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Resiliency/Cost-Based Optimal Design of Distribution Network to Maintain Power System Stability Against Physical Attacks: A Practical Study Case

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ABSTRACT Unexpected natural disasters or physical attacks can have various consequences, including extensive and prolonged blackouts on power systems. Energy systems should be resistant to unwanted events, and their performance is not easily affected by such conditions. The power system should also have sufficient flexibility to adapt to severe disturbances without losing its full version; it should restore itself immediately after resolving the disturbance. This critical feature of the behavior of infrastructure systems in power grids is called resilience. In this paper, the concepts related to resilience in the power system against severe disturbance are explained. The resilience and evaluation process components are introduced; then, an optimal design of resilient substations in the Noorabad city distribution grid against physical attack is presented. This research proposes an optimal solution for simultaneously allocating the feeder routing issue and substation facilities and finding the models of installed conductors and economic hardening of power lines due to unexpected physical attacks on vital urban operational infrastructure. The values of distribution networks are calculated using the grey wolf optimization (GWO) algorithm to solve the problem of designing an optimal distribution network scheme (ODNS) and optimal resilient distribution network scheme (ORDNS). Obtained results confirm the effectiveness of the proposed resiliency-cost-based optimization approach.

INDEX TERMS Power distribution network, grey wolf optimization, high-impact low-probability event, optimal design, resilience.

I. INTRODUCTION

A. BACKGROUND

Today's society heavily depends on services provided by the power grid infrastructure. When a crisis occurs, these networks often lose their ability to provide services because of damage to network equipment. As a vital infrastructure, the security of power systems is recognized as a global challenge closely linked to society's stability and the improvement of economic conditions. Therefore, it has always been one priority of different authorities, organizations, and social institutions at different levels. The explanation given is that the power system as a valuable and vast capital profoundly affects human life. High-Impact Low-Probability (HILP) accidents of occurrences have increased concerns about the usual reliability and resilience-oriented approach [1]–[5]. Coping with unexpected and rare difficult situations is recognized as a significant challenge. As a vital infrastructure, the power system is expected to be far more resilient to HILP events. Resilience is called the power

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system's ability to effectively withstand HILP events to ensure a definite minimum possible power supply and rapid restoration to regular operation [6]. Thus, different parts of society pose challenges to improving network responsiveness to HILP events.

As soon as the power system's security is severely affected by different threats, the power system may be subdivided into several zones, and large zones may face global blackouts. As a result, there is widespread economic loss and, sometimes, human life and even national privacy and security. Many similarities in recent blackouts are seen in various references [7], [8]; for example, on 4 November 2006. A blackout in the west part of the Union for the coordination of the transmission of electricity (UCTE) network resulted in a severe deviation of frequency resulting in the division of the entire network into three zones and interruptions in supplying the needs of over 15 million European home subscribers. Besides, in recent decades, human life has found a growing dependence on integrating interdependent systems on a large scale. As a source of energy for other infrastructures, electricity is centrally located and plays a vital role in other systems [9].

A good example was an American blackout in 2003; water pressure dropped sharply due to the lack of back-up power due to the lack of electric pumps. All New York-bound trains stopped, the mobile telecommunication equipment was disrupted, and the cable television system was shut down [10]. Various threats have long been recognized and investigated to ensure the security of power systems [11]. These threats that cause an outage of the power grid include a range of internal and external factors (including natural disasters, technical errors, human failures, sabotage, terrorism, or even war) [12]. Potential threat factors include accidents, line breaks, bus breaking, or overload; this might cause the power failure and the possibility of power outages. Conventional hazards to power systems usually are divided into two different categories: natural disasters and accidental hazards [13]. Natural threats are caused by adverse climatic conditions, including heat waves, tornadoes, lightning, and geological hazards such as volcanic eruptions and earthquakes, tsunamis, and landslides, accidental hazards as errors in performance, failure to maintain, impairment of equipment. With the increasing importance of power systems, it has gradually become a favorite victim of malicious threats. Destructive hazards refer to terrorism and crimes, such as attacks, insurgency, product manipulation, explosions, and bombings [14]. With the evolution, development, and transition of the power system, threads such as cyber-attacks have emerged. In recent years, the rapid advancement of technology in power electronics, computers, information technology, and materials has been promising for the ever-expanding power system [15]–[19]. Also, varieties in power systems technology have created an increasing chance for emerging threats to system security. Besides, the threat posed by human attacks on power systems in recent years has become more serious [20]. For instance, the deployment of communications-based intelligent network equipment to make them more manageable has increased the possibility of cyber-attacks [21]–[24], and the growing share of renewable energy sources (RESs) with the alternating nature of power supply has altered the system and posed a variety of security challenges [25]–[29]. Also, recent research focuses on this issue; for instance, in papers [30], [31], authors proposed different strategies, including natural disaster modeling, equipment vulnerability and grid resilience analysis, and grid resilience enhancement. Paper [32] presented the benefits of having sections micro-grids (MGs) to manage distributed energy resources (DERs), to develop power grid resilience to HILPs.

Therefore, there is a fundamental need to categorize and evaluate the system security considerations' current and emerging threats. A critical drawback of previous research is the lower speed for step-by-step load restoration in the power network to maintain its stability. This paper's significant advantage is to provide optimal scheduling of resilient substations in the real power distribution system to lower operational costs in both standard and critical operational modes with higher performance speed. Another advantage of the proposed resilience strategy is to provide minimal load curtailment in the crucial physical attack mode, considering priority given to critical loads. Also, the suggested method can restore total blackout or local outage.

B. MOTIVATION AND MAIN CONTRIBUTION

Hardening is the physical change of infrastructure to make it less prone to high-impact, low-probability damage. However, hardening transmission systems models cannot be used directly in power systems' resilience, as most distribution systems have a radial network-like tree configuration. In contrast, transmission grids are usually more interconnected than lattice grids. Therefore, this research is designed to present a comprehensive analysis of the flexible scheme of distribution networks. This study's significant contribution is to find an optimal solution for simultaneously allocating the feeder routing issue and substation facilities and finding the models of conductor's installation and the economic hardening techniques in power lines due to malicious attacks on vital urban operational infrastructure (VUOI). The characteristics in normal and resilience modes of distribution systems are calculated using the grey wolf optimization (GWO) algorithm. To solve optimal design problem in two different modes: optimal distribution network scheme (ODNS) and optimal resilient distribution network scheme (ORDNS). The proposed technique is applied to an actual study case (Noorabad City, Iran), comprising different distributed and renewable generations, substations, transmission and distribution lines, and consumers. Obtained results confirm the effectiveness of the proposed approach.

C. PAPER STRUCTURE

The rest of this research study is formed as follows: Section II defines resilience issues in power systems and introduces a hardening strategy in power systems; in Section III, problem formulation of a resilient network is provided. Also, the problem constraints of the proposed method will be introduced. Section IV provides the study's simulation results, and finally, the conclusions are stated in Section V.

II. DEFINING RESILIENCE ISSUES IN POWER SYSTEMS

A. INTRODUCING PERFORMANCE INDEX (PI) IN A RESILIENCE POWER SYSTEM

To evaluate a power system's resiliency, first, quantitative indicators should be defined and calculated to describe features' components. Figure 1 shows a typical Performance Index (PI) of the power system in terms of time and the event of a severe disturbance. In defining the PI, a system's load can be considered its goal. Depending on the need, the value of the remaining loads on the grid. The number of healthy and electrified equipment in the system may be selected as an indicator of system performance.

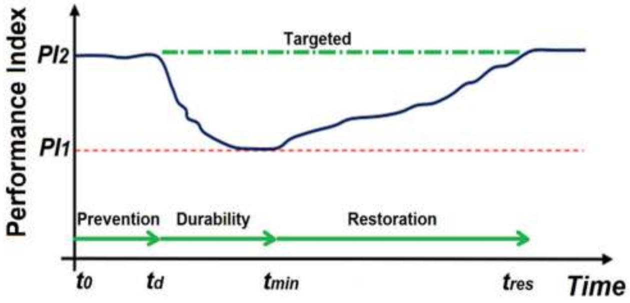

FIGURE 1. **A typical Performance Index (PI) of the power system.**

As can be seen from Figure 1, the curve shows well that the restoration or resilience process of the grid is not exponential or linear with a fixed slope in practice. Also, system performance does not decrease rapidly after the disturbance t_0, and given the amount of endurance it has, it may take a while for system performance to decline. This stage of system behavior can be called the prevention phase, depending on the user's operational status and the network's strength. Whatever the network operator is aware of the danger that threatens the system and what is happening and has enough knowledge and experience to deal with this condition, it will take longer to decline system performance. Therefore, the duration $t_d - t_0$ can be considered a quantitative indicator to describe the quality of the prevention phase. As the system's performance falls, the system enters a sustained phase until the situation is adjusted to the new situation. The degree of network vulnerability measured in terms of the maximum loss in the network's performance relative to its value in the normal case depends on the degree of system adaptation to perturbation. As system compatibility increases, performance drops lower, and vulnerability decreases. Equation (1) gives a quantified normalized indicator (QNI) to describe the system's exposure to a disturbance.

$$QNI = \frac{PI_2 - PI_1}{PI_2} \tag{1}$$

The restoration phase begins after the conditions are established in the post-accident situation. The operator rearranges the network and retrieves the offloads. Restoration time can also be an indicator that describes the restoration process's quality after a specific disturbance. Finally, in measuring the whole restoration process by a quantitative index, it can the normalized index is shown in equation (2).

$$R(T) = \frac{\int_0^T P_R(t)dt}{\int_0^T P_T(t)dt} \tag{2}$$

where $P_R(t)$ is the actual value of the PI at moment t, and $P_T(t)$ is the optimal value of the PI at moment t.

Experiences from natural disasters show that conventional power systems have been fragile systems due to the geographical extent of the disaster due to the type of equipment architecture and central control network. The destruction of less than one percent of their equipment can lead to significant outages. Therefore, it is projected that regions with a larger power system grid are more likely to experience a higher proportion of exit. In this way, the network may not be available for critical load lines and neighboring areas for days to weeks. This may not be the case for all disasters or all areas. Still, there is evidence of such activity worldwide following various disasters such as Hurricane Katrina, the Sichuan China earthquake, Japan earthquake, and tsunami [33]. The resilient power system should be able to overcome disorders with HILP of occurrence. Based on the experiences gained from recent natural disasters, the essential features of such events that distinguish them from conventional power system errors are as follows:

- The timing and duration of these disorders are strongly associated with uncertainty and may take days.
- They are entirely dynamic, and it is challenging to predict future events or sequences effectively.
- Their occurrence may cause multiple equipment failures within a short time; for instance, transmission and distribution facilities such as substations, transmission lines, and towers may be damaged.
- Power sources may not be accessible or available.

Because of the features mentioned above, to have a resilient system, the system in question should have the following characteristics:

- Due to high uncertainty, diversification of supply sources should be maximized and avoid dependence on a limited set of power supplies.
- There should be sufficient flexibility to respond quickly to events and to adjust operating procedures even during short times.
- Due to the scarcity of resources, priorities for supplying different loads should be identified.

Long-term actions refer to long-term adaptation planning to enhance system resilience to climate-related

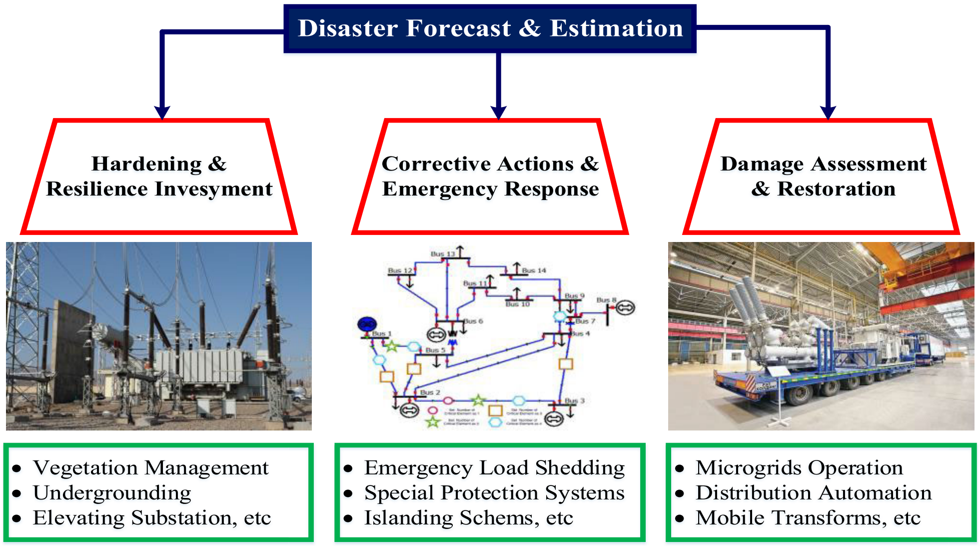

FIGURE 2. Temporal response of the power system to natural disasters.

events and climate change. The essential parts of these actions include:

- Risk assessment and management to measure and prepare for such events
- Accurate estimation of the probable location of the event and its severity
- Upgrading emergency preparedness plans
- Tree pruning and vegetation management to clear the transmission lines along the way
- Under grounding distribution and transmission lines
- Upgrading equipment with stronger materials
- Increasing the redundancy of transmission routes by the construction of new transmission facilities
- Redirecting transmission lines to areas less affected by adverse weather conditions
- Upgrading switchgear posts and installations to more minor flood-prone areas
- Warehousing and maintenance of towers and backing materials
- Increasing visualization and environmental awareness through advanced monitoring and forecasting tools

The impact of HILP events on the power system and its subsequent economic and social hazards has created a fundamental need globally to raise power systems' resiliency [34]. Figure 2 summarizes the temporal response of the power system to natural disasters.

B. MAKING RESILIENCE POWER SYSTEMS

The threats that may affect the energy system's resiliency vary depending on the likelihood of occurrence—the severity of the consequences, the predictability, and the availability of technologies. Meanwhile, electricity infrastructure and assets are usually divided based on performance between generation, transmission, and distribution systems. Each of them has a physical scope and vulnerability to threats and different governance patterns regarding ownership and management responsibility. Identifying a more systematic resiliency framework and specific criteria that can be used to monitor and evaluate resiliency in the electricity system is a rapidly evolving research field.

III. MATERIALS AND METHOD OF MAKING GRIDS AND SUBSTATIONS RESILIENT

The primary objective should be to provide sufficient electrical energy to consumers with the lowest possible cost and required standards. From the asset management point of view, economic strategies should be implemented to reduce the impact of various threats on their assets and continuously meet consumer demand, especially in critical situations. The Objective Function (OF) should include normal and critical operating conditions. Therefore, the proposed OF is given by:

$$\begin{aligned} OF = \min(Total\_Expense) &= E_{substation} + E_{feeder} \\ &+ E_{loss} + E_{reliability} + E_{resiliency} \end{aligned} \quad (3)$$

A. SUBSTATION INSTALLATION COST

This article assumes that the substation location, location, and number of loads are specified. Therefore, the total energy supply of loads and losses should be provided by the substation. The capacity of the substation should be determined by solving the ORDNS problem. The cost of installing the substation is given in (4).

$$\begin{aligned} E_{substation} &= E_{ground} + E_{construction} + E_{transformer} + E_{equipment} \\ &= E_{substation/MVA} \times MVA_{sub} \end{aligned} \quad (4)$$

Substation cost is often due to land acquisition, construction, the transformer's expense, and equipment expense. Therefore, the substation cost can be calculated by multiplying the cost of installation per megawatt-amp at the capacity of the substation by MVA. Hence the total cost of substation 690000.67 is assumed in this paper.

In this work, to calculate the cost of installing a feeder, a method for designing a distribution network at minimum costs is presented. Feeder routing is determined by searching through all candidate routes and considering limitations, including voltage drop and geographical constraints. In the proposed approach, the GWO algorithm is used to find the optimal path of feeders. Also, the current limit of the feeders is determined during optimization. It should be noted that the feeder's cost will be proportional to the length of the feeder and for a specific type of cable conductor. Therefore, due to limited financial resources, the minimum budget is assigned to improve the distribution network's resilience with the optimal retrofitting of network lines.

The installation of ground feeders requires more investment due to the cost of land buried in Kabul, the crew's high work, and the long process. Also, due to limited financial resources, it is assumed that the design can be accepted if the cost of installing the feeder, increased by a maximum of 20% compared to the cost of conventional feeders.

$$E_{feeder} = \sum_{n} (yE_{oh_{f/km}} + y'E_{ug_{f/km}})M_n \tag{5}$$

where M_n is the feeder length n, $E_{oh_{f/km}}$ represents the expense of installing one kilometer of overhead line, and $E_{ug_{f/km}}$ gives the cost of one kilometer of ground cabling; y and y' are binary variables that represent the type of feeder. Table 1 provide characteristics of overhead lines used in the real case study (Noorabad city of Fars in Iran).

TABLE 1. Characteristics of overhead lines.

Type of conductor	R (ohm/km)	X (ohm/km)	Current (A)	Cost ($/ km)
1	0.74	0.1745	60	7933.33
2	0.4793	0.1672	83	10266.66
3	0.307	0.1595	113	14000
4	0.1971	0.1495	155	19600
5	0.722	0.1441	207	25200
6	0.1207	0.1260	302	39666.66
7	0.0722	0.1216	399	58333.33
8	0.0486	0.1195	452	65333.33
9	0.0404	0.117	499	77000
10	0.0246	0.113	644	102666.66
11	0.018	0.10	699	126000
12	0.016	0.08	849	144666.66

Reducing the cost of network losses is a key goal for utilities and consumers. Therefore, a network structure that can significantly reduce losses has attracted a lot of attention. The result is reduced losses, energy savings, and improved distribution network operation. In the transmission network, the X/R ratio is often high, so the impact of resistance could be denied, but in the distribution network, the X/R ratio is usually high and brings a large voltage drop, leading to large losses during the distribution feeders. By decreasing losses at all levels of the power system from production to the final subscribers, electricity's final cost is reduced. Thus, the economic increase of electric companies would be faster. Also, from the electricity market point of view, low losses increase electricity companies' efficiency. The equations for calculating the cost of losses are presented as follows [35], [36].

$$P_{loss} + jQ_{loss} = \sum_{n} I_{(n)}^2 \times (R_{(n)} + jX_{(n)}) \tag{6}$$

$$E_{loss} = [(P_{loss} \times E_{P-loss}) + (Q_{loss} \times E_{Q-loss})] \tag{7}$$

where P_{loss} is an active power loss, Q_{loss} provides reactive power loss, $R_{(n)} + jX_{(n)}$ represents the impedance of line n; E_{P-loss} is the expense of active losses, and E_{Q-loss} gives reactive losses.

B. RELIABILITY EXPENSE

In today's daily life, it should be noted that distribution networks are recognized as the basic infrastructure in the supply of energy demand. Given that human or natural errors and the occurrence of outages are normal in the power system, distribution companies meet the demand of their consumers even in the event of errors, so interruptions must be calculated for all subscribers. Reliability can be calculated based on the amount of fault in every branch, the number of loads interrupted in the occurrence of a fault. Besides, the estimation of the load not supplied (LNS) is based on interruptions. Therefore, it should be considered $E_{Reliability}$ as an influential factor in the study. The low value of this index guarantees the level of stability of the power system performance.

$$E_{Reliability} = \sum_{n} r_n \times \lambda_n \times E_{LNS} \times LNS_{(n)} \tag{8}$$

where, r_n represents the time of repair for feeder n (h), λ_n provides the rate of failure for feeder n (fail/km/year), E_{LNS} gives the expense of reliability for unsupplied power ($/kWh), and $LNS_{(n)}$ represents the not supplied load because of the outage in the feeder n. One crucial point here is that the amount λ_n and r_n varies between the overhead line and underground line.

As mentioned earlier, attackers usually attack vital urban operational infrastructures (VUOIs) that cause the most damage. The attacker's purpose is often to disrupt crisis management and bring unrest and fear to the community. The crisis conditions will be much more severe if the electricity distribution grid is destroyed, and therefore, there is a widespread power outage. It causes extensive financial damage and may endanger human life and national security. Therefore, the power system must experience the least failure after every internal or external hazard. From the perspective of the distribution grid, installing and repairing damaged equipment and the cost of removed load can a suitable measure to show the network's level of resilience. Due to the time required to repair or replace equipment, so the costs should be considered.

When the distribution network is affected, the required crew and facilities should be at the shortest distance from the site with the most damage to minimize the cost of repairing and replacing equipment. Because of human response, the delay of his action after the occurrence of an event has been considered. It is assumed that any equipment's repair or replacement time varies depending on the model (bus load or line) and its capacity.

As mentioned earlier, attack modeling is defined by different scenarios, and the VUOI defines each strategy under attack. The cost-benefit assessment of the attacker obtains every approach's probability, and the likelihood of every process differs from the other. Given the status quo, equation (9) gives the cost of the resilience of the system.

$$E_{Resilience} = \sum_{s} \pi^{s} \times (LSE_s + RDE_s) \tag{9}$$

where, LSE_s represents the expense of load shedding, RDE_s provides the expense for repair and replacement of damaged equipment in approach s. π^s also represents the probability for approach s.

C. LIMITATIONS

1) LOAD DISTRIBUTION EQUATIONS

In this part, load flow equations are presented as a constraint on implementing the proposed method. So the following equation is presented as:

$$P_{sub} - \sum_{i} P_{load,i} - V_i \sum_{k=1}^{N_{bus}} V_k Y_{ik} \cos(\delta_i - \delta_k - \theta_{ik}) = 0 \tag{10}$$

$$Q_{sub} - \sum_{i} Q_{load,i} - V_i \sum_{k=1}^{N_{bus}} V_k Y_{ik} \sin(\delta_i - \delta_k - \theta_{ik}) = 0 \tag{11}$$

where, i displays the number of buses.

2) SUBSTATION VOLTAGE ANGLE

Another important limitation that should be considered is voltage and its angle. As a result, the following equation is presented:

$$V_{sub} = 1p.u. \tag{12}$$

$$\delta_{sub} = 0 \tag{13}$$

3) VOLTAGE LIMITATION SATISFACTION

Voltage limitation satisfaction is usually planned as an error function; therefore, it is better to keep the voltage in a normal (safe) condition so that it is not violated. The voltage limits satisfactions (normal and critical conditions) for the bus i in scenario s are defined as follows:

$$\mu^{V}_{i,s} = \left\{ \begin{array}{c} \dfrac{V_{i,s} - V^{\min}_{critic}}{V^{\min}_{norm} - V^{\min}_{critic}}, \; V^{\min}_{norm} \le V_{i,s} \le V^{\max}_{critic} \\ 1, \; V^{\min}_{norm} \le V_{i,s} \le V^{\max}_{norm} \\ \dfrac{V_{i,s} - V^{\max}_{critic}}{V^{\max}_{norm} - V^{\max}_{critic}}, \; V^{\max}_{norm} \le V_{i,s} \le V^{\max}_{critic} \\ 0, \; else \end{array} \right\} \tag{14}$$

where, $V^{\min}_{norm} = 0.95$, $V^{\max}_{norm} = 1.05$, and $V^{\max}_{critic} = 1.10$.

Due to the different network scenarios in question, there are several satisfaction levels for the desired bus. Therefore, the weighted average of satisfaction is necessary to obtain an index that shows the bus condition I as:

$$\mu^{V}_{i} = \sum_{s} \pi^{s} \times \mu^{V}_{i,s} \tag{15}$$

Finally, the best way to get the whole grid voltage condition index is to compute the average value μ^{V}_{i} for all buses, which is given as:

$$\mu^{V} = \frac{\sum_{i} \mu^{V}_{i}}{Buses.No} \tag{16}$$

4) FEEDER LIMITATIONS

The value of the feeder current μ^{l} and the voltage are similar in the calculations. But with current, there is only a high limit for the feeder current. According to the voltage and current constraint modeling, the limitations are soft, and each violation is added to the objective function as follows. Therefore, the expense of technical dissatisfaction (ETD) is calculated by:

$$ETD = dc \times \max \left\{ (1 - \mu^{V}), (1 - \mu^{l}) \right\} \tag{17}$$

where, dc represents dissatisfaction cost.

IV. SIMULATION RESULTS

In this section, the simulation's results on the real power distribution network of Noorabad city of Fars in Iran-based on the proposed method are presented. Figure 3 displays the absolute configuration of the power distribution network of Noorabad city. A graphical image of the power distribution grid is shown in Figure 4, where the substations' places are known, and the optimal size should be obtained. Also, the size and position of the loads (kW and kVar) have been specified.

MATLAB software is also used to perform simulations using the GWO algorithm and prepare results. In this section, the optimal distribution network design is done for two modes: optimal conventional distribution network scheme (ODNS) and optimal resilient distribution network scheme (ORDNS). In both cases, the substations' capacities, feeder paths, and type of feeders installed are optimized. Also, the optimal ORDNS determines the reinforced lines. For ensuring the feasibility and efficiency of the presented approach, it has been performed on a relatively large distribution grid. So, the goal function includes several cases that GWO algorithms have solved.

It should be noted that all the restrictions in the final network are considered. Figure 5 shows the candidate routes for distribution network design and the location of VUOIs, where the red circle displays the radius of destruction. The conventional configuration routes of main lines are provided in Table 2. As can be seen from Table 2, we have 79 main lines in the basic configuration.

A. OPTIMAL DISTRIBUTION NETWORK SCHEME

This section presents the conventional network design of the above distribution substation network in ODNS mode. In this method, the substation's optimal capacity is determined from

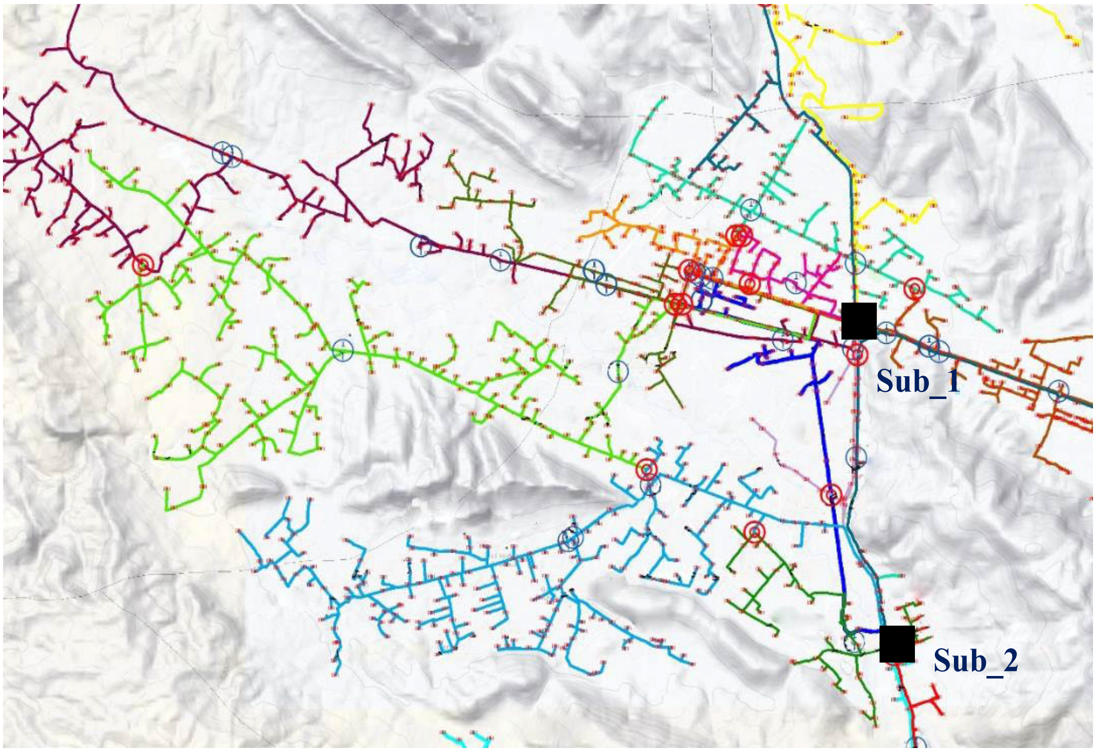

FIGURE 3. Real configuration of the electricity network of Noorabad city.

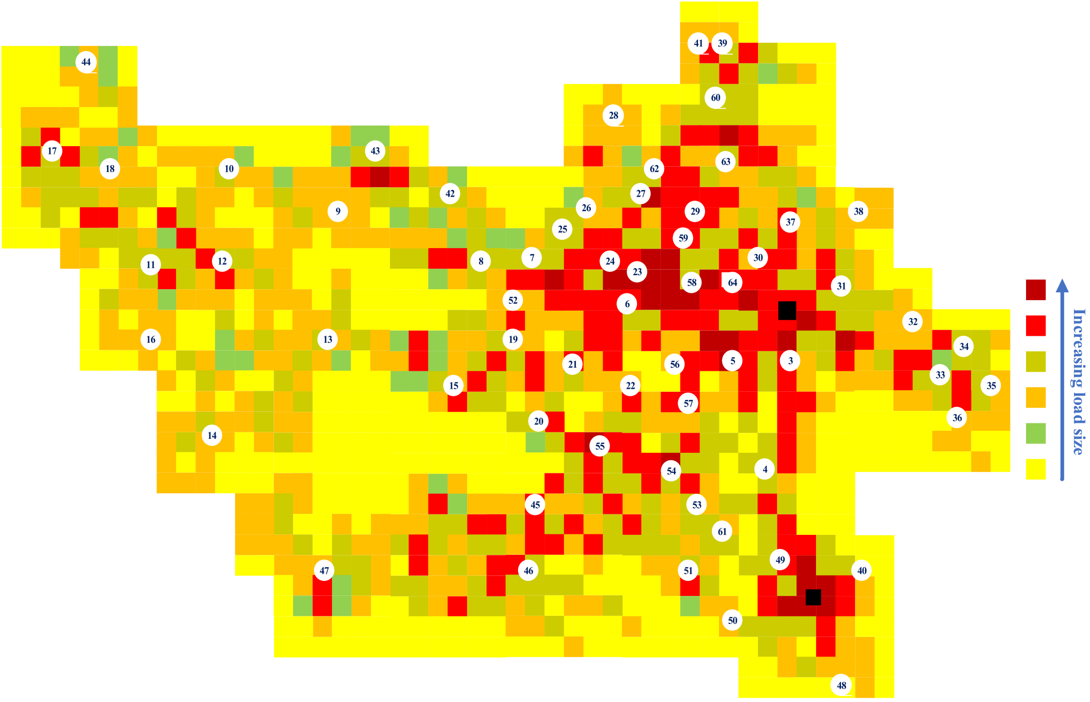

FIGURE 4. A graphical image of the real study case network (Noorabad city).

reliability economics, simultaneously with the feeders' path and feeders' type. As can be seen, all the loads are fed by post, and the final grid structure is tree-like and radial.

Voltage amplitude should be considered a critical indicator that affects the distribution grid in terms of load distribution, losses, power quality, and voltage stability. Therefore, the voltage range is defined as limiting the final answer to keep the bus voltage within the standard range. For proving that the voltage is within the allowable range, the following figure has been prepared. Figure 6

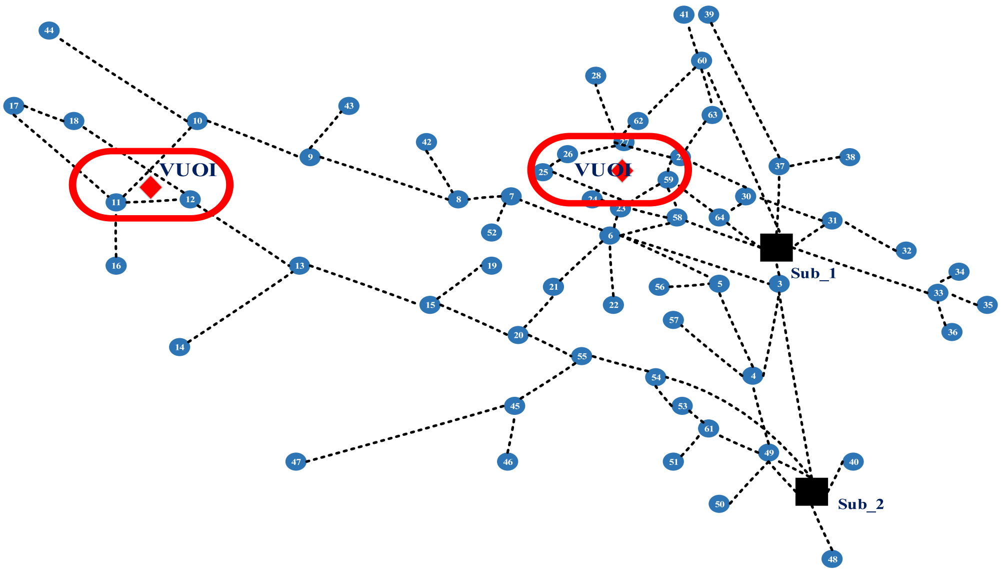

FIGURE 5. The candidate routes and the location of VUOIs for the distribution network scheme.

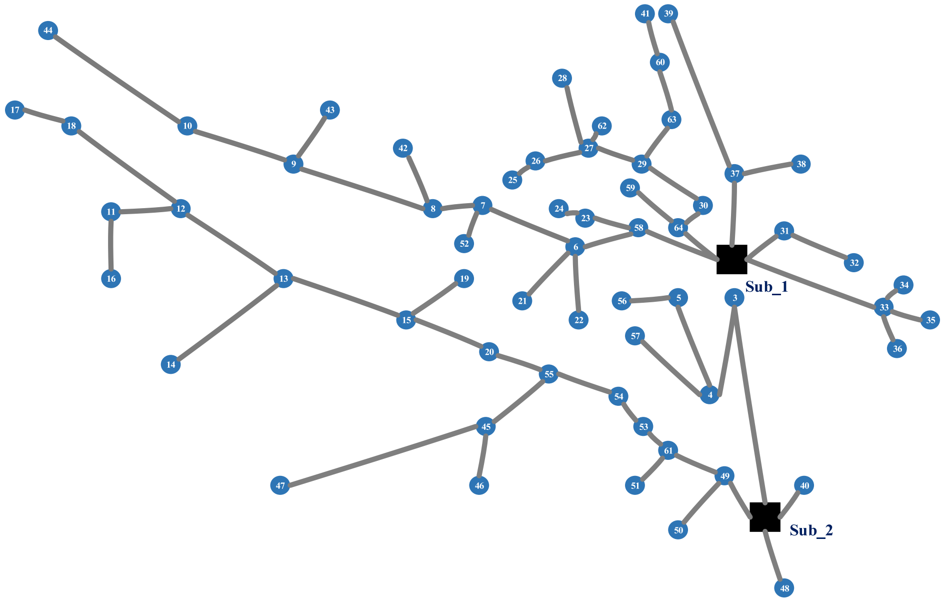

FIGURE 6. The configuration of ODNS.

displays the configuration of ODNS. The configuration routes of prominent lines for the ODNS method are provided in Table 3. Figure 7 depicts the optimal results of bus voltages for ODNS. The bus voltage amplitude is given per unit (pu).

B. OPTIMAL RESILIENT DISTRIBUTION NETWORK SCHEME

The results related to the resilient design of the above ORDNS distribution substation's power supply network are presented in this part. The purpose of ORDNS is to determine the substation's optimal capacity and, at the same time, the feeder path, the type of feeders installed, and the reinforced lines. In this regard, the GWO algorithm has converged to an answer that effectively reduces the defined objective function.

As can be seen, the defined objective function includes the economics-reliability design of the ODNS and distribution network resilience issues. Figure 8 displays the optimal configuration for ORDNS. As can be seen from Figure 8, the network structure obtained from ORDNS is radial. Also, some lines are shown in brown. The proximity of these lines to VUOIs that are physically attacked has led to the selection of these lines as terrestrial. Loads in crises are fed through the local network. Like ODNS, the voltage range of the buses is shown to confirm the effectiveness of the presented approach within the allowable range.

TABLE 2. The conventional configuration of main lines.

Line number	From (bus number)	To (bus number)	Line number	From (bus number)	To (bus number)
1	Sub 1	58	41	9	43
2	Sub 1	64	42	9	10
3	Sub 1	60	43	10	44
4	Sub 1	37	44	10	11
5	Sub 1	31	45	11	17
6	Sub 1	33	46	11	16
7	Sub 1	3	47	Sub 2	49
8	31	32	48	Sub 2	54
9	33	34	49	Sub 2	40
10	33	35	50	Sub 2	48
11	33	36	51	Sub 2	3
12	30	29	52	49	4
13	37	38	53	49	50
14	37	39	54	61	53
15	58	6	55	61	51
16	58	59	56	4	3
17	29	27	57	4	5
18	27	28	58	4	57
19	27	26	59	5	56
20	26	25	60	54	55
21	63	60	61	55	20
22	60	41	62	20	21
23	60	62	63	20	15
24	58	59	64	15	19
25	58	23	65	55	45
26	23	24	66	45	47
27	6	22	67	45	46
28	6	7	68	15	13
29	7	52	69	13	12
30	7	8	70	13	14
31	8	42	71	12	18
32	8	9	72	27	62
33	31	30	73	23	25
34	64	30	74	6	23
35	64	59	75	6	3
36	29	59	76	6	5
37	29	63	77	6	21
38	59	23	78	18	17
39	49	61	79	11	12
40	53	54			

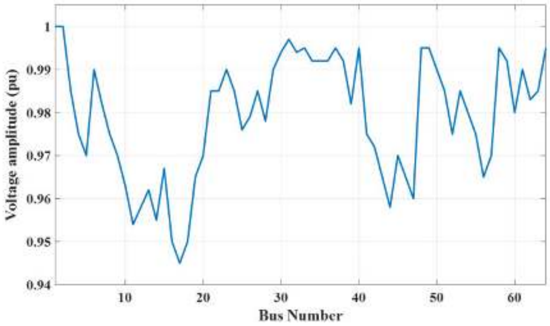

FIGURE 7. Optimal results of buses voltages for ODNS.

The configuration routes of main lines for the ORDNS method are provided in Table 4. Figure 9 depicts the optimal results of bus voltages for ORDNS.

C. COMPARISON BETWEEN ODNS AND ORDNS

As mentioned earlier, resilience refers to the system's ability to withstand low-probability events - high destructive power. Besides, the distribution grid is a vast and valuable asset that greatly impacts human life. Therefore, different companies make great efforts to make their network resilient to HILP events. As a result, the basic need for a method that can determine the optimal investment for retrofitting is essential. This method can have high savings and can also improve network resilience. The main obstacle to promoting resilience is the limited financial resources of companies. It seems that the transition from ODNS to ORDNS should be cost-effective. Therefore, cost increases should be a constraint on optimization. Figure 10 displays a comparison of resilience for different scenarios in the transmission line online. Also, Table 5 compares the results of costs for ODNS and ORDNS. As shown in Figure 10, the resilience in conventional, ODNS, and ORNDS modes is compared. It has been demonstrated that ONDS resilience is higher than traditional resilience and ORNDS resilience is higher than the other two modes, which reflects the fact that the proposed optimization scheme has higher and better resilience than different modes.

TABLE 3. The configuration of main lines.

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

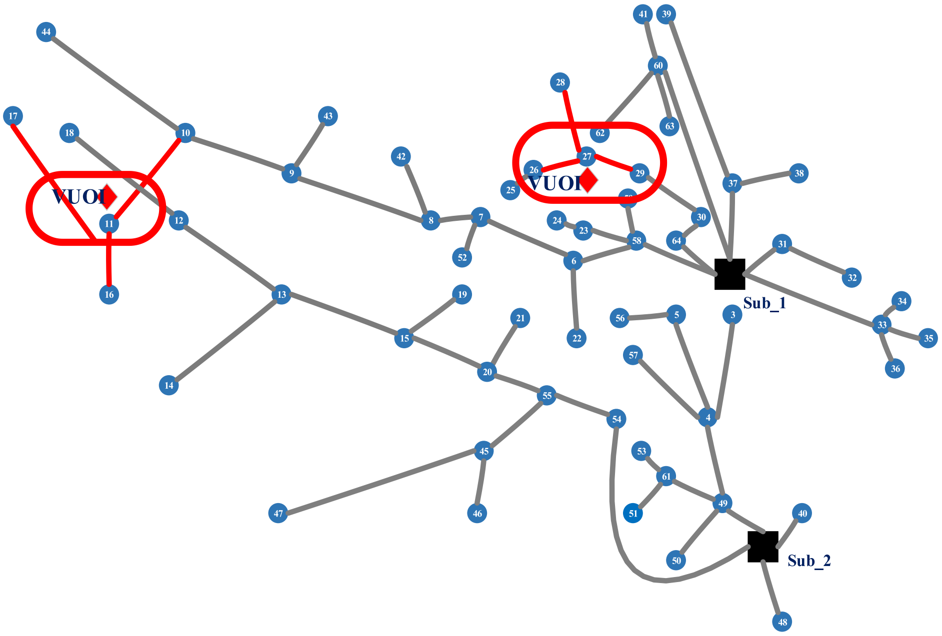

FIGURE 8. Optimal configurations for ORDNS.

The reinforcement of the lines raises the cost of installing feeders in ORDNS compared to ODNS. The impact of reliability and resilience costs on the goal function has led optimization to seek a network that often delivers critical loads close to VUOIs. Also, the reinforcement of long lines is more expensive. These reasons may justify the high cost of feed in the ORDNS approach. Besides, the above reasons have limited search space during ORDNS optimization.

TABLE 4. The configuration of the main lines.

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

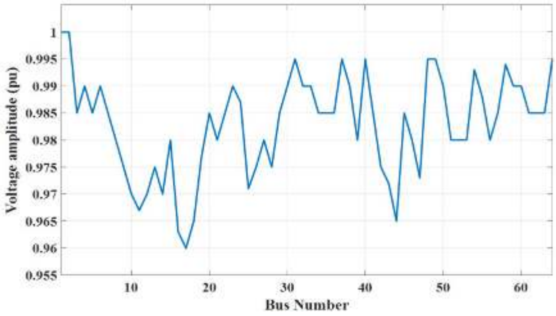

FIGURE 9. Optimal results of buses voltages for ORDNS.

TABLE 5. Comparison of costs between ODNS and ORDNS.

Values ($)	ODNS	ORDNS
Cost of substation	690000.67	690000.67
Cost of feeder installation	124844.45	133111.12
Cost of loss	162611.12	137055.56
Cost of reliability	160711.12	126311.12

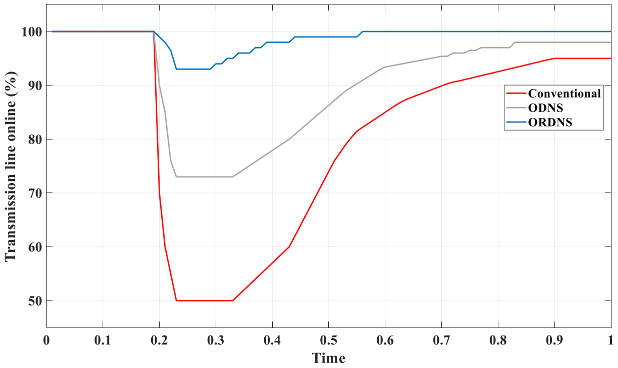

FIGURE 10. A comparison of resilience for different scenarios in transmission line online.

Table 6 compares the load flow results, analysis of losses, and energy not supplied (ENS) between ODNS and ORDNS methods. As shown in Table 6, the load flow results in ORDNS mode in substation-1 and substation-2 have lower energy losses, ENS, and peak power losses than ODNS. Also, the peak voltage minimum is closer to one than ODNS, which indicates the superiority of ORDNS compared to ODNS.

Another critical point is that the final network should keep the voltage within the allowable range. Furthermore, the cost of its power losses affects the goal function.

Given these facts and due to the limited search space, feeders should be selected from a type that has a high flow rate. Feeders with high current limits have low resistance and reactance, resulting in a low voltage drop across the feeder. As a result, the voltage profile is improved, and the losses are reduced. Instead, the cost of feeding is increased.

TABLE 6. Comparison of load flow, losses, and energy not supplied between ODNS and ORDNS.

Value	Peak input current (A)	Peak input active power (MW)	Peak input power factor (%)	Peak load maximum (%)	Peak voltage minimum (pu)	Peak power losses (MW)	Input energy (MWh)	Energy losses (MWh)	ENS (MWh)
ORDNS (Feeder Sub-1 to Bus 64)	163.2	9.15	92.87	55	1.007	0.1864	20432.6	470.23	12.386
ODNS (Feeder Sub-1 to Bus 64)	227.3	12.1	91.64	72	1.012	0.27	26814.8	627.33	13.528
ORDNS (Feeder Sub-2 to Bus 54)	128.2	6.86	91.77	51	1.008	0.161	16050.4	193.91	10.739
ODNS (Feeder Sub-2 to Bus 54)	148.3	7.94	91.68	58	1.01	0.169	174.95.1	210.26	11.472

From the reliability perspective, the overhead lines are more reliable. The presented results confirm the fact that the cost of unsecured energy in ORDP is lower. The results demonstrate the proposed method's effectiveness, which ultimately leads to a proper network structure from a technical point of view, reliability, and resilience. Also, the cost of implementation is minimal. Given the geographical limitations, the proposed approach is implemented on a real power distribution grid of Noorabad city in Iran, whose information is derived from GIS.

V. CONCLUSION

A power system should be designed to be resistant to different unexpected events, such as natural disasters or cyber or physical attacks with high-impact low-probability (HILP) effects on the network's stability. At the same time, the system should also have sufficient flexibility so that it can adapt to a severe disturbance without losing its full performance. Besides, it should restore itself immediately after resolving such a disturbance.

In this paper, the concepts related to resilience in the power system against severe disturbance were explained, and the components of this concept, its evaluation process were introduced. The optimal design of resilient substations in a real-power grid (Noorabad city) against physical attack to maintain network stability was presented. This paper proposed an optimal solution for simultaneously allocating the feeder routing issue and substation facilities and finding the types of installed conductors and economic hardening of power lines due to physical attacks on a vital urban operational infrastructure. The distribution network parameters were calculated using the GWO algorithm to solve optimal functional forms, including optimal distribution network design and optimal resilient distribution network design modes. The effectiveness of the proposed resilience method was confirmed according to the analysis of the obtained results.

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