Resiliency enhancement with vulnerability mitigation and redundancy improvement of distribution network against severe hurricane

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Vulnerability mitigation and redundancy improvement are of the solutions for creating resilient distribution networks that aim to prevent the uncontrollable outage propagation. In this paper, a comparative study is proposed for optimal feeder routing problem and HV substation placement considering cost and resilience. In the first case, the network is planned based on cost minimization, and then the proposed resilience index is calculated for the planned network. While in the second case, the network is designed based on resilience enhancement, and afterward, the planned network cost is calculated. In the case of resilient-based planning, the studied area is divided into small sites with different wind speed to evaluate the geospatial characteristics of a hurricane. A fragility index is calculated for each distribution network component located at each site. Furthermore, in this paper, the effect of HV substation number as redundancy improvement is considered in cost and resilient based planning performance. Results show that with increasing of the HV substation number, the cost of feeder routing is less increased. While it has more effect on the improvement of the resilient performance index. The obtained results validate the feasibility and efficiency of the proposed method.

keywords: Network planning, Resilience, Distribution network, Disaster, Geospatial map, Fragility.

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Nomenclature

λ_{Φ}	Poles fragility index.
λ_{Tr}	Transformer fragility index.
λ_{Con}	Conductor fragility index.
w	Site-specific wind speed.
λ	Average number of hurricane.
h	Number of hurricane per year.
hv	Indicator of HV substations.
dt	Index for distribution transformer.
z	Index for load buses.
N_{Feeder}	Number of feeders.
N_{MV}	Number of MV transformers.
N_{HV}	Number of HV substations.
N_{LB}	Number of load buses.
γ_i	Binary decision variable.
T_P	Planning period.
λ_{dt}	Binary decision variable.
N_{DistTr}	Number of distribution transformers.
N_{MVF}	Number of MV feeders.
d_f	Distance of f-th MV feeder, m.
VD_{MVF}	Acceptable voltage drop for MV feeder.
R_f	Resistance of f-th feeder.
$P(h)$	Annual occurrence of the hurricane.
F_{Con}	Number of conductors.
$I(\mathrm{MVF}_f)$	Current of f-th MV feeders.
N_{Φ}	Number of distribution poles.
$\Psi_{Network}$	Resilience index of whole network.
$P_{SCL}(S_{HV}^{hv})$	Short-circuit loss of a HV substation, kW.
$HV_{Load}(S_{HV}^{hv})$	Current of a HV substation.
$AvLoss(S_{HV}^{hv})$	Average annual loss factor of a HV substation.
ELCF	Energy loss cost factor,($/kWh).
S_{HV}^{hv}	Supplied load for high voltage substation (KVA).

$\cos\theta_{HV}^{hv}\left(S_{HV}^{hv}\right)$	Power factor of hv-th HV substation.
S_{DisTr}^{dt}	Supplied load for medium voltage distribution transformer (KVA).
P_{DisTr}^{dt}	Active power of a MV distribution transformer, kW.
$\cos\phi_{DisTr}^{dt}$	Power factor of dt-th MV distribution transformer.
$P_{NLL}\left(S_{HV}^{hv}\right)$	No load loss of a HV substation, kW.
$\mathrm{AvLd}\left(\mathrm{DT}_{dt}\right)$	Average annual load factor of a HV substation.
$\mathrm{AvLd}(\mathrm{Load}_{LB}^{dt})$	Average annual load factor of a MV distribution transformer.
$CC^{dt}{}_{DisTr}$	Cost of construction of new MV distribution transformer.
$CL^{dt}{}_{DisTr}$	Cost of resistive and core loss of MV distribution transformer.
$P_{NLL}\left(S_{DisTr}^{dt}\right)$	No load loss of A MV distribution transformer, kW.
$TL\left(S_{DisTr}^{dt}\right)$	Current of a MV substation.
CC_{HV}	Cost of construction of new HV substation.
$P_{SCL}\left(S_{DisTr}^{dt}\right)$	Short-circuit loss of a MV distribution transformer, kW.
$ALSF\left(S_{DisTr}^{dt}\right)$	Average annual loss factor of a MV substation.
P_z	Active power of z-th load, kW.
$CC^{f}{}_{MVF}$	Cost of construction of new MV feeder.
$CL\left(S_{HV}^{hv}\right)$	Cost of resistive and core loss of HV substation.
Ω_{HV}	Cost function of HV substation.
Ω_{DisTr}	Cost function of MV distribution transformer.
Ω_{MVF}	Cost function of MV feeders.
Ω_{F}	Total cost function of distribution network.
Ψ_{Feeder}	Resilience index for feeder.
Ψ_{Φ}	Resilience index poles.
Ψ_{Tr}	Resilience index transformers.
Ψ_{Con}	Resilience index conductors.
pd	Distance between two poles.

1. Introduction

Security and reliability are the two vital parameters of electric power systems operation that must be considered carefully. In recent years, many destructive weather conditions occurred that causes large blackouts like the 2005 Hurricane Katrina blackouts, 2011 Japan Earthquake blackouts, and the 2012 Hurricane Sandy blackouts. From 2003 till 2012, 679 large blackouts occurred, which in each at least 50000 customers were affected by natural disasters in the U.S. [1]. Also, 933 events that occurred from 1948 to 2006 have been reviewed in [2]. The first studies of an adverse weather event on the electric network have been done during the 1930s, when a strong storm of New England Hurricane occurred in 1938 [3]. In the last decades, a noticeable improvement in assessing techniques of weather condition's effect on power systems have 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 a financial loss of $80 billion annually in the United States. Due to progressive climate change in the 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 the network's resilience. Based on the references [5]–[7], resilience can be defined as the ability of the power system to be strong enough against different hazards and recover quickly from attacks or naturally occurring events. The research about the adverse impacts of natural disasters on the power system has 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 the resilience of energy infrastructures. In [11], the resilience of the power system has been analyzed regarding customer benefits. Assessing power distribution system resilience enhances control decisions made by the network's operator as corrective actions. Moreover, a recently developed technique in distribution automation can be involved in the suggested methods [12]. Mainly, resilience studies of critical infrastructures are based on complex network theory, which has been proposed by authors in [13], [14]. In [15], the analytical hierarchical process (AHP) has been used to evaluate the resilience of a distribution system. Also, in [16], proper assessment metrics are suggested to evaluate the efficiency of the power system after a disaster. The method includes the repair process of transmission lines, generators, and distributed generation. After this stage, components' state and system power flow have been done to analyze the state of the system and effective corresponding metrics are calculated. In [17], 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 the resilience of a distribution network against wildfire has been proposed in [18]. The resilience investigation of power distribution networks has been proposed supposing as a multi-criteria decision-making problem [19]. It should be noted that incorporating smart grid technologies in power distribution networks can significantly improve the resilience of electrical networks and make them more harden by speeding up the restorative actions, but it may lead distribution network more vulnerable to cyber-attack [19]. Additionally, using factors affecting the resilience of electrical networks are restricted and have not been applied in published works yet. In this regard, there is a great need for a methodology able to optimize the hardening program 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 problems, 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 conventional distribution networks by developing proper resilience metrics based on the network topology. The total cost and resilience index of both planned network is compared. Moreover, the effect of the number of HV substations on the resilience of the network is evaluated. So obtained consequences for different planning case studies validate the efficiency and effectiveness of the proposed method.

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 modeling power components, but most of the works suppose two states known as fail or survive. Generation, transmission and distribution consist of three main parts of a power grid. Because of the high reliability of the generation side, it is not needed to incorporate their components in failure assessment this time [21-22]. Here, an effective assessment tool is known as Federal Emergency Management Agency's Multi-Hazard (HAZUS-MH) (FEMA 2008) is used to anticipate the adverse impact of outages as destructive results of natural disasters on vital elements of transmission and distribution systems [23].

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

Different types of power system components lead to different classifications of damage models. Distribution poles, spans, Pad-mount devices such as transformers and conductors damages are the key equipment that should be modeled from a fragility point of view. If there is no sufficient data or properly 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 modeling failures of distribution equipment.

$$\eta_{\Phi} = 10^{-4} \times e^{0.0421w} \quad \mathbf{(1)}$$

$$\eta_{Tr} = 2\times 10^{-7} e^{0.0834w} \quad \mathbf{(2)}$$

$$\eta_{Con} = 8\times 10^{-12} w^{5.173} \quad \mathbf{(3)}$$

Here w is site-specific wind speed.

A. Hurricane model

In this paper, a probabilistic model is applied for hurricane using Poisson distribution function as (4):

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

Where, the annual occurrence of the hurricane is obtained by P that is defined as a Poisson probability distribution function. Also, λ and h indicate the average number of hurricanes and the number of hurricanes per year, respectively.

B. Resilient distribution network planning

In this section, the distribution network's planning model is presented. In the case of cost-based planning scenario, the objective of the optimal planning is the minimization of total network cost and at the next step calculation of the resilience index for the optimal cost-based planned case. It should be mentioned that in this stage, the resiliency index is calculated only without any optimization. On the contrary, in the case of resilient-based planning, the aim of the objective function is to minimize the network resilience index. Similar to the previous stage in this stage, the network cost for the optimal resilient –based plan is only calculated without any optimization on cost.

B.1. High Voltage Substation Modelling

An HV substation's load is defined as the summation of all distribution transformers connected to an HV substation through MV feeders. Equation (1)-(5) describes the load supplied by kth S_{HV}^{hv} :

$$\mathrm{S}_{HV}^{hv} = \sum_{dt=1}^{\mathrm{N_{DistTr}}} \frac{P_{DisTr}^{dt}}{\cos\theta_{dt}^{Tr} \cdot \mathrm{AvLd}\left(\mathrm{DT}_{dt}\right)} \cdot \lambda_{dt} \quad \mathbf{(5)}$$

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

$$\Omega_{HV} = \sum_{hv=1}^{\mathrm{HV}^{N}} \left\{ \mathrm{CC}_{HV}\left(S_{HV}^{hv}\right)\cdot \mathrm{S}\left(S_{HV}^{hv}\right) + \mathrm{CL}\left(S_{HV}^{hv}\right)\cdot \mathrm{T_P}\cdot 8760 \right\}\cdot \gamma_i \quad \mathbf{(6)}$$

Where

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

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

B.2. Medium Voltage Distribution Transformer Modelling

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

$$\mathrm{S}_{DisTr}^{dt} = \frac{\left(\sum_{z=1}^{N_{LB,dt}} P_z\right)}{\cos\theta_{DisTr}^{dt}\cdot \mathrm{AvLd}(\mathrm{Load}_{LB}^{dt})} \quad \mathbf{(9)}$$

$$\Omega_{\mathrm{D}isTr} = \sum_{dt=1}^{\mathrm{N_{DistTr}}} \left\{ \mathrm{CC}^{dt}{}_{DisTr}\cdot \mathrm{S}_{DisTr}^{dt} + \mathrm{CL}^{dt}{}_{DisTr}\cdot \mathrm{T_P}\cdot 8760 \right\}\cdot \lambda_i. \quad \mathbf{(10)}$$

Where,

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

$$\mathrm{TL}^{dt}{}_{DisTr} = \frac{\sum_{z=1}^{N_{LB}} P_z}{(\mathrm{S}_{DisTr}^{dt}\cdot \cos\theta_{DisTr}^{dt})} \quad \mathbf{(12)}$$

B.3. Medium Voltage Feeder Modelling

Several important factors such as minimum length, cost and cross-section can affect the optimal feeder routing problem. Proper feeder routing can efficiently improve distribution network resilience. In this paper, a distribution network is represented using a 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. As an effective and fast algorithm, the minimum spanning tree (MST) is applied to the construction of a tree from a connected graph in general with a minimum length of the tree and satisfy radially structure constraint. There are many efficient algorithms such as Prim, Greedy, Kruskal and Dijkstra to solve the MST problem that, in this paper, the Greedy algorithm is used [24].

Cost of medium voltage feeder:

The formulation of the cost function of selected feeders is shown using Eq. (13):

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

Regarding the satisfaction of below constraints, we have:

$$I\left(\mathrm{MVF}_f\right) < \mathrm{I_M}\left(\mathrm{MVF}_f\right) \qquad \forall\ f \in S_{HV}^{hv} \quad \textbf{(14)}$$

$$\mathrm{VD_{MVF}} < \mathrm{VD_{MV,max}} \quad \textbf{(15)}$$

Here, $\mathrm{VD_{MV,max}}$ is defined as 2% for urban planning in Iranian standard. Finally, the total cost function of the distribution network can be evaluated as below:

$$\Omega_{\mathrm{F}} = \sum_{hv=1}^{N_{HV}} \Omega^{hv}{}_{HVDist} + \sum_{dist=1}^{N_{MV}} \Omega^{dist}{}_{MVDist} + \sum_{f=1}^{N_{Feeder}} \Omega^{f}{}_{MVFeeder} \quad \textbf{(16)}$$

C. Resilience Modelling

The area under study that 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 the Greedy algorithm must be applied for each HV substation area.

The distances between MV substations, and between the MV and HV substations which are used in Greedy evaluations as weighting factors. However, in the case of resilience planning of distribution networks, components' fragility index is used instead of distances in the Greedy algorithm to model the effect of the hurricane on MV feeders damage.

Due to the adverse impact of the hurricane on distribution networks' components and as a result of destructive damages leading to long-term outages of the networks, it is necessary to map the geographical locations of networks component with their associated fragility curves. If the line length span between two poles is divided into $pd = 30$ meters, for example, the number of distribution poles and conductors along a feeder can be obtained. Finally, the resilient-based modeling process of the network component and total network resilience index is evaluated in the following.

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

$$\Psi_{Feeder} = \omega_{\Phi}\Psi_{\Phi} + \omega_{Tr}\Psi_{Trans} + \omega_{Con}\Psi_{Con} \quad \textbf{(17)}$$

Where Ψ_{Feeder}, Ψ_{Φ}, Ψ_{Tr} and Ψ_{Con} are resilience index for feeder f, poles, transformers and conductors, respectively. Also ω_{Φ}, ω_{Tr} and ω_{Con} refer to constant coefficients representing the effectiveness degree of each component [4-8].

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

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

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

$$\forall\ S \in\ HV$$
$$\forall\ F \in\ Feeder$$
$$F_{Dist}(s_i, s_j) = \sqrt{(x_{s_i} - x_{s_j})^2 + (y_{s_i} - y_{s_j})^2} \quad \textbf{(19)}$$

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.

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

$$F_{Con} = N_{\Phi} - 1 \quad \textbf{(21)}$$

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):

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

Finally, the total network fragility index with N_{HV} HV substation and N_{Feeder} feeder for each HV substation is given by (23).

$$\Psi_{Network} = \sum_{h=1}^{N_{HV}} \sum_{f=1}^{N_{Feeder}} \Psi_{Feeder}(h, f) \quad \textbf{(23)}$$

3. Numerical Results

The main goal of this paper is to achieve the optimal comparative resilient 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 scenarios, a comprehensive comparison is prepared regarding optimal plan of MV distribution network based-on the resiliency and cost design.

A. Test case system

The test case network with its associated geographical data which is illustrated in Fig. 1 is used to apply the proposed planning technique. As shown in Fig. 1, the study area is divided into several 50*50 blocks or sites to characterize the geographical location of network components and hurricane wind speed at each site. Besides, the area is represented with the color spectrum from white to red that each color represents the speed density of each block. The 72 candidate feeder's route and 32 MV substations location are also indicated. In the current figure, red and yellow color indicate higher and lower wind speed, respectively. Furthermore, Fig. 2 illustrates a three dimension plot of the wind speed in the study area. In Fig. 3 a counter plot of the wind speed value is depicted.

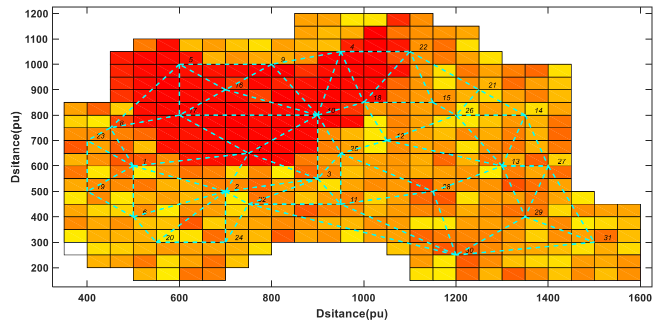

Fig. 1. Geospatial map of wind speed density in study area.

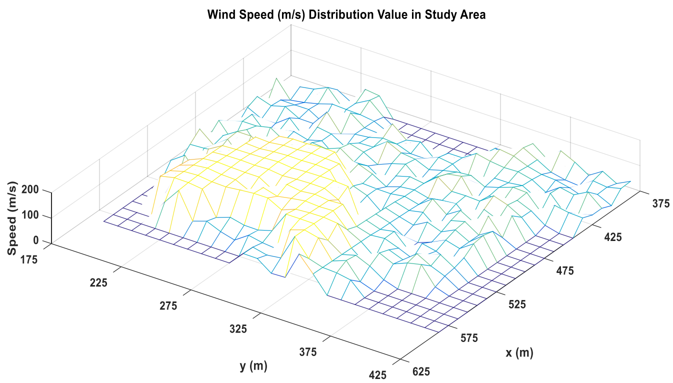

Fig. 2. 3D plot of the wind speed in study area.

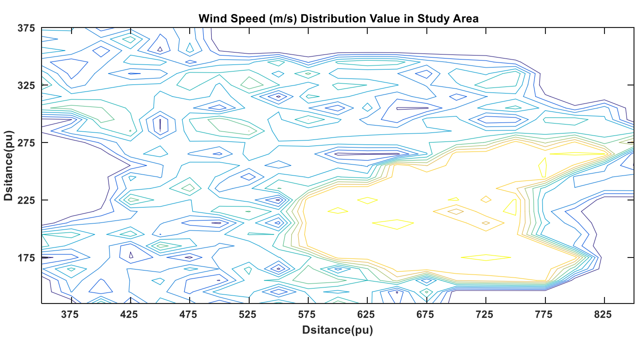

Fig. 3. Counter plot of the study area wind speed amplitude.

B. First stage: Planning considering two HV substation

The rest of the paper is focused on the optimal network planning technique in order to plan the best network configuration from both resilient and cost-based planning point of view.

B.1. First scenario: Resilient-based planning

In this paper, the Greedy algorithm is applied to solve optimal network configuration with the aim of finding a radial network with a minimum feeder fragility index. The voltage drop and feeder power limitations are checked by the Gauss-Seidel load flow algorithm during the planning process to be in an acceptable range. Optimal network configuration in terms of resilience planning is depicted in Fig. 4. In this figure, the selected feeders connected MV to HV substation are shown. The number of MV feeders can be obtained from the number of MV substations minus the number of HV substations. Regarding the resilience index of feeders as optimization function for the Greedy algorithm, the fragility index of network components such as distribution poles, conductors and transformers should be determined from related fragility curves.

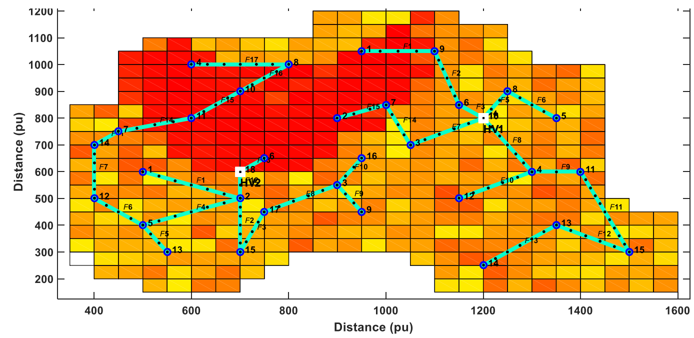

Fig. 4. Optimal distribution network configuration: Resilient-based planning.

The location of distribution poles for each feeder and the number of falling poles in a block is determined and indicated in the figure. Finally, the fragility index of each pole and consequently the total feeder section's fragility index is obtained. For each HV substation, its related feeder section's fragility index obtained by summation of distribution component' fragilities are illustrated in Figs. 5 and 6. For example, in Fig. 5, the feeder's fragility indexes for HV substation 1 for resilient-based planning are illustrated. Considering Fig. 5 it can be seen that the fragility indexes of feeders 12-17 are relatively high. It can be concluded from Fig. 4 that the location of the above feeders is located in a very high hurricane wind speed. In Table 1, detailed information for the fragility index calculation of a feeder section is indicated. Based-on the table, this sample feeder section has five poles. In this table, their coordination (X, Y), related site, wind speed and fragility indexes of each pole are shown. In Table 1 the overall network fragility index (optimized) and overall network cost (evaluated) are indicated.

Table 1. Detailed information for a feeder section in fragility calculation

Feeder Poles	Pole X	Pole Y	Pole Site Number	Wind Speed	Pole Fragility
Pole1	950	1050	218.0	88.995	0.097
Pole2	987.5	1050	218.0	88.995	0.097
Pole3	1025	1050	236.0	101.131	0.188
Pole4	1062.5	1050	258.0	92.366	0.118
Pole5	1100	1050	272.0	43.149	0.002

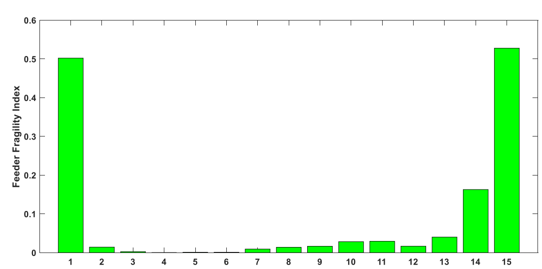

Fig. 5. Fragility index of HV1 feeders: Resilient-based planning.

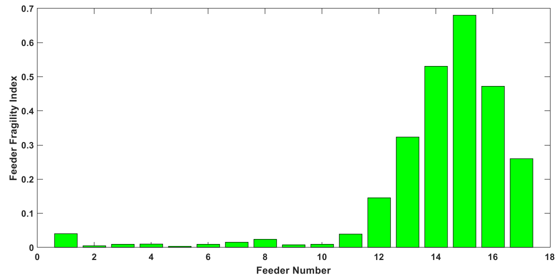

Fig. 6. Fragility index of HV2 feeders: Resilient-based planning.

Table 2. Total result of resilient-based planning with two HV substation

Planning type		Cost index	Resilience index
Resilient-based	HV1	2342.80	1.37
	HV2	2544.81	2.58
Sum	Total	4887.61	3.95

B.2. Second scenario: Cost-based planning

In this section, the same MST technique using the Greedy algorithm is applied to solve the optimal network planning problem with respect to cost. The cost-based planning configuration of the network is represented in Fig. 7. Here, cost (optimized) and resilience index (evaluated) are calculated as primary and secondary aims regarding the resilience index of feeders as the optimization function of the planning problem. Like the first scenario, for each HV substation, related each feeder section's fragility index obtained by summation of distribution poles fragilities are illustrated in Figs. 8 and 9.

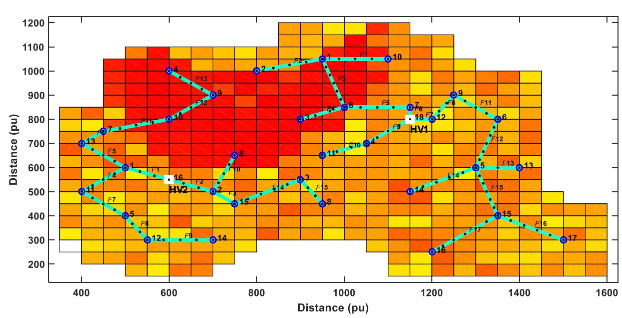

Fig. 7. Optimal network configuration: Cost-based planning.

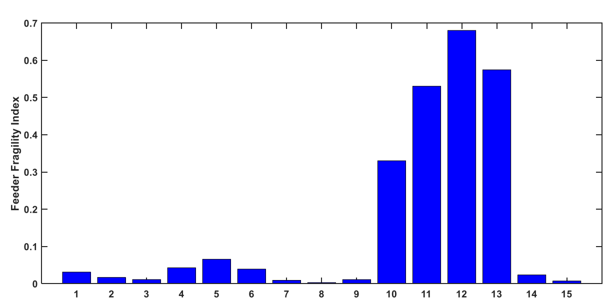

Fig. 8. Fragility index of all feeders for HV1: Cost-based planning.

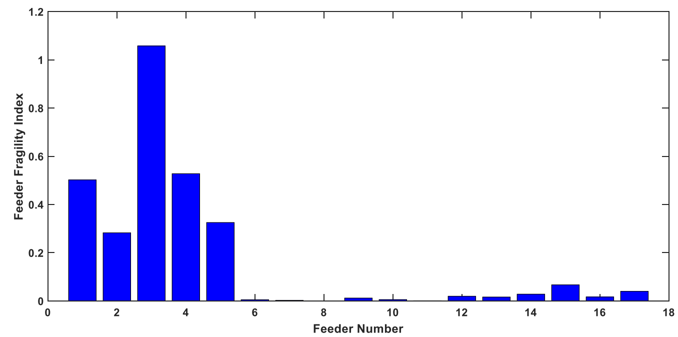

Fig. 9. Fragility index of all feeders for HV2: Cost-based planning.

At the end, the final results of this stage are given in Table 3. In addition, the overall results of two stages, considering one HV substation is given in Table 4. In Table 4, the total network fragility and cost in two scenarios with two HV substations are compared. Based on this table, in the case of resilient-based planning, the network fragility is improved 35% with respect to cost based-planning, while the network cost is improved 10 % with respect to resilient-based planning.

Table 3. Overall result of cost-based planning with two HV substation

Planning type		Cost index	Resilience index
Resilient-based	HV1	1942.25	2.38
	HV2	2467.52	2.91
Sum	Total	4409.77	5.295

Table 4. Comparison between total network cost and resilience index in stage 1 (two HV substation)

Planning Type	Cost	Resilience Index
A-Resilient Network	4887.61	3.95
B-Minimum Cost Network	4409.77	5.29
B/A%	90	135

C. Second stage: Planning considering Five HV substations.

The same process which has been done for first stage planning will be done in the presence of five HV substations and related consequences for cost-based and resilient-based planning are obtained. Due to similar explanations of the planning process detailed in the previous stage, just significant results are provided.

C.1. First scenario: Resilient-based planning

According to the optimal configuration plotted in Fig. 10, some feeders of three HV substations encounter destructive natural events; however, they are routed in a way that does not meet a higher fragility index. Based on the current figure, five optimal radial MV networks are planned with respect to the resilience index. For each HV substation, related each feeder section's fragility index obtained by the summation of distribution poles' fragilities are illustrated in Figs. 11-15. As explained before, the higher value of the fragility index indicates the higher risk of components to be damaged facing natural disasters. Based on the comparison between Figs. 11-15, it can be seen that the number of feeders with high fragility index differs for each HV substation. Also, the resilience index for each HV substation and as a result total network's resilient index is provided in Table 5.

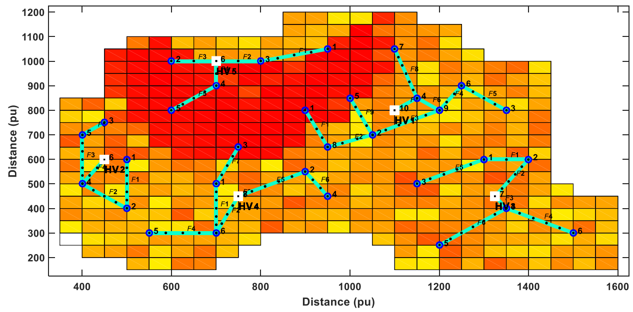

Fig.10. Optimal configuration in terms of resilient-based planning considering five HV substations.

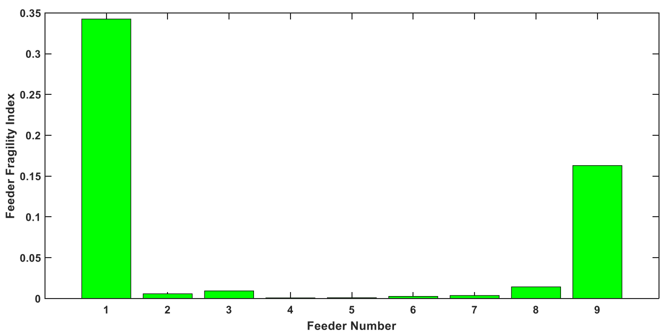

Fig. 11. Fragility index of all feeders for HV1: Resilient-based planning.

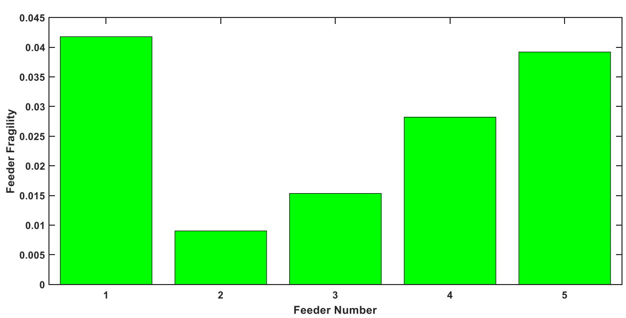

Fig. 12. Fragility index of all feeders for HV2: Resilient-based planning.

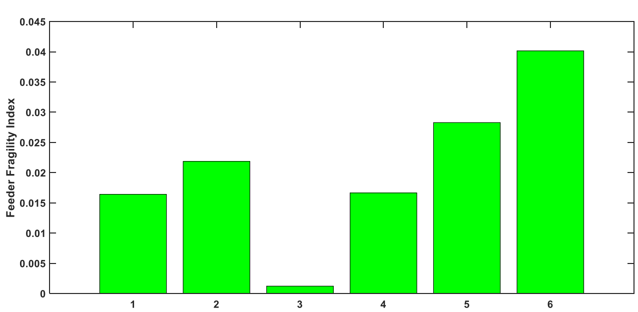

Fig. 13. Fragility index of all feeders for HV3: Resilient-based planning.

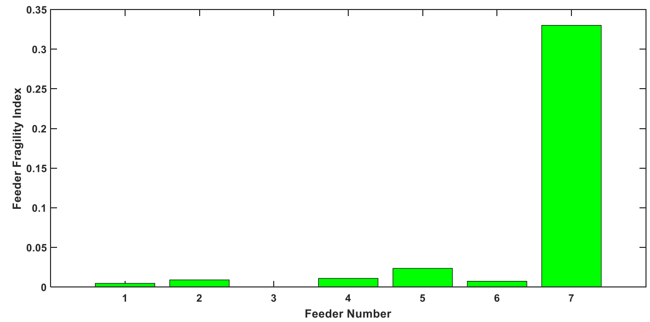

Fig. 14. Fragility index of all feeders for HV4: Resilient-based planning.

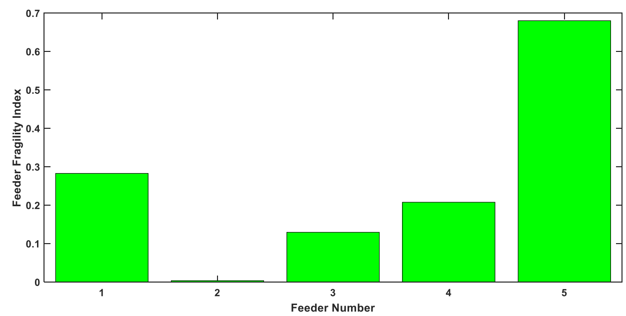

Fig. 15. Fragility index of all feeders for HV5: Resilient-based planning.

Table 5. Final resilience index and cost for resilient-based planning with five HV substation

Planning		Cost	Resilience index
Resilient-based	HV1	1209.11	0.54
	HV2	723.93	0.14
	HV3	896.29	0.13
	HV4	958.31	0.39
	HV5	599.53	1.30
Sum	Total	4387.17	2.5

C.2. Second scenario: Cost-based planning

The optimal planning of network using feeder routing algorithm aiming at reducing total feeder cost regarding cost as fitness function is illustrated in Fig. 16. Similar to the previous scenario, some feeders of three HV substations pass from venturous areas, which lead to increased fragility index. The total network's resilience index and cost of this scenario are given in Table 5. Also, for each HV substation, the fragility index of feeders evaluated based on the placement of feeders is obtained and plotted as shown in Figs. 17-21. Also, the resilience index for each HV substation and as a result total network's resilient index is given in Table 6.

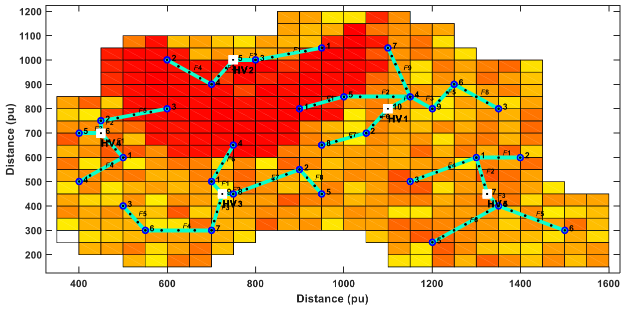

Fig. 16. Optimal configuration in terms of cost-based planning considering five HV substations.

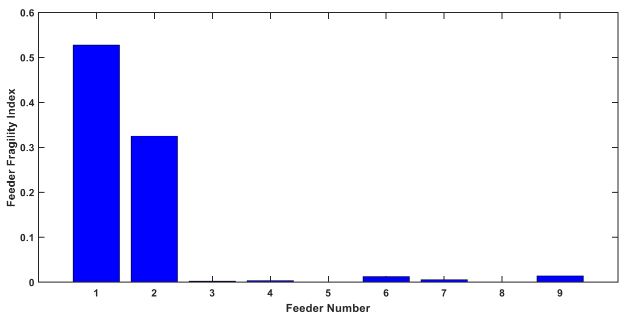

Fig.17. Fragility index of all feeders for HV1: Cost-based planning.

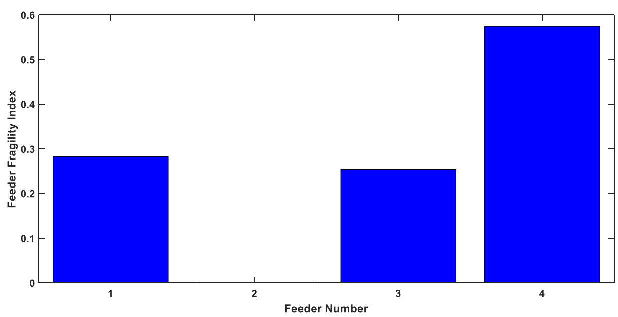

Fig. 18. Fragility index of all feeders for HV2: Cost-based planning.

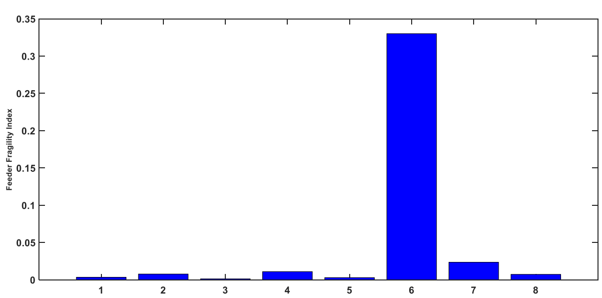

Fig. 19. Fragility index of all feeders for HV3: Cost-based planning.

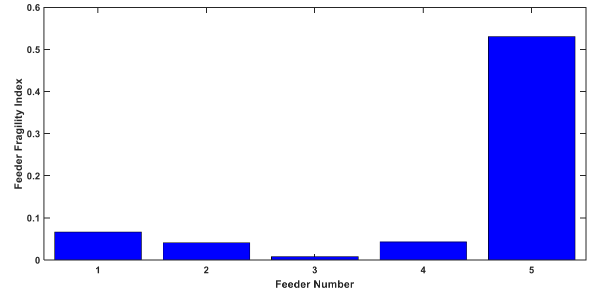

Fig. 20. Fragility index of all feeders for HV4: Cost-based planning.

At the end of this stage, a complete comparison according to previously obtained consequences of two scenarios is provided in Table 7. It can be concluded that resilient-based planning with a smaller resilience index can withstand effectively and is less vulnerable, encountering destructive events. As seen, the last line of the table is dedicated to the ratio of two values that is an indicator of resilience improvement of the network. In this regard, the cost of network decreased to 88.5% while the network resilient increased to 129.2%.

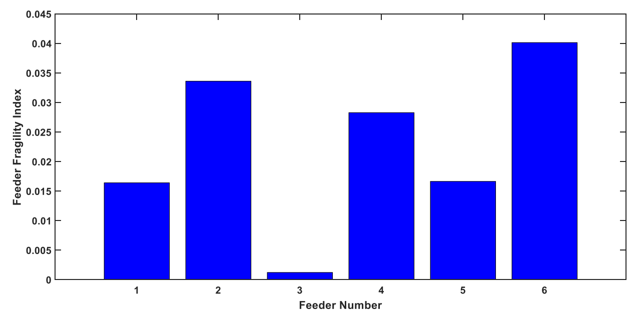

Fig. 21. Fragility index of all feeders for HV5: Cost-based planning.

Table 6. Final resilience index and cost for cost-based planning with five HV substation

Planning		Cost index	Resilience index
Cost-based	HV1	1086.21	0.89
	HV2	461.34	1.12
	HV3	944.67	0.39
	HV4	511.34	0.69
	HV5	880.67	0.14
Sum	Total	3884.23	3.23

Table 7. A comprehensive comparison between total network cost and resilience index in stage 2, with five HV substation

Planning Type	Cost index	Resilience Index
A-Resilient Network	4387.17	2.5
B-Minimum Cost Network	3884.23	3.23
B/A%	88.5	129.2

In Table 8, on the other hand, a comprehensive comparison considering both stages is provided. Based on results in Table 8, the total network cost of two stages is almost the same, while the resilience index of the first stage (considering two HV substations) is more and better than the first stage (considering two HV substations). As the last point of this paper, although the resilient based planning of the network may increase the cost of the system, it is negligible in comparison with relatively high resilience improvement of the distribution network as the main goal of the suggested planning technique. Comparing the optimal configuration of the network with minimum fragility index (Figs. 4 and 10) and minimum cost (Figs .7 and 16) clearly shows that in case of resilient planning the network feeders are prohibited from entering the area with high wind speed and tend to routed in sites with low wind speed to reduce the risk of damage.

Table 8. Summary comparison stage 1 and stage 2 (two and five HV substation planning)

Network with two HV	Cost Ratio	Resilience Index
B/A%	90	135
Network with five HV	Cost Ratio	Resilience Index
B/A%	88.5	129.2

4. Conclusion

In this paper, due to the adverse impacts of natural disasters on the distribution network's component, resilient and cost-based planning of MV distribution network using the Greedy algorithm is proposed and discussed. The optimal planning problem is solved with attention to a fitness function based on network cost and component fragility during a hurricane. The geographical information for a 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 the fragility index of each network's component is evaluated. Comparing the optimal configuration of the network with minimum fragility index and the network minimum cost it clearly shows that in case of resilient planning, the network feeders are prohibited from entering the area with high wind speed and tend to routed in sites with low wind speed to reduce the risk of damage. The obtained results show that the ratio of total network cost is the same for both stages, while the resilience index of a network with two HV substations is better than five HV substations case. It can be concluded that the amount of increasing cost, as the result of resilience planning, is acceptable regarding the improvement of distribution network resilience as a significant goal of this paper to be achieved.

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