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Resilience assessment and improvement of distribution networks against extreme weather events

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ABSTRACT

The storm, as one of the most frequent natural disasters, has a significant impact on the critical electrical power infrastructure. Therefore, providing a framework to enhance the strength of components of the power system, such as conductors and poles, is a practical means to reduce damage caused by extreme weather events. In response to this critical requirement, this paper presents a framework that includes three stages, i.e. natural occurrence modeling, component vulnerability and network resilience assessment, and network resilience improvement. In order to evaluate the resilience of the network components, fragility models of conductors and poles and Monte Carlo simulation are used. Furthermore, to improve the resilience of the network, vegetation management and upgrading and repairing of network poles are employed as the network hardening strategies. Then, to determine the components of the network that need reinforcement, the hardening problem is formulated as an optimization problem and solved by the genetic algorithm where budget constraints, the criticality of loads, and the accessibility of network components are considered. Finally, the proposed method is applied to a real network to demonstrate the effectiveness of the approach.

1. Introduction

In recent years, natural disasters have caused many problems, like severe damage to the electricity infrastructure. Considering the growth of power systems' importance and applications, the significance of system resilience evaluation and improvement has been increased [1].

National Infrastructure Advisory Council (NIAC) outlines the key features of resilience as the robustness, resourcefulness, rapid recovery, and adaptability [2]. Therefore, resilience improvement can be carried out via enhancing different factors. However, resilience enhancement strategies are generally divided into two main parts that are system hardening [3–5] and operational resilience improvement methods [6]. The operational solutions include the use of distributed generations (DGs) [7], storage systems [8,9], demand-side management [10], microgrids [11–13], and other smart operational strategies [14] which improve system performance during and after disasters [15]. Nonetheless, if the system operator implements operational solutions such as DG installation and distribution network automation for resilience enhancing, system may still fail in case of natural disaster occurrence because of insufficient strength of components. On the other hand, hardening solutions increase the robustness of equipment against natural catastrophes that can reduce the lost load amount and the required time to repair the network.

Most literature in the scope of power system hardening has focused on transmission systems [5,14,16,17]. Some works of literature have also studied system hardening to improve power system reliability [18,19]. However, while transmission systems are designed to withstand natural disasters, distribution systems are more vulnerable to extreme weather conditions [20]. Moreover, the historical data show that the major power outages have been placed in the distribution systems. Therefore, it is important to study the impact of natural disasters on distribution networks [21].

On the other hand, some papers have focused on the resilience improvement of the distribution system. For instance, a resilient distribution system planning problem has been proposed in [22] to coordinate the hardening and DG units' allocation with the goal of minimizing network damage. In addition, some research has introduced multi-level models to enhance system resilience. For example, in [7], a tri-level defender-attacker-defender (DAD) model has been introduced to find the best hardening strategy under malicious attacks where hardening measures, topology reconfiguration, and optimal DG islanding formation have been considered as power system resilience components. Similarly, Ref. [23] has proposed a tri-level defender-attacker-operator (DAO) model to improve power system resilience against natural disasters using hardening strategies. Ref. [24] has also proposed an optimal hardening technique as a tri-level optimization problem to minimize system hardening cost and load shedding in extreme weather incidents where vegetation management and upgrading of poles have been considered as hardening strategies. Furthermore, a two-stage stochastic distribution system hardening problem has been

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addressed in [3] that has considered an approach for selection of components to harden and scheduling of post-disaster recovery. Ref. [8] has also proposed a solution for distribution systems hardening against earthquakes based on the battery energy storage where fragility curves of system elements have been employed to model the hazard and estimate the unavailability of the components.

Moreover, some papers have studied the resilience enhancement problem of power systems in the presence of other vital infrastructures. For example, Ref. [25] has introduced a resilience improvement strategy using line hardening and DG placement considering the coupled power distribution network and urban transportation system. In addition, a tri-level system hardening model has been proposed in [4] for integrated electricity and natural gas distribution systems to minimize total weighted gas and electricity load shedding with respect to the limitation of budget.

This paper presents a framework for the evaluation and improvement of network resilience. To evaluate system resilience, quantitative or qualitative assessment can be employed where the former method is considered here. Moreover, respect to the concept of structural resilience, network hardening strategies are considered to improve system resiliency. Furthermore, three hardening techniques, including vegetation management, upgrading poles' classes, and repairing and refurbishments of poles are used. The purpose of the proposed framework is to find the optimal components of the network for hardening considering the fragility probability of each component, load importance factors, availability factors, and repair time of each section of the network. This approach is not considered in the previous works. To include the probabilistic aspect of the optimization problem, MCS is employed where network component fragility curves are used. Finally, a genetic algorithm (GA) is used to solve the problem and determine the optimal sections of the network for hardening.

The remainder of the paper is organized as follows: The second section explains the proposed framework and the model of each step of the problem. While Section 3 describes the objective function and constraints of the problem, Section 4 presents the solution method. Furthermore, Section 5 demonstrates and analyzes the numerical results. To sum up, the last section presents the conclusions of the paper.

2. Framework for evaluating and improving network resilience

The main objective of this section is to describe the proposed structure for assessing and enhancing the network resilience to an extreme weather event. To achieve this goal, firstly, the extreme weather event is modeled. After that, the vulnerability models of conductors and poles, network response evaluation, and optimal network hardening model are discussed. According to this, the main framework of the proposed approach, including these steps, is illustrated in Fig. 1.

2.1. Extreme weather occurrence model

In the first step, to extract a comprehensive model for assessing and improving network resilience, the modeling of natural disasters is necessary. While storms rarely affect power plants and transmission lines and substations, the distribution networks can be severely affected by intense storms. Most distribution system damage is due to the high-speed of windstorm or hurricane as follows:

- Pole failure or conductor failure due to the wind forces
- Conductor and pole failure due to the falling trees and flying debris
- Failure of pole components such as crossarm or insulator due to the physical damage as a result of the severe windstorm

The wind speed is predicted by a Weibull distribution function, which is a probability density function according to Eq. (1) [26,27].

$$f_v(v) = \frac{\alpha}{u}\left(\frac{v}{u}\right)^{\alpha-1} e^{\left[-\left(\frac{v}{u}\right)^{\alpha}\right]}, \tag{1}$$

where α and u are the parameters related to the Weibull distribution, and v is the speed of the wind or storm. In case of hurricane and storm events, the critical value concept can be used to calculate the maximum speed of wind [28]. This concept can examine historical data to model the storm event as a probabilistic distribution. In other words, the critical value states that there is an expected speed v at the return period T that can be calculated from Eq. (2) [29].

$$v = u\left[-\ln\left(\frac{1}{T}\right)\right]^{\frac{1}{\alpha}}. \tag{2}$$

By applying Eq. (2) and based on the meteorological models for determining the parameters of the Weibull function, the speed of windstorm in the return period can be calculated. Typically, return periods are defined as fixed periods of 50, 100, and 250 years. However, it should be noted that due to the climate and the geographical area of the threat occurrence, the wind speed as well as the return period may change.

2.2. Vulnerability assessment of components

While the natural disasters may damage the system components, the extent of the destruction depends on the various factors such as the nature and the severity of the catastrophe, besides the type and the age of the infrastructure. Therefore, in addition to determining the behavioral patterns of the threat, the vulnerability model of system components should also be obtained. Although various components such as poles, conductors, transformers, switches, etc. operate in the distribution network, the poles and conductors are reported to be the most vulnerable elements against storm and hurricane because they are directly exposed to the wind force. Totally, there are three models to investigate network vulnerability, including statistical models, structural models, and fragility curves [20]. In this paper, the last method is used to estimate the failure probability of components. In fact, the fragility curve determines the probability of component failure as a function of the intensity of the event. These curves can be obtained in a variety of ways, such as experimental methods, statistical approaches, analytical techniques, the use of expert judgment, or through a

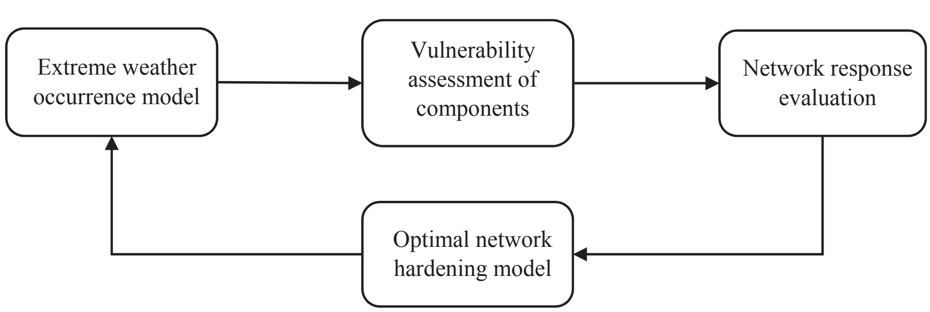


Fig. 1. Framework for evaluating and improving network resilience.

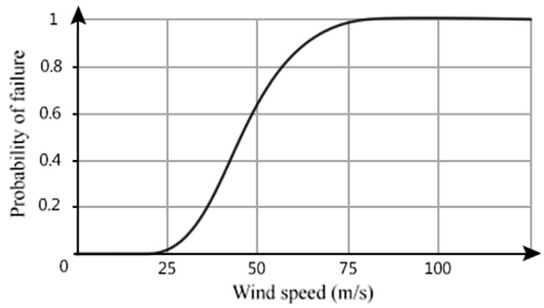


Fig. 2. The fragility curve of an equipment.

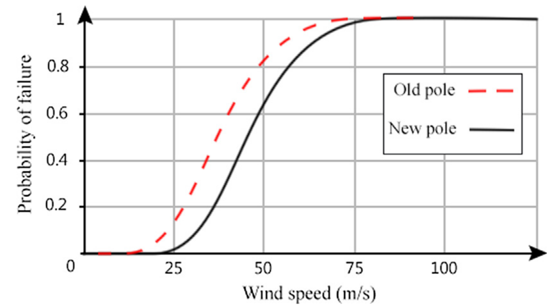


Fig. 3. Modeling the pole aging by fragility curve.

combination of these methods. Fig. 2 shows a typical fragility curve.

2.2.1. Fragility model of poles

In order to use the fragility curves to evaluate the resilience of the system, it is necessary to determine the mathematical function of these curves. These functions are obtained by fitting the historical and experimental data related to the failure of the poles according to the intensity of the incident. Therefore, the probability of pole failure should be expressed as a function of wind speed. According to the studies in [30,31], the fragility function of poles typically follows Eq. (3). This is because, in data fitting, one uses the exponential function when the rate of changes of the predicted variable corresponding to the changes of the input variable has an accelerating increasing or decreasing trend.

$$P_p = A_p \times e^{B_p \times v}, \tag{3}$$

where A_p and B_p are the related coefficients for pole. These coefficients' values vary depending on the geographical condition, age, type, and class of the poles.

2.2.2. Fragility model of conductors

To acquire the fragility curve of conductors, like the pole fragility model, a mathematical function can be obtained for the conductors using fitting methods on the recorded historical and experimental data as Eq. (4) [31].

$$P_c = A_c \times e^{B_c \times v}, \tag{4}$$

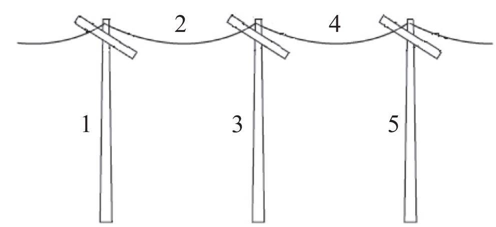
where A_c and B_c are the related coefficients for the conductor. These coefficients' values vary depending on the geographical condition, age, type, and area of the conductors.

2.2.3. Aging of poles

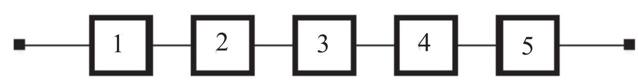
Component aging is one of the most destructive factors in infrastructure failure. The strength and resilience of the network's poles, whether concrete or wooden types, decrease over time. For example, wooden poles would be rotten and damaged over time due to the attacks of fungi and insects. The rate of wood decay depends on many factors such as wood type, climatic conditions, maintenance, and attack of fungi and insects. On the other hand, the destruction of concrete poles is mainly due to environmental factors such as moisture, salt, water, and pollution where because of capillary suction, the concrete would erode gradually [32]. As a general rule, because of the aging effect, the fragility curve would move toward the left, which shows less pole strength against wind force as shown in Fig. 3 [18].

2.3. Network response to catastrophe

This section evaluates the impact of the storm on the network, which is obtained using the indicator of the amount of energy not supplied (ENS). To do this, first, the network lines are modeled, and then the impact of the disaster is evaluated using MCS.



a. Components of network's lines



b. Block diagram of series model of line components

Fig. 4. Network lines model.

2.3.1. Network lines model

Each line or section of the distribution network consists of poles and conductors (see Fig. 4a). Therefore, the failure of one of these components causes the line failure. As a consequence, each line operates as a series system and can be governed by the rules of the series systems, as can be seen in Fig. 4b and Eq. (5).

$$P_l = 1 - [(1 - P_{f1})(1 - P_{f2})(1 - P_{f3})(1 - P_{f4})(1 - P_{f5})], \tag{5}$$

where P_l is the failure probability of line l, and P_{fi} is the failure probability of component i.

2.3.2. Resilience assessment method

In this paper, MCS and fragility curves are used to evaluate system resilience. To perform the assessment method, initially, the intensity of the event, windstorm speed, is plotted for each component on its related fragility curve so that the damage probability for each pole and conductor (p_x) would be determined; then, in each iteration, a series of random numbers ($r \in [0.1]$) is produced according to the number of the line components. For each component, generated random number is compared with p_x that if $r > p_x$, it is assumed that the component is not failed, but if $r < p_x$, it is assumed that it is failed. Therefore, in each iteration, a sequence of numbers is created, consisting of zero and one, indicating the failed or not failed state of each component and line. Therefore, in each iteration, one can calculate estimations of different indices, such as ENS.

2.3.3. Repair time model

After a disaster, equipment repair time depends on a variety of factors, including the severity and type of disaster, the number of repair crews, the availability of adequate spare equipment, and the ability of the operator to quickly identify the problem and decide on the most appropriate measures to take. Nevertheless, considering the real cases, it is assumed that the required times to repair each failed pole and conductor, $t_{restoration_{p,c}}$, are random numbers between 3–5 h and 1–2 h, respectively, as follows:

$$t_{restoration_{p,c}}(h) = \begin{cases} r(3, 5) & for\ pole \\ r(1, 2) & for\ conductor \end{cases} \tag{6}$$

So, if N_{p_l} and N_{c_l} are the numbers of failed poles and conductors in each section, the recovery time for each section will be equal to T_l:

$$T_l = (N_{p_l} \times t_{restoration_p}) + (N_{c_l} \times t_{restoration_c})$$

2.4. Network hardening

In order to find the best approach for network strengthening, it is necessary to analyze and compare different hardening strategies. These strategies can be classified as follows:

- Vegetation management programs for clearing the right-of-way paths of the distribution lines using tree trimming and removal.
- Structural hardening, including replacing available poles with higher-order class poles, refurbishment of poles, crossarms, and wire ties, span length control, and pole guying.
- Electrical hardening using bare wire reconductoring, lightning protection, and fuse sectionalizing.
- Replacing overhead conductors with underground lines.
- Moving lines and substations to safer areas.

Nonetheless, two latter methods impose high costs on distribution companies. Furthermore, while bare wire reconductoring with tree wire (contains poles, covered wires, and crossarms) can be implemented as a long-term hardening solution, it is also an expensive strategy. On the other hand, because network strengthening is costly for distribution companies, the main concern in this context is how to select solution methods and prioritize system components for strengthening due to the budget constraints. In line with that, in this paper, vegetation management strategy and upgrade, refurbishment, and reinforcement of poles are used to strengthen the network against severe storms.

2.4.1. Vegetation management

During an extreme windstorm or hurricane, falling branches or trees on the conductors or poles can cause problems for the network (see Fig. 5). On the other hand, tree pruning is usually part of the routine maintenance program of distribution companies, but given the severe damage from recent storms, many trees are also likely to be damaged after regular pruning. Hence, it is necessary to use other measures of vegetation management for resilience improvement goals, such as increasing awareness of the people and authorities for planting suitable trees with regard to the geographical environment and electric network configuration, creating a database of pruning programs, analysis of tree lifespan and soil characteristics of the area, cut downing dried trees in the surrounding area, etc.

2.4.2. Upgrading, refurbishment and strengthening of poles

Considering that network poles are the relay points of the overhead lines, special attention to this equipment is of paramount importance. When natural disasters occur, pole destruction may take place due to the insufficient strength because most distribution networks are planned for normal weather conditions and cannot withstand much force of intense storms or falling tree branches or trunks. As a matter of fact, the low class of poles installed in the grid as well as their aging over time are some of the main causes of their failure in the face of extreme weather events. It is worth noting that in addition to the selecting the right class according to the geographical area and the likely wind speed, the selection of the proper material used in the pole construction is important in order to meet the mentioned requirements and extend the lifespan of the poles. Therefore, to decrease the failure probability of a pole, the solution is to increase the strength of the pole by different ways, like using guy wires or replacement of the old pole by a new stronger one.

3. Problem modelling

Generally speaking, developing a suitable model for network resilience improvement needs wisely and carefully selection of the objective function and constraints, which is explained here. Therefore, in this section, in order to extract a mathematical model for the problem, the proper formulation of the objective function and the constraints in addition to the solution method of the hardening problem are described.

3.1. Objective function and constraint

Based on the effects of storms on the power distribution systems, the process of system hardening consists of two parts; what efforts should be made to harden each line, and how to prioritize distribution lines for hardening. For the first part, as already explained, there are various ways in which some are ignored here due to their cost burden. For that reason, in this paper, pole replacement and upgrading strategies and the aforementioned vegetation management method are used according to the geographical conditions of the network. Furthermore, the ENS amount and value of lost load (VoLL) are selected as assessment criteria for prioritization of different sections of the system for hardening. The VoLL can actually estimate the overall damage caused by interruptions in energy supply. In other words, the VoLL can represent the cost and value of not delivered electricity in energy supplying; therefore, it can take the importance of load into account. Moreover, to harden the distribution network, the VoLL provides an insight into the value of the security of energy supply by considering sensitive loads and including total social welfare in the problem [33]. Therefore, the objective function of the problem determines the optimal sections for hardening according to the specified strategies as Eq. (8).

$$\text{ObjF} = \text{Min}\{\text{ObjF}_{\text{CENS}} + \text{ObjF}_{\text{Cost}}\}. \tag{8}$$

As Eq. (9) demonstrates, the first part of the objective function relates to the amount of ENS and is calculated using the flowchart presented in Fig. 6. The flowchart implies that the ENS totally depends upon the strength of components, the severity of the event, repair time, load demand, and the position of the component along the line.

$$ObjF_{C_{ENS}} = \sum_{i=1}^{N} C_i \times ENS_i, \tag{9}$$

where C_i is the VoLL in bus i, and N is the number of network buses. In

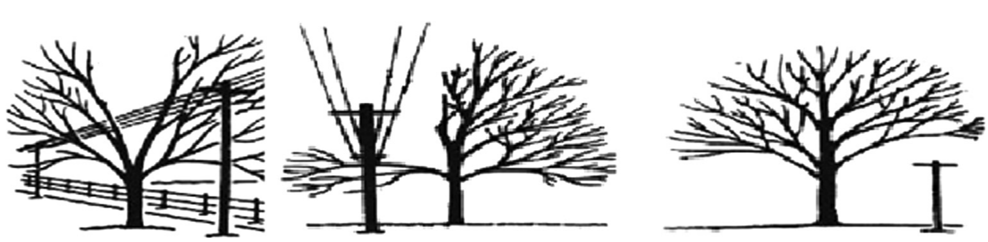


Fig. 5. Typical troubles of trees in distribution network areas.

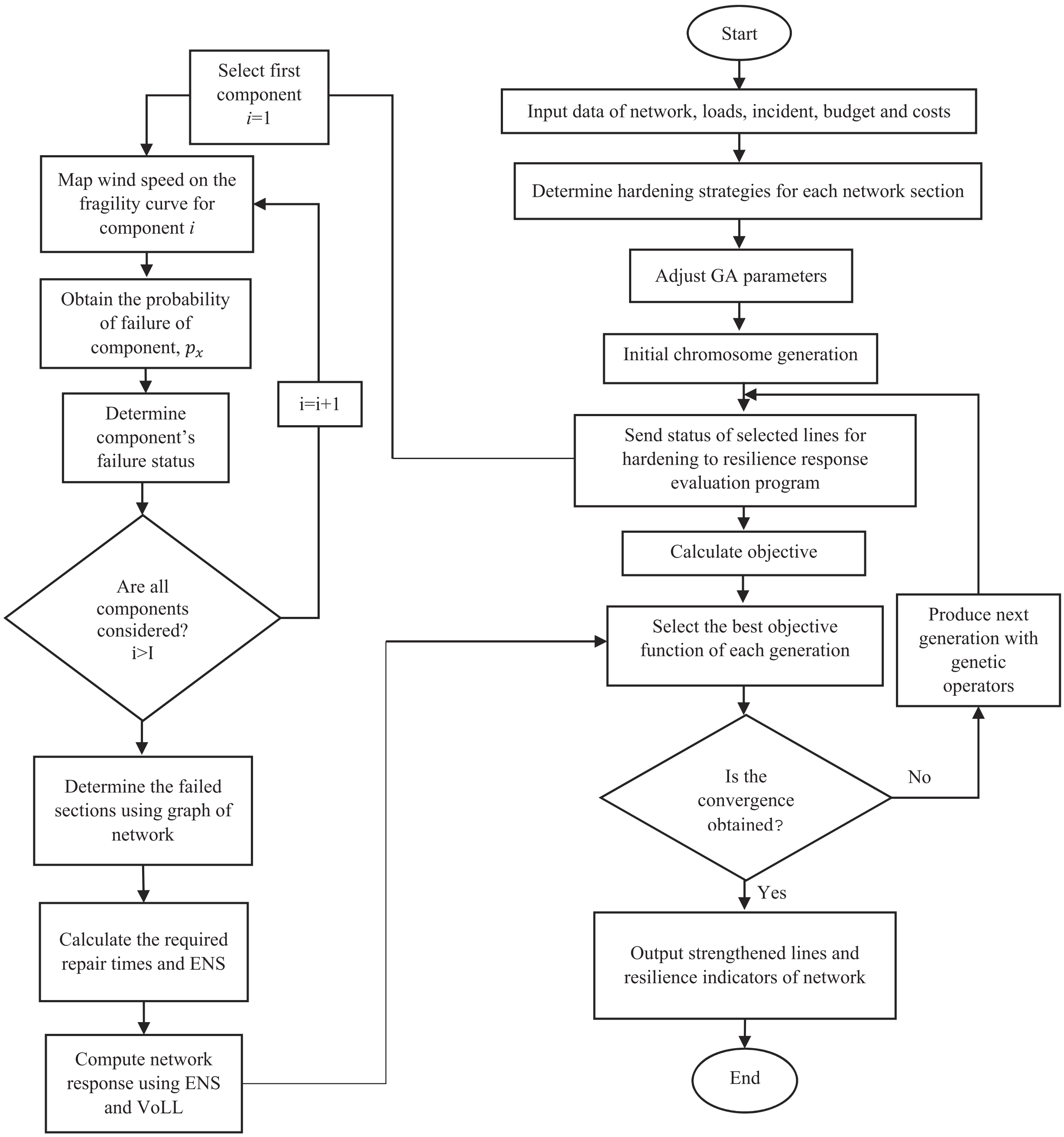


Fig. 6. Flowchart of the proposed hardening model.

this paper, it is assumed that the value of C_i depends upon the importance and interruption priority of load. The second part of the objective function relates to the cost of network hardening represented by (10).

$$ObjF_{Cost} = \sum_{j=1}^{M} x_j \times Cost_j, \tag{10}$$

where the binary variable x_j is used to express whether the line j is selected for hardening by the optimization algorithm; M is the number of components, and $Cost_j$ is the cost of hardening of component j considering the type of applied reinforcing strategy.

The constraint of the problem presented in (11) relates to the amount of the hardening budget.

$$\sum_{j=1}^{M} x_j \times Cost_j \le B, \tag{11}$$

where B is the amount of the hardening budget. According to this constraint, the total hardening cost cannot exceed the total hardening budget of the Distribution Company.

4. Problem-solving method

To propose a solution algorithm for resilience improvement, the GA is used to determine the best network lines for hardening where the probability of failure, strengthening cost, load importance, repair time, and different hardening strategies are considered for the network. The MCS-based approach, described in Section 2.3.2, is used to calculate the amount of ENS in each iteration, considering different repairing times of components and various importance factors of loads. Finally, after

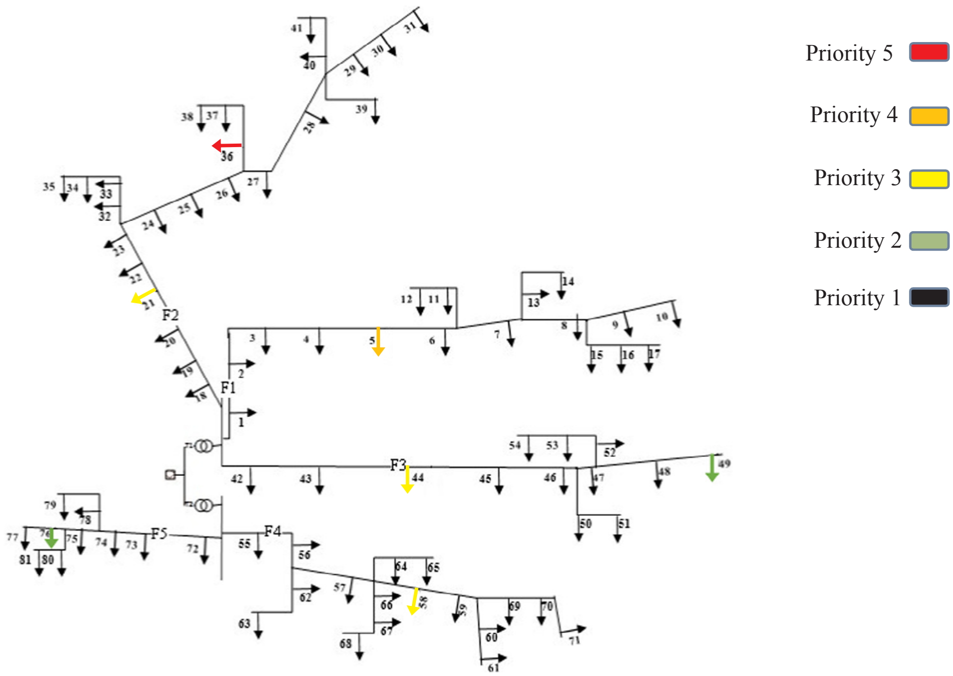


Fig. 7. Rostam Kola distribution network.

running the program, the GA selects the optimal sections of the network for hardening due to the budget constraints, where it comprises a complete criterion for prioritizing different sections of the network. For the sake of clarification, the flowchart of the proposed model is presented in Fig. 6.

5. Numerical results

In this section, the simulation results of the proposed method, applied to a real distribution network in the city of Rostam Kola, is presented and discussed. The simulation is carried out using MATLAB software. Rostam Kola, which is a city in Mazandaran province in the north of Iran, is selected because of its specific geographical conditions in terms of the storm threat. Using an actual network would improve the competence of the study due to the real data for the age of the poles, the locations of the vegetation, and hard-to-access regions. Therefore, all realistic conditions are taken into consideration in the problem. Fig. 7 shows the test system in which loads are classified into five priorities, where loads with priority 1 have the lowest importance for the system operator. On the other hand, loads with priority 5 are the most significant loads of network, and other loads' priorities vary between these two numbers. The system operator determines the priority of each load based on different parameters, such as the economic value of the interrupted load, the type of customer, the value of security, and the social and strategic importance of load. For instance, critical facilities and public services like hospitals, gas compressors, fire stations, and water pumping may be considered high-priority customers. Moreover, whereas industrial and commercial sections can be categorized as medium-priority loads, the residential customers may have lower priorities [33]. Nonetheless, the priority of load may vary associated with the time of incident occurrence, interruption duration, etc.

Fig. 8 represents the load demands of system buses addressing the accessibility factor. The accessibility factor for mountainous areas is supposed to be 2, which is considered in the calculation of required repairing time of associated feeders and sections.

5.1. Specifications of storm

Different regions have diverse climatic characteristics depending on their geographical locations. Hence, storm data from the Mazandaran province is used in this paper. Based on the meteorological data of this area, the parameters of Weibull function are calculated as Table 1.

Therefore, according to Eq. (2) and considering the worst-case return period, the wind speed would be 50 m/s that is considered for the study.

5.2. Fragility model of network poles

Most of the poles in Iran are wooden or concrete, where wooden poles are usually used in hard-to-reach areas. The specifications of network poles before hardening are 12/200 (height/ nominal strength) and 12/5 (height/ class) for concrete and wooden poles, respectively. Actual data for the fragility functions of network poles and lines are extracted, which are inquired from the Power Distribution Company of Mazandaran. The parameters of the fragility function of poles are given in Table 2.

The concrete poles of the network are divided into three types in terms of age: new, medium, and old. Besides, wooden poles are divided into two types of new and old. It should be noted that the probability of failure obtained from Table 2 using Eq. (3) is related to the old wooden poles, and the corresponding probability for new wooden poles is 30% lower than that. In addition, for old concrete poles, the probability of failure is 20% lower than that of old wooden poles, and for medium and new concrete ones, the failure probabilities are reduced by 30% and 40%, respectively.

5.3. Fragility model of network conductors

Data of network conductors' fragility model is shown in Table 3. At high winds, the conductors that are exposed to the storm, are usually more vulnerable than other equipment. Therefore, in this study, the probability of failure of these conductors is increased by 35% compared to the other parts.

5.4. Hardening strategies

The strategies presented in Table 4 are used to strengthen the network. It is assumed that poles with two-higher-order classes comply

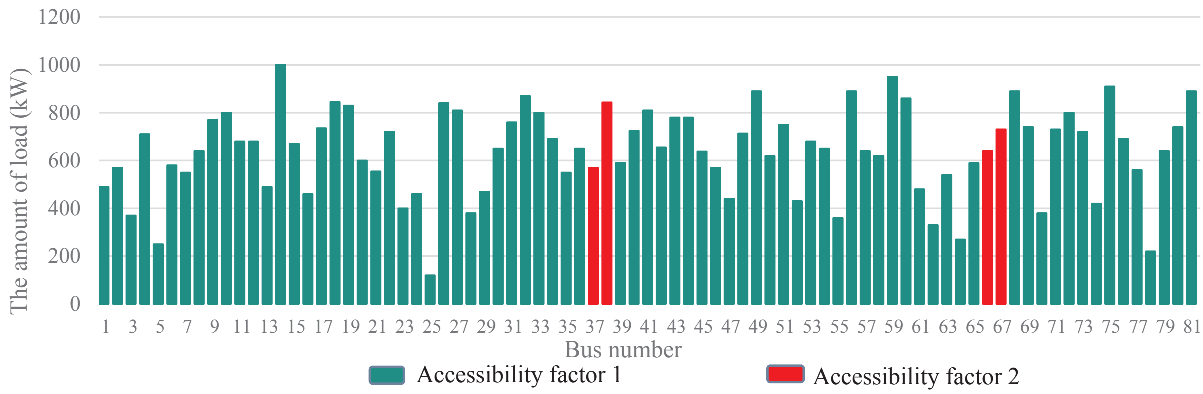


Fig. 8. The load demands of system buses.

Table 1
Storm data.

Weibull function parameters	
u	α
18.22	1.714

Table 2
Data of fragility function of poles.

Function parameters	
A_p	B_p
0.004768	0.07249

Table 3
Data of fragility function of conductors.

Function parameters	
A_c	B_c
0.006727	0.1114

Table 4
Costs of hardening strategies

Cost (USD)	Hardening solution
800	Replacing the concrete pole with the same class pole
1000	Replacing the concrete pole with two higher-order class pole
675	Replacing the wooden pole with the same class pole
800	Replacing the wooden pole with two higher-order class pole
300	Repairing pole
167	Vegetation management of each span

Table 5
Data of fragility function of higher class pole

Function parameters	
A_p	B_p
0.0001	0.0421

with the fragility model of Ref. [34], in which the related data is presented in Table 5.

For the repair strategy, it is assumed that the probability of failure of the poles after repairing is reduced by 30%. For vegetation-involved lines, it is assumed that after tree pruning, the failure probability of these lines is equal to that of normal lines. To investigate the impacts of different strategies, three scenarios are considered.

5.5. Scenario I: Network response before hardening

In the first scenario, none of the hardening solutions are applied to the network, and the network is in its original state when exposed to the extreme weather event. In real cases, different sections of the network have distinct recovery times considering their locations and geographical conditions. Therefore, the repair time of hard-to-access and distant sections of the network is considered twice the repair time of the other sections. Moreover, it is assumed that there are sufficient repair crews to repair different sections of the network simultaneously. Table 6 presents the obtained variables for this scenario. It can be seen that the cost of ENS in this scenario is $875,143.

5.6. Scenario II: First approach of network hardening

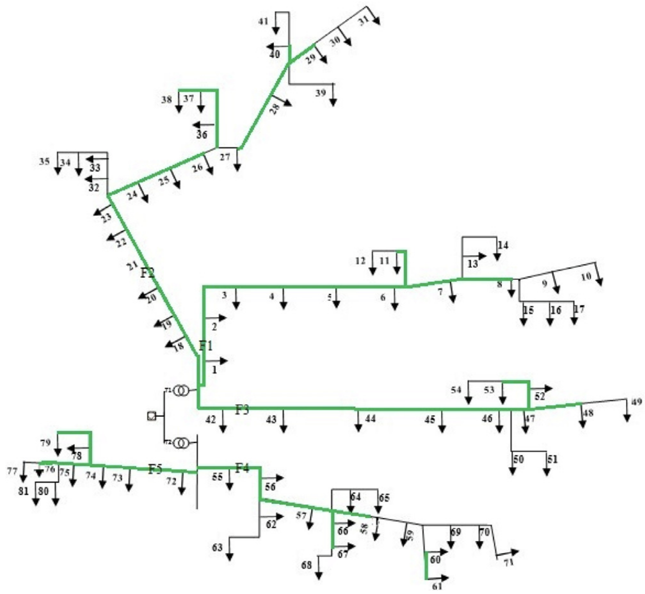
In this scenario, three hardening strategies are used, including vegetation management, replacing old wooden and concrete poles with the same class poles, and refurbishment of defective poles. Moreover, the budget of hardening is set at $100,000. By simulating the model using the flowchart of Fig. 6, the optimal lines for hardening are obtained and shown in green in Fig. 9a. Table 7 also presents the output variables of this scenario. It can be seen that the optimal number of lines selected for hardening is 47 lines, which $99,929 is needed to strengthen them. By strengthening the network using the aforementioned strategies, the cost of ENS is reduced to $580,669, a 34% decrease in the amount of ENS cost.

5.7. Scenario III: Second approach of network hardening

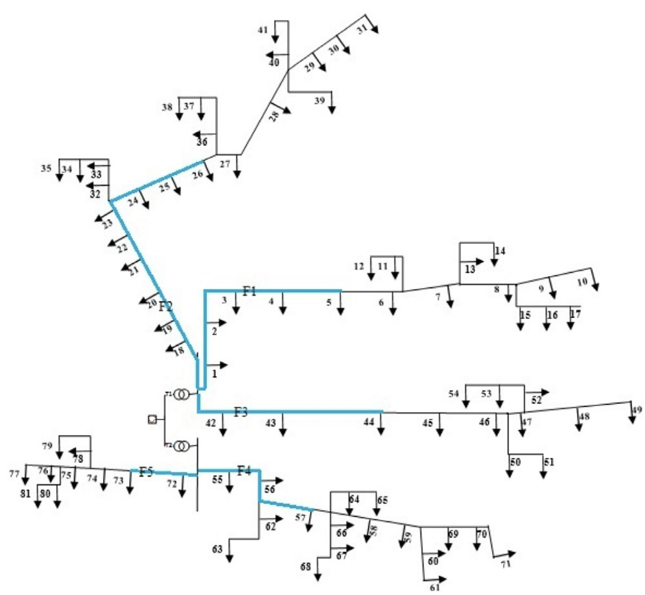
In this scenario, two hardening strategies are used, including vegetation management and replacement of poles with two-higher-order class ones. The optimal lines for hardening are shown in blue in Fig. 9b considering the assumption of the previous scenario. Table 8 also presents the output variables of this scenario. The number of lines selected in this scenario is reduced to 22 lines due to the further cost of hardening strategies, compared to the second scenario, with a total cost of $99,206.

Table 6
The results of the first scenario

Variable	Amount
Expected number of broken poles	81
Total expected repair time (h)	195
Total ENS cost ($)	875,143



a. Reinforced lines in the second scenario



b. Reinforced lines in the third scenario

Fig. 9. The results of different hardening scenarios.

Table 7
The results of the second scenario

Variable	Amount
Expected number of broken poles	60
Number of reinforced lines	47
Total expected repair time (h)	141
Total hardening cost ($)	99,929
Total ENS cost ($)	580,669

5.8. Discussion

In scenario 3, as can be seen from the comparison of Tables 6 and 8, the cost of ENS is reduced by about 50% compared to scenario 1, while in scenario 2, this decline is around 34%. Accordingly, the expected

Table 8
The results of the third scenario

Variable	Amount
Expected number of broken poles	52
Number of reinforced lines	22
Total expected repair time (h)	129
Total hardening cost ($)	99,206
Total ENS cost ($)	429,946

number of broken poles and expected repair time would decrease almost 36 and 34, respectively, by applying the second approach of network hardening. This expresses a better performance, nearly 13% and 8.5%, comparing the first approach. At the same time, the hardening cost for both scenarios is approximately equal. These results demonstrate the lower objective function value for the second approach. Consequently, the proposed approach in scenario 3 is more successful in reducing costs and increasing system resilience. Furthermore, considering the budget limit, the results imply that the system operator can achieve a higher level of resilience with an approximately constant investment by applying more suitable strategies.

Fig. 10 also compares different scenarios using the resilience trapezoid, which can provide a deep insight into the impact of the strategies on the resilience of the system. Resilience trapezoid is actually a curve that represents all the situations the network experiences following a natural event. The index of the number of healthy grid poles is used to draw the resilience trapezoid. Based on the sample real data, the storm is assumed to have 4 h long. Moreover, it is assumed that the repair phase begins 6 h after the end of the catastrophe because, in the emergency situation, the system operator does not have access to sufficient and exact information about the network damages; additionally, the preparing and sending repair crews need enough time. In Table 9, three indices, i.e. R_d, R_r, and A, are extracted with respect to the resilience trapezoid, which represent the slope of the curve during the incident, the slope of the curve during restoration, and the resilience trapezoid area, respectively. According to the results of Table 9 and Fig. 10, it can be seen that the hardening of the network in the third scenario, compared to the second scenario, can improve the resilience of the network more significantly in all parts of the resilience trapezoid. It is also observed that using the resilience trapezoid area index, which is an appropriate indicator for evaluating the overall resilience of the network, the system resilience is greatly enhanced in the third scenario. Therefore, the third scenario is chosen as the best approach for network hardening.

5.9. Sensitivity analysis

To investigate the performance of the proposed hardening algorithm, the ENS value for three scenarios at different wind speeds are compared in Fig. 11. As one can see, at different wind speeds, the strategy of Scenario 3 has better performance. Furthermore, to analyze how changes in hardening budget and windstorm speed can affect the results of the proposed approach in Scenario 3, a sensitivity analysis is carried out. As can be seen from Fig. 12, the increase in the hardening budget can reduce ENS costs associated with the VoLL. As a result, the operator and planner of the system can achieve a higher optimal level of resilience for the network by raising the budget. However, reaching the same level of resilience in higher storm speeds needs more budget.

6. Conclusion

Considering the consequences of severe weather events on distribution networks, this paper presented a framework for evaluating and improving the resilience of these systems. To reach this goal, the network hardening was considered as one of the best strategies to reduce the destructive impacts of storms and hurricanes on the network.

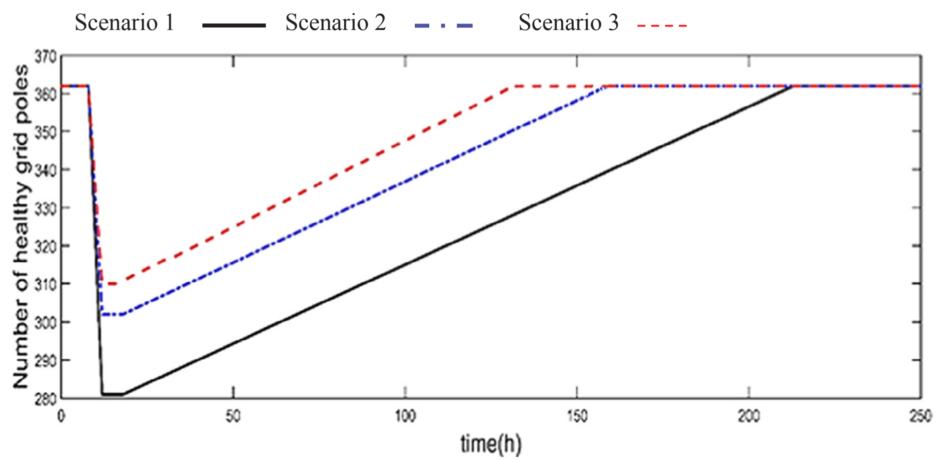


Fig. 10. Resilience trapezoid for three scenarios.

Table 9
Resilience indices for different scenarios

Index	Scenario 1	Scenario 2	Scenario 3
R_d	−20.71	−14.72	−12.85
R_r	0.464	0.475	0.510
A	8545.5	4710.4	3770.2

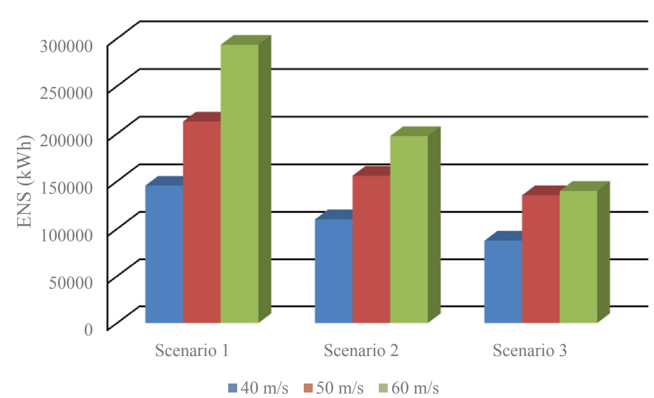


Fig. 11. Comparison of ENS of three scenarios at different wind speeds.

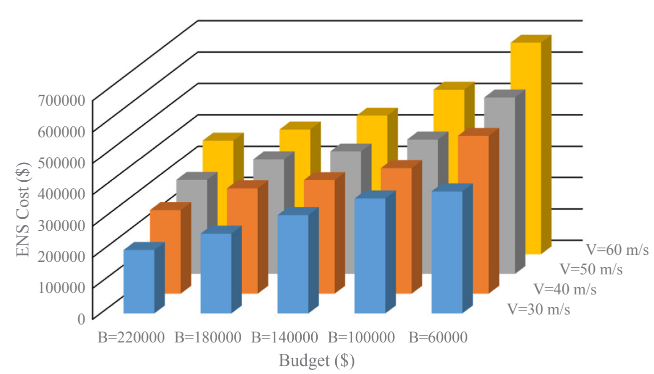


Fig. 12. ENS costs at different budgets and wind speeds for Scenario 3.

In the proposed method, firstly, using network component fragility curves and MCS, the resilience of the network was evaluated. Then, the network hardening problem was modeled in the form of an optimization problem to minimize ENS and component hardening costs subject to the budget constraint. Three hardening techniques, including vegetation management and upgrading and repairing of poles were employed to improve system resilience. After that, a flowchart based on the GA was introduced to solve the proposed model. The problem framework, then was applied to a real distribution network in Iran, and the results were obtained and discussed. Numerical results from different scenarios showed the effectiveness of the proposed approach to evaluate and increase the resilience of real distribution networks.

CRediT authorship contribution statement

Amir Najafi Tari: Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Visualization. **Mohammad Sadegh Sepasian:** Conceptualization, Project administration, Supervision. **Meghdad Tourandaz Kenari:** Conceptualization, Validation, Writing - review & editing.

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 A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijepes.2020.106414.

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