheduling against a hurricane as a high impact–low probability event considering chaos theory, IET Generation, Trans. Distrib. 15 (2) (2021) 194–213.
[33] J. Winkler, L. Due˜nas-Osorio, R. Stein, D. Subramanian, Performance assessment of topologically diverse power systems subjected to hurricane events, Reliab. Eng. Syst. Saf. 95 (4) (2010) 323–336.
[34] M. Panteli, C. Pickering, S. Wilkinson, R. Dawson, P. Mancarella, Power system resilience to extreme weather: fragility modelling, probabilistic impact assessment, and adaptation measures, IEEE Trans. Power Syst. 32 (5) (2017) 3747–3757.
[35] FEMA, Hazards U.S. multi-hazard (HAZUS-MH) assessment tool vs 1.4, Washington, DC, 2008.
[36] S. Najafi Ravadanegh, R.Gholizadeh Roshanagh, On optimal multistage electric power distribution networks expansion planning,, Electrical Power Energy Syst. 54 (2014) 487–497.