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Reliability Assessment Based on Optimal DGs Planning in the Distribution Systems

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HIGHLIGHTS

- The Enhanced Particle Swarm (EPSO) algorithm is proposed and successfully applied to the simultaneous distributed generation (DG) planning and distribution network.
- The EPSO technique is proposed to handle the problem with the multiobjectives of total active power loss minimization and bus voltage profile improvement.
- ETAP program was employed to assess the distribution system reliability after inserting the DG units in the optimal place and size.

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ABSTRACT

Due to increased load demands, distribution systems suffer from high power losses, low voltage levels, high current, and low reliability. To solve these problems, integrate distributed generator units (DG) into the distribution system. DG units are among the most popular methods of improving distribution system reliability, power losses, and bus voltage improvement through the placement and selection of distributed generator units in an optimal location and size. This work proposed Enhanced Particle Swarm Optimization (EPSO) technology to find the optimum location and size of DG units to reduce power losses, improve bus voltage level, and employed the Transient Electricity Analyzer (ETAP) to evaluate the reliability of the distribution system network. ETAP is a programming tool for modeling, analysis, design, optimization, operation, and control of electrical power systems. These findings may be useful in conducting reliability assessments and correctly utilizing dispersed generation sources for future power system growth by power utilities and power producer companies. The proposed method was employed on the Iraqi distribution system (AL-Abasia distribution network (F10 feeder)). After adding three DG units to the distribution system, theer adding three DG units to the distribution system, the obtained simulation results showed a significant reduction in power losses, voltage levels, and reliability enhancement.

1. Introduction

The growing load demand in the distribution system results in increased currents drawn by the loads on the low voltage side, higher power losses, and voltage profile degradation. These conditions impact the distribution system, making it unstable and inefficient. The most critical difficulties of the distribution system are maintaining a stable voltage profile and minimizing power losses. The electrical power system comprises generation, transmission, and distribution systems. The distribution system is the power system component. A power system aims to provide its customers with electricity in reliable and economical methods. The electric generating industry has undergone significant changes in deregulation and competition [1]. The ability to ensure an adequate standard of the customer's energy supply is called the power system's reliability. System reliability subdivisions can be analyzed by improvement, i.e., generation, transmission, and distribution, by reducing the duration or number of service interruptions for customers [2]. There is a growing trend to incorporate DG units into the electrical power delivery system due to the environmental and economic values, reducing power losses, improving the voltage profile [3-5], etc. Usually, DGs are integrated near load centers that help to minimize the cost of transporting electric power. Also, since they are smaller in size than centralized generating stations,

DGs Integration has some advantages for the distribution systems operation because the proper allocation of DG dramatically increases the total voltage and eliminates power loss. DG positioning and sizing, however, are of immense importance as any inappropriate position and greater DG penetration provide increased power loss and decreased system efficiency [6]. Through the many research and papers published in this area, some of the related research reports are summarized below:

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The proposed Genetic Algorithm (GA) in reference [7] is based on a power flow analysis for the electrical distribution system with the representation of the DGs using MATPOWER software to find the optimal placement and size of DGs for loss minimization and voltage profile using MATPOWER software. Assess the benefits of adding DGs to the system's performance using the Cost-Benefit Factor. The proposed method is evaluated on two different distribution systems: the 13-Bus radial system and the actual 66 kV distribution network in Alexandria. The disadvantage of the (GA) algorithm is that the encoding and decoding procedures can take a long time to compute. The effect of DG penetration on the reliability of a radial delivery network was addressed in [8]. At various load points, the authors assess the reliability of a radial electrical distribution network (EDN) with and without DGs installation. Monte Carlo Simulation (MCS) and analytical methods assess reliability. The Monte Carlo simulation approach has a very simple calculation structure. Still, because the error is inversely proportional to the experiment times, a longer calculation time is required to reduce the error. In reference [9], three algorithms were used in the electrical distribution system to determine the best placement of DGs for power loss reduction: the genetic algorithm (GA), the harmony search algorithm (HSA), and the modified HSA. Simulation results for multiple algorithms are evaluated for an IEEE 33 bus network, and the best algorithm for minimizing losses is established. (HSA) drawback it has low effectiveness, efficiency, and lower convergence speed. In [10], For DG optimal placement and size in the distribution system, an offline-online technique was used, splitting the solution of the relevant parametric power flow problem and optimization into two stages. The offline and online phases are treated separately is a potential disadvantage of this method. The applicability of the best methods for online decisions is limited by the need for high responsiveness.

In contrast, offline decisions are made without regard for the abilities of downstream online solvers. In reference [11], an integrated voltage stability index and Dragonfly approach enhanced bus voltage and minimized power losses by placing DG units in the distribution network. The proposed method was tested on IEEE 83 bus test system. However, the dragonfly algorithm drawback lacks internal memory, which causes its premature convergence to the local optima.

The generation properties of DG are established in [12] using a probabilistic model of DG unit output. Moreover, using the DG and the island's load models, a method for calculating the probability of the island's successful operation is proposed. Then, the enhanced minimal path technique assesses the distribution system's reliability with DGs. The main disadvantage of methods based on minimal cut sets is that as the size of the system grows, the number of minimal paths or cut sets grows rapidly. The number of cut sets increases in large systems, resulting in a combinatorial explosion. In [13], an innovative method based on dynamic programming was used to solve the multi-objective function to evaluate the best placement for DGs to be placed in the electrical distribution system to reduce system power loss and enhance reliability and voltage profile. Multi-objective functions are examined throughout the planning period based on a cost/benefit form that maximizes the benefits of DG allocation in the system to compensate for system loss, system reliability, and the cost of purchased electricity through transmission lines. The dynamic programming method has the disadvantage of requiring a large amount of memory to store the calculated result of each problem without guaranteeing whether the stored value will be used or not.

For power losses and bus voltage profile enhancement, a new master-slave hybrid technique was proposed based on the parallel PBIL (PPBIL) algorithm and the PSO [14]. The parallel implementation of the Population-Based Incremental Learning (PBIL) method was used for optimal DG placement, and Particle Swarm Optimization was used for optimal capacity. The Loss Sensitivity Factor (LSF), a Genetic Technique (GA), and a Parallel Monte-Carlo algorithm (PMC) are all compared to the proposed technique. In [15], a complete Markov method is used to describe the overall reliability condition of individual components and integrate the effects of protection system failures into the power system's reliability evaluation. The drawback of the Markov method is that the calculation quantity grows exponentially with the number of components, making it extremely difficult to calculate reliability when the number of components is large.

This work is divided into two stages: first, the classical PSO approach is enhanced by linear decreasing of inertia weights. This linear decrease of inertia weights is used to get the preferable solution. It allows easy convergence toward the optimum solution and quick and almost linear convergence to find the optimal DG units' location and size. Employed the EPSO method to find the optimal location and size of DG units with three cases for power loss reduction and improving bus voltage profile. The second stage is the reliability assessment was implemented by the ETAP program after inserting the DG units into the distribution system. Finally, six scenarios for reliability assessment were applied to the reliability indices: System Average Interruption Duration Index (*SAIDI)*, System Average Interruption Frequency Index (*SAIFI)*, and Expected Energy Not Supply (*EENS)*, whose value was affected by changing the repair time (r_i) and the average failure rate (λ_i) of the DG units.

2. DGs Overview

DG units are generally divided into technologies for fossil or non-fossil fuels. Fossil fuel technologies: reciprocating internal combustion engine, microturbine, and electrochemical energy sources. For non-fossil fuel technologies (renewable): Solar PV, wind turbines, and storage devices [16]. Different technologies of DG are shown in Figure 1 [17-20]. The many advantages of DGs have been made more attractive than the conventional generation stations based on fossil fuels. Therefore, many kinds of literature have defined DGs in various terms [21]. The DGs based on power generation capacities and technologies in each module size are presented in Table 1[22].

The majority of the advantages of using DGs in the distribution system are both economic and technical, and they are intertwined. As a result, it is suggested that the benefits be divided into three categories: technical, economic, and environmental [23,24]. Technical Benefits like peak load shaving, better voltage profile, minimizing power system losses, enhanced continuity reliability, and elimination of specific power quality issues are just a few technical benefits. The most significant technological advantages [25- 27]: are decreased line losses, improved bus voltage profile, overall energy efficiency have improved, improved the reliability of distribution system, and security and power quality has improved. The critical technical advantages [27]: reduction Operation and Maintenance O&M of DGs technologies cost, increased productivity, decreased health-care costs due to improved climate, lower fuel costs caused by increased overall performance, reduced reserve requirements and related costs, reduced operating costs due to peaking, and increased protection for critical loads.

Environmental benefits, like wind turbine (WT), PV, and hydroelectric turbines, use no fossil fuels, while others, such as fuel cells, microturbines, and some internal combustion units, use natural gas, most of which is manufactured in the US. The economy is becoming more diverse, which helps to protect it from price shocks, outages, and fuel shortages. Environmental benefits include reduced noise and emissions and more green power.

3. Objective Function (G)

The purpose of adopting DG units for a multi-objective distribution network is to reduce total power system losses, reduce voltage square error, and improve voltage profiles. The reliability indices are then evaluated by selecting the best DGs placement and size. The following equations can be used to express the objective functions (G):

$$G=C*E\_1+E\_2*(1-C) \tag{1}$$

$$E\_1=P\_(TL,with\ DG)/P\_(TL,without\ DG) \tag{2}$$

$$E\_2=\llbracket Verror \rrbracket\_(with\ DG)/(\llbracket Verror \rrbracket\_(without\ DG)*n) \tag{3}$$

Where: E1 is the percentage of active power losses with DG units compared to what was previously, E2 is the average ratio of Verror at each bus with DG units to total Verror before adding DG units, PTL, with DG active power losses after adding DG units, PTL, without DG active power losses before inserting DG units, VerrorwithDG voltage profiles square error after inserting DG units, Verrorwithout DG voltage profiles square error before inserting DG units, n number of buses, and C is weight factor, where 1 ≥ C ≥0.

3.1 Load Flow

For load flow analysis of radial distribution systems, the Backward/Forward sweep algorithms method is utilized. First, Kirchhoff's current law (KCL) and Kirchhoff's voltage law (KVL) compute the bus voltage from the farthest bus in the backward sweep. Then, starting at the source node, the downstream bus voltage is updated in a forward sweep. After that, using the updated bus voltage, line losses are estimated. This method can be used to find a load flow solution for a distribution network without solving a set of simultaneous equations [28].

3.2 Voltage Profile Square Error "Verror"

When Verror is reduced, the voltage profile can be improved in the radial distribution system as follow:

$$\mathrm{V_{error}} = \sum_{y=1}^{Nbus} (V_y - V_r)^2 \tag{4}$$

Where Vy is bus voltages at nodes y, Vr is rated voltage and equal to (1) p.u, and Nbus is the number of buses.

Table 1: DGs technologies and typical size

No.	DG technologies	Capacity
1	Combined Cycle Gas Turbine	(35 _400) MW
2	Internal combustion engines	(5) kW _(10) MW
3	Micro-Turbines	(35) kW _(1) MW
4	Micro hydro	(25) kW_(1) MW
5	Small hydro	(1) MW - (100) MW
6	WT (Wind Turbin)	(200) Watt - (3) MW
7	Solar thermal: a-central receiver	(1) MW - (10) MW
	b-Lutz system	(10) MW- (80) MW
8	Solar PV (photo-Voltaic)	(20) kW – (5) MW
9	Fuel cells: a-photoacid	(200) kW - (2) MW
	b-molten carbonate	(250) kW- (2) MW
	c- proton exchange	(1) kW - (250) kW
	d- solid oxide	(250) kW- (5) MW
10	Geothermal	(5) MW- (100) MW
11	Ocean energy	(100) kW _(1) MW
12	Battery storage	(500) kW_ (5) MW

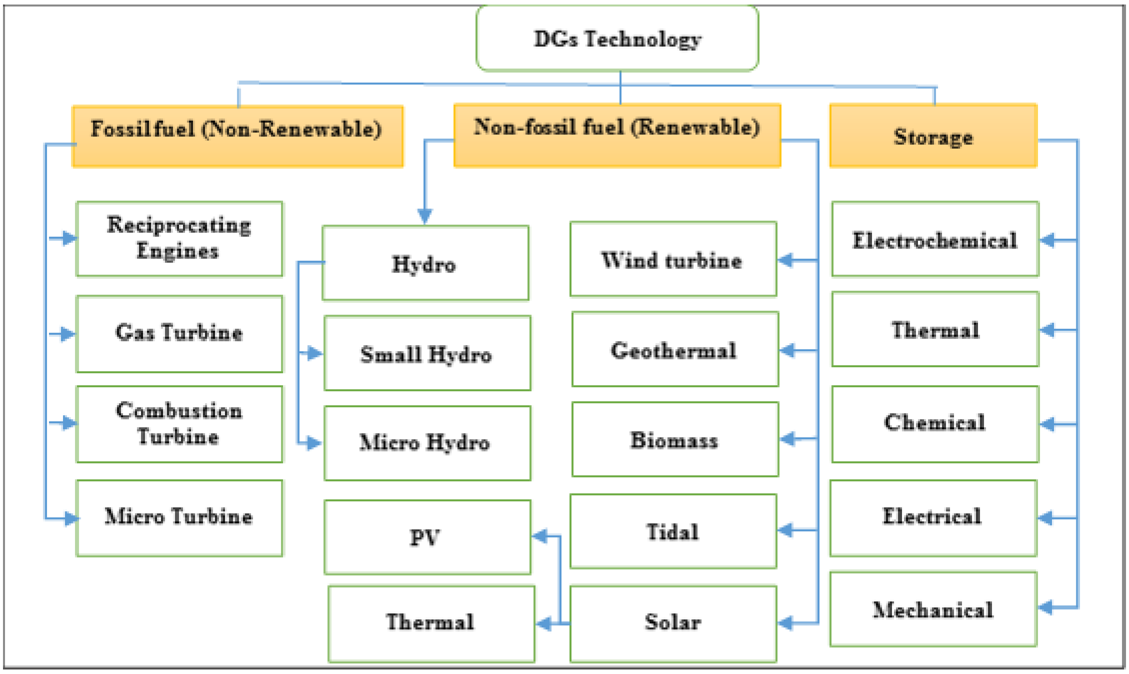


Figure 1: Different technologies of DG

4. Constraints

All of the system's parameters are shown in Figure 2 to specify the set of constraints. The output and input (r) and (y) buses, respectively, as well as the line parameters (Rry, Xry), and a load allocated to the input bus (y).

The system's bus balance of real and reactive power is represented by the limitations in equations (5) and (6), respectively.

$$P_{g_r} - P_{d_r} - v_r \sum_{y\in\Omega N}^{n} v_y y_{ry} \cos\left(\delta_r - \delta_y + \theta_{ry}\right) = 0 \quad \forall r \in \Omega_N \tag{5}$$

$$P_{g_r} - P_{d_r} - v_r \sum_{y\in\Omega N}^{n} v_y y_{ry} \cos\left(\delta_r - \delta_y + \theta_{ry}\right) = 0 \quad \forall r \in \Omega_N \tag{6}$$

Where, (Q_{gr}): reactive power injected into bus r, (P_{dr}, Q_{dr}): active and reactive power demanded at bus r, (δ_r, δ_y): voltage angles at buses r and y, and Y_{ry} is the admittance of the line ry.

The distribution system bus voltage restrictions are represented by equations (7).

$$0.9\, p.u. \leq \mathrm{Vm} \leq 1.05\, p.u. \tag{7}$$

The current in the system feeders must be regulated, and the maximum current must not be exceeded. The current limitation is represented by equations (8).

$$Ii \leq I_{max,i} \tag{8}$$

The DGs also have the power generation min and max limits. Equations (9,10) represent the capacity limits of the DG units [29]

$$\sum_{i=1}^{nDG} P_{gri} \leq 0.85 \times \sum_{i=1}^{n_{bus}} P_{loadi} + P_{Loss} \tag{9}$$

$$P_{gr}{}^{min} \leq P_{gr} \leq P_{gr}{}^{max} \tag{10}$$

Where: P_{gr} is the DGs active power, $P_{gr}{}^{min}$= Zero, $P_{gr}{}^{max}$ is the maximum DGs power from Equation (9), and n_{DG}= number of DG units in the distribution system.

5. Enhanced Particle Swarm Algorithm (EPSO)

The optimal solutions to the multi-objective problem of the location and size of DG units are determined using the PSO algorithm. PSO is a mathematical technology. Using simpler social model simulations to develop this technology.

The concept of the PSO approach is based on the kinetic and social behavior of flocks (birds, fish) in search of food. A flock of birds travels from one place to another in search of food. As they search for the best place to find food, information is passed on between them during the search. Moreover, when exploring the flock of birds' optimal location for food quality, the flock of birds uses this location to get the best food. As a result, the technique uses search and repetition, both of which are based on the best results within the selected search space [30].

PSO approach comprises particles (swarm population) that move around the search area. The procedure is set up at random, depending on the number of particles. These particles are affected by the particle's speed and location, updated depending on prior instances of the particle's optimal position and symbol (Xbest) and on the best location of the particles in the swarm (Xgbest). During each iteration of the algorithm, adjust the speed and position of each particle by using Equations. (11) and (12) until the stop criteria are reached.

$$V_i^{k+1} = W * V_i^k + c_1 r_1 \left(X_{pbest_i^k} - X_i^k\right) + c_2 r_2 \left(X_{gbest^k} - X_i^k\right) \tag{11}$$

X_i^(k+1)=X_i^k+V_i^(k+1) (12)

Where, V_i^k : particle i velocity at iteration k, X_i^k : current particle i at iteration k,($X_{pbest_i^k}$, X_{gbest^k}): the best fitness values and best values for any particle in the population, (r_1, r_2): random number between (0,1) and (c_1, c_2): acceleration constants.

Particle velocities are not limited when PSO is run. They can quickly climb to unacceptable levels in just a few iterations. As a result, constraint coefficients have been introduced to regulate particle velocity [31]. Therefore, the PSO approach has been enhanced. The coefficient drives and controls particle movement towards convergence. The modified particle velocity can be represented as:

$$V_i^{k+1} = WO * V_i^k + c_1 r_1 \left(X_{pbest_i^k} - X_i^k\right) + c_2 r_2 \left(X_{gbest^k} - X_i^k\right) \tag{13}$$

$$X_i^{k+1} = X_i^k + V_i^{k+1} \tag{14}$$

Where, O: the constriction factor, (c_1, c_2): constant acceleration coefficients and can be written as follow:

$$c1 = O * \Delta 1 \tag{15}$$

$$\text{c2=O*}\Delta 2 \tag{16}$$

and

$$O = \frac{2}{\left|\Delta - 2 + \sqrt{\Delta^2 - 4\Delta}\right|} * \left(1 - \left(\frac{t}{T}\right)^2\right)^2 \tag{17}$$

$\Delta = \Delta 1 + \Delta 2,\ \Delta 1 + \Delta 2 \geq 4$

Where, Δ: the co-efficient, Δ1 is equal to Δ2, T is the number of iterations, and t = 1, 2, 3, …, T. Figure 3 shows the flowchart for the EPSO algorithm model.

6. Reliability

One of the primary goals of incorporating DGs into the distribution system is to improve power supply reliability. DG units can be used as a backup system or as the primary energy source.

To eliminate extra costs, DGs can be used during peak load periods. Measuring the efficacy of the previous service is a fundamental problem in evaluating distribution reliability. Condensing the results of service interruptions into system performance indices is a popular approach. System planners and operators use reliability indices to increase the quality of service provided to customers. Reliability is the ability of a system or equipment to operate adequately for the scheduled conditions' expected duration. The reliability advantages are appreciated from a customer perspective. DGs' optimal location and size lead to increase power supply reliability and are essential somewhere. However, the service interruption is unacceptably expensive or risks health and safety.

Each customer can choose their reliability, which raises consumer awareness of the importance of a reliable electricity supply. As a result, small consumers are unconcerned about supply interruptions because they do not perceive them as a significant risk.

On the other hand, high reliability comes with high network and generation investment and maintenance costs. As a result, some industries that rely on reliable power could find the grid's reliability inadequate and be willing to invest in DGs. The implementation of the distribution system focuses on the normal operation of each component and the effect on customers. Reliability indices evaluate the performance of the distribution network to provide consumers with reliable power. Reliability indices severely affect distribution network planning and operation, affecting the system's profit, quality of power, and stability [32]. The IEEE-P1366 standard presents several reliability indices, including momentary interruption incidents and sustained interruptions [33]. These indices are categorized as load based "point" and system-based reliability indices.

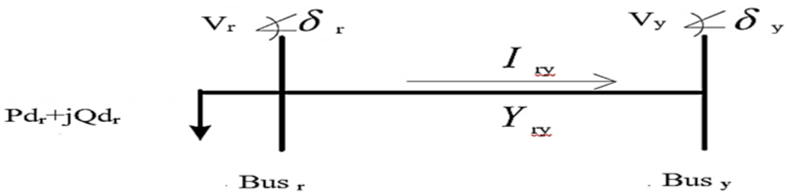


Figure 2: Distribution System single-line diagram

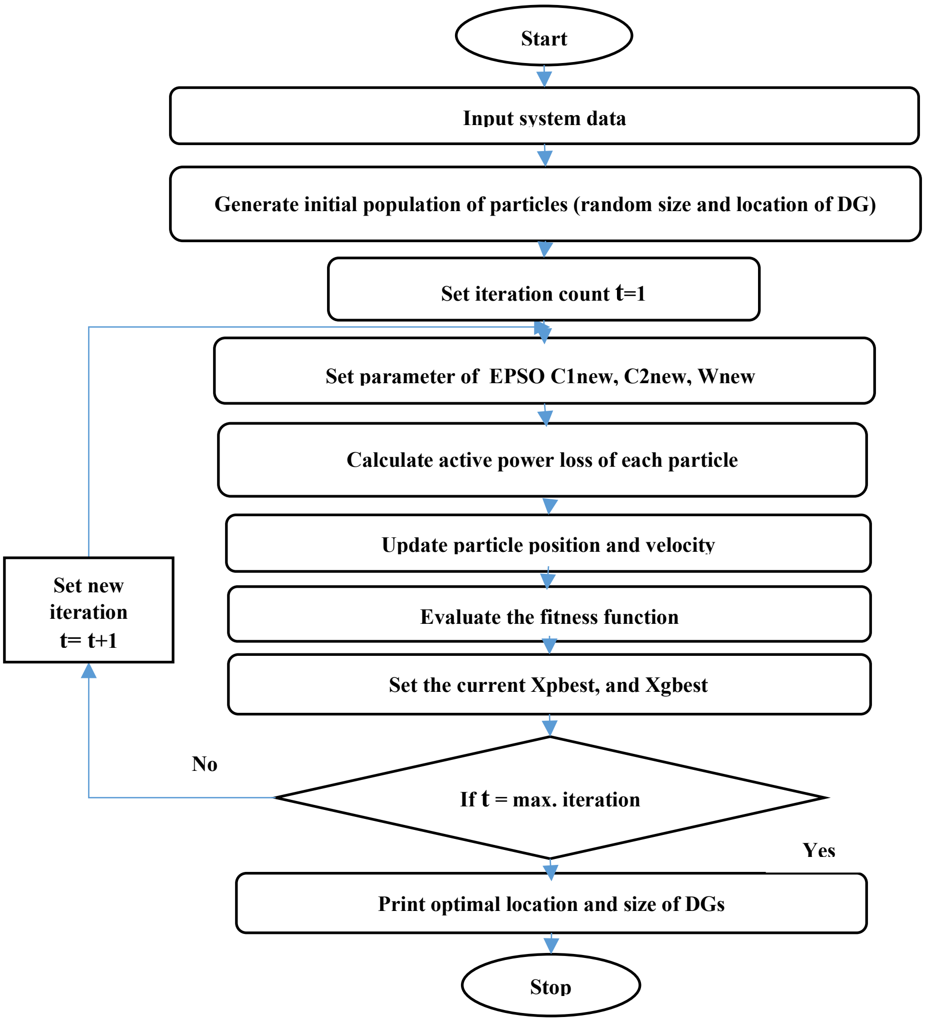


Figure 3: Flowchart EPSO model

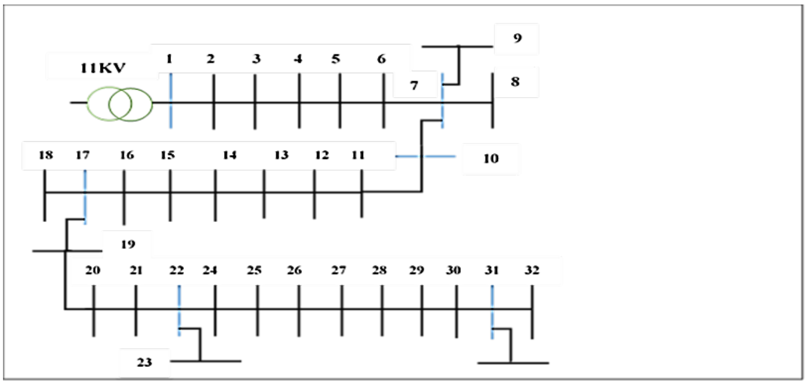


Figure 4: AL-Abasia distribution network (F10 feeder)

6.1 Load Point Reliability Indices

1. Average Failure Rate at Load Point (*lp*), λ_{lp} (failure per year):

$$\lambda_{lp} = \sum_{j\in \mathrm{Ne}} \lambda_{e,j} \tag{18}$$

Where: λ_{lp}: average failure rate at load point (*lp*), *Ne*: total number of the elements whose faults will interrupt load point *lp*, and $\lambda_{e,j}$: the average failure rate of element j.

2. Annual Outage Duration at Load Point (*lp*), U_{lp} (an hour per year):

$$U_{lp} = \sum_{\mathrm{j\in Ne}} \lambda_{e,j} . r_{\mathrm{lp,j}} \tag{19}$$

Where $r_{i,j}$: failure duration at load point (*lp*) due to a failed element *j*.

3. Average Outage Duration at Load Point (*lp*), r_{lp} (hours):

$$rlp = \frac{Annual\ outage\ duration\ at\ load\ point\ lp, Ulp}{Average\ failure\ rate\ at\ load\ point\ lp, \lambda lp} \tag{20}$$

6.2 System Based Indices

1. System Average Interruption Frequency Index "SAIFI".

$$SAIFI = \frac{\Sigma\ \text{Number of interruptions} * \text{Number of Customers Interrupted}}{\text{Total Number of Customers Served}}$$

$$SAIFI = \frac{\sum_{lp=1}^{n} \lambda_{lp} N_{lp}}{NT}\ \text{(inter./cust.yr)} \tag{21}$$

Where, N_{lp}: Is the total number of customers of (load point), *NT*: Is the total number of customers served, *Lp*: Load point, and n: Is the total number of load points.

2. System Average Interruption Duration Index "*SAIDI*".

$$SAIDI = \frac{\Sigma\ \text{Customer hours of Interruption}}{\text{Total Number of Customers Served}}$$

$$SAIDI = \frac{\sum_{lp=1}^{n} U_{lp} N_{lp}}{NT}\ \left({}^{h}/_{cust.yr}\right) \tag{22}$$

Where, U_{lp}: annual outage duration at load point (*lp*).

3. Customer Average Interruption Duration Index "*CAIDI*".

The average time required to restore service.

$$CAIDI = \frac{SAIDI}{SAIFI}\ \left({}^{h}/_{cust.inter}\right) \tag{23}$$

Average Service Availability Index "*ASAI*".

$$ASAI = \frac{\text{Customer Hours Service Availability}}{\text{Customer Hours Service Demands}}$$

$$ASAI = \frac{\sum_{lp=1}^{n} N_{lp} * 8760 - \sum_{lp=1}^{n} U_{lp} N_{lp}}{\sum_{lp=1}^{n} N_{lp} * 8760} \tag{24}$$

4. Average Service Unavailability Index (*ASUI*).

$$ASUI = 1 - ASAI\ \text{(p.u)} \tag{25}$$

5. The annual total energy not supplied due to interruptions.

$$EENS = \sum_{lp=1}^{n} KW_{lp} * U_{lp}\ \left({}^{kwh}/_{yr}\right) \tag{26}$$

Where: KW_{lp}: is the average load of load point.

6. Average Energy Not Supplied "*AENS*".

$$AENS = \frac{EENS}{NT} \tag{27}$$

7. Results and Discussion

To assess the effectiveness of the proposed approach, the AL-Abasia distribution network (feeder F10) in AL- Najaf city was selected. This feeder consists of 32 overhead line sections, 33 load points, and one power transformer of 33/11 kV with a rated voltage is 11 kV, as shown in Figure 4. As shown in appendix (A), the total load is 5504 kW (5.504 MW), as given in appendix (A). The suggested design was developed using Matlab R2015a programs on a computer with a 2.5 GHz Intel(R) Core(TM)i7 CPU and 8 GB of RAM. EPSO is used to evaluate the optimal location and size of DG units with unity power factors using three case studies: Case (1) adding a single DG unit, Case (2) adding two DG units, and Case (3) adding three DG units. Table 2 shows how the proposed technique reduced real power losses and improved voltage profiles in three different cases, adding one, two, and three DG units in the distribution network. Adding a single DG unit in 33-bus (F10) feeder with the best size and location is (1190KW) at bus 22, the active power losses (Plosses) are decreased to (135KW), a (59.04%) reduction, the minimum voltage (Vworst) is increased to (0.922 p.u) at bus 22. Verror is reduced to (0.0986p.u), a (60.68p.u) reduction. Two DG units with the best sizes and locations are (3049KW) at bus 25 and (281kW) at bus 30. This configuration lowers the active Plosses (61.61%) to a value of (129.756 kW). Vworst is increased to (0.931 p.u) at bus 32 and 33, and Verror is reduced 65.87% to a value of (0.0856p.u). Adding three DG units with the best sizes and locations are (1210KW) at bus 11, (1210kW) at bus 20, and (2000KW) at bus 33. Plosses are decreased to (104.83KW), a (69.01%) reduction, Vworst is increased to (0. 939p.u) at buses 26, 27, and Verror is reduced to (0. 0687p.u), a (72.6%) reduction. The results obtained for total Plosses reduction and voltage profile improvement in the AL-Abasia distribution network for the three cases comparison are shown in Figures 5 and 6. Employed ETAP program to assess the reliability of the (F10 feeder), as shown in Figure 7. Reliability assessment in the distribution network was done after adding the DG units for three different cases in the optimal location and size. Finally, six scenarios for reliability assessment were applied to three indicators, SAIDI, SAIFI, and EENS, whose value was affected by changing the repair time (ri) and the average failure rate (λi). In the current work, only different reliability data for DG units were considered as Scenarios:

1. Scenario (1): (0.2 f/yr) average failure rate and (12 h) repair time for DG units.
2. Scenario (2): (0.4 f/yr) average failure rate and (12 h) repair time for DG units.
3. Scenario (3): (0.6 f/yr) average failure rate and (12 h) repair time for DG units.
4. Scenario (4): (0.2 f/yr) average failure rate and (24 h) repair time for DG units.
5. Scenario (5): (0.2 f/yr) average failure rate and (48 h) repair time for DG units.
6. Scenario (6): No failure.

Reliability data, failure rate, and repair or replacement time of the components are shown in Table 3. Table 4 shows the number and type of loads in the load point of the AL-Abasia distribution network.

The following assumptions are taken into account for this network:

- Fuse, breaker, and switch failures are ignored.
- The fuse at any lateral clears the fault.
- The protection system operates successfully when required.

Table 5 shows the simulation results for the reliability indices of the F10 feeder for the base case and three different cases for DG units' reliability data, (12 h) ri and (0.2f/yr) λi as described previously. The SAIDI, SAIFI, EENS, and AENS indices were reduced to (32.4109), (13.0014), (166.972), and (0.2609), respectively, and the ASAI index increased to (0.9963) when inserting one DG unit. The SAIDI, SAIFI, EENS, and AENS indices were reduced to (30), (12.221), (164.341), and (0.2510), respectively, and the ASAI index increased to (0.9966) when inserting two DG units. Inserting three DG units, the SAIDI, SAIFI, EENS, and AENS indices reduced to (29.0161), (11.3501), (162.1010), and (0.2491), respectively, and the ASAI index increased to (0.9970). Table 6 shows the simulation result for *SAIDI, SAIFI,* and *EENS* indices of three different cases based on the six different scenarios. It is observed that Increasing the failure rate and repair time of DG units leads to an increase in the reliability indices. As a result, the reliability of the distribution system decrease. The value of the *SAIFI* index was not affected when changing the DG unit repair time. This means the SAIFI index is independent of (r_i). Figure 8 (a-c) shows reliability indices for three different cases based on the six different scenarios

Table 2: Simulation results of the AL-Abasia distribution network for the three cases and the base case

Method	DGs Location	DGs Size (MW)	Plosses (MW)	%Plosses Reduction	Verror (p.u)	%Verror Reduction	Vworst (p.u)
Without DGs	---	---	0.3384	----	0.2508	---	0.877
MPSO with case1	22	1.19	0.135003	59.04	0.0986	60.68	0.922
MPSO with case2	25,30	3.049,0.281	0.129756	61.61	0.0856	65.87	0.931
MPSO with case3	11, 20, 33	1.21,1.21,2	0.104839	69.01	0.0687	72.6	0.939

Table 3: Reliability parameters for different components

Item	Failure rate λi (failure/yr.)	Repair time r_i
Transformer 33/11 kV	0.07	4
Transformer 11/0.4 kV	0.07	3.68
Overhead Line	1.15	2.42
Substation	0.6	50
Load point@7,17,22,31	0.95	4
Load point@(1-6, 8–16, 18-21,23-30, 32, 33)	0.9	3

Table 4: Number and type of load in the AL-Abasia distribution network

Bus No. or Load Point	No. of Loads	Type of Load
3,10	20	Government
2,4,5,11,12,15-22, 25-29,31-33	20	Residential
6,7-9,13 ,14,23,24, 30,	20	Agriculture

Table 5: Reliability indices results of the EDN

Item	SAIDI	SAIFI	EENS	AENS	ASAI
Base case	62.9862	13.8302	324.609	0.5072	0.9928
Case 1	32.4109	13.0014	166.972	0.2609	0.9963
Case 2	30	12.221	164.341	0.2510	0.9966
Case 3	29.0161	11.3501	162.1010	0.2491	0.9970

Table 6: SAIDI, SAIFI, and EENS indices were evaluated for different Scenarios

SAIDI						
Item	Scenario1	Scenario2	Scenario3	Scenario4	Scenario5	Scenario6
Base case	62.9862	62.9862	62.9862	62.9862	62.9862	62.9862
Case 1	32.4109	32.7211	32.9461	32.7211	33.2023	32
Case 2	30	30.491	30.7359	30.491	31	29.5240
Case 3	29.0161	29.50120	29.8891	29.50120	30.2101	28.3251
SAIFI						
Item	Scenario1	Scenario2	Scenario3	Scenario4	Scenario5	Scenario6
Base case	13.8302	13.8302	13.8302	13.8302	13.8302	13.8302
Case 1	13.0014	13.2189	13.4712	13.0014	13.0014	12.8111
Case 2	12.221	12.4450	12.6339	12.221	12.221	12
Case 3	11.3501	13.2189	11.7662	11.3501	11.3501	11
EENS						
Item	Scenario1	Scenario2	Scenario3	Scenario4	Scenario5	Scenario6
Base case	324.609	324.609	324.609	324.609	324.609	324.609
Case 1	166.972	167.632	168.5001	167.632	169.4331	165.7231
Case 2	164.341	165.342	166.5449	165.342	167.6622	163.2
Case 3	162.1010	163.2256	164.367	163.2256	165.4012	161.2

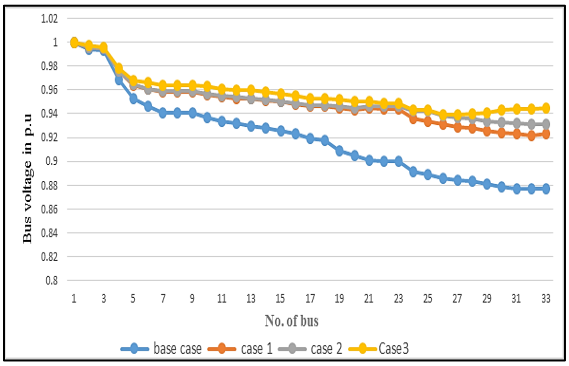


Figure 5: Comparison voltage profile improvement for the three cases with the base case

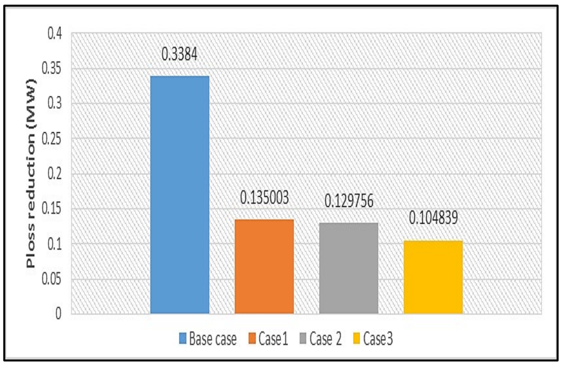


Figure 6: Comparison of real power loss reduction for the three cases with the base case

8. Conclusion

The scope of this study is to reduce losses, improve voltage profile, and improve distribution network reliability. In this paper, two programs have been used; the first is MATLAB R2015a to implement the (EPSO) technology, while the second is the Transient Electricity Analyzer (ETAP) to evaluate the reliability of the distribution system after integrating the DG units on the optimum site and size. The Backward/Forward sweep algorithms are used to analyze power flow because they support the analysis of integrated distributed generators, get faster power flow solutions, and reduce overall computational time, even for large-scale distribution networks. After adding three DG units to the AL-Abasia distribution system, the obtained simulation results significantly reduce power losses and voltage square error. Furthermore, employed EPSO method to find the optimal location and size of the DG units resulted in reduced power losses to (69.01%), reduced voltage square error to (72.6%), and improved voltage profile to (0.939 p.u), and reliability enhancement.

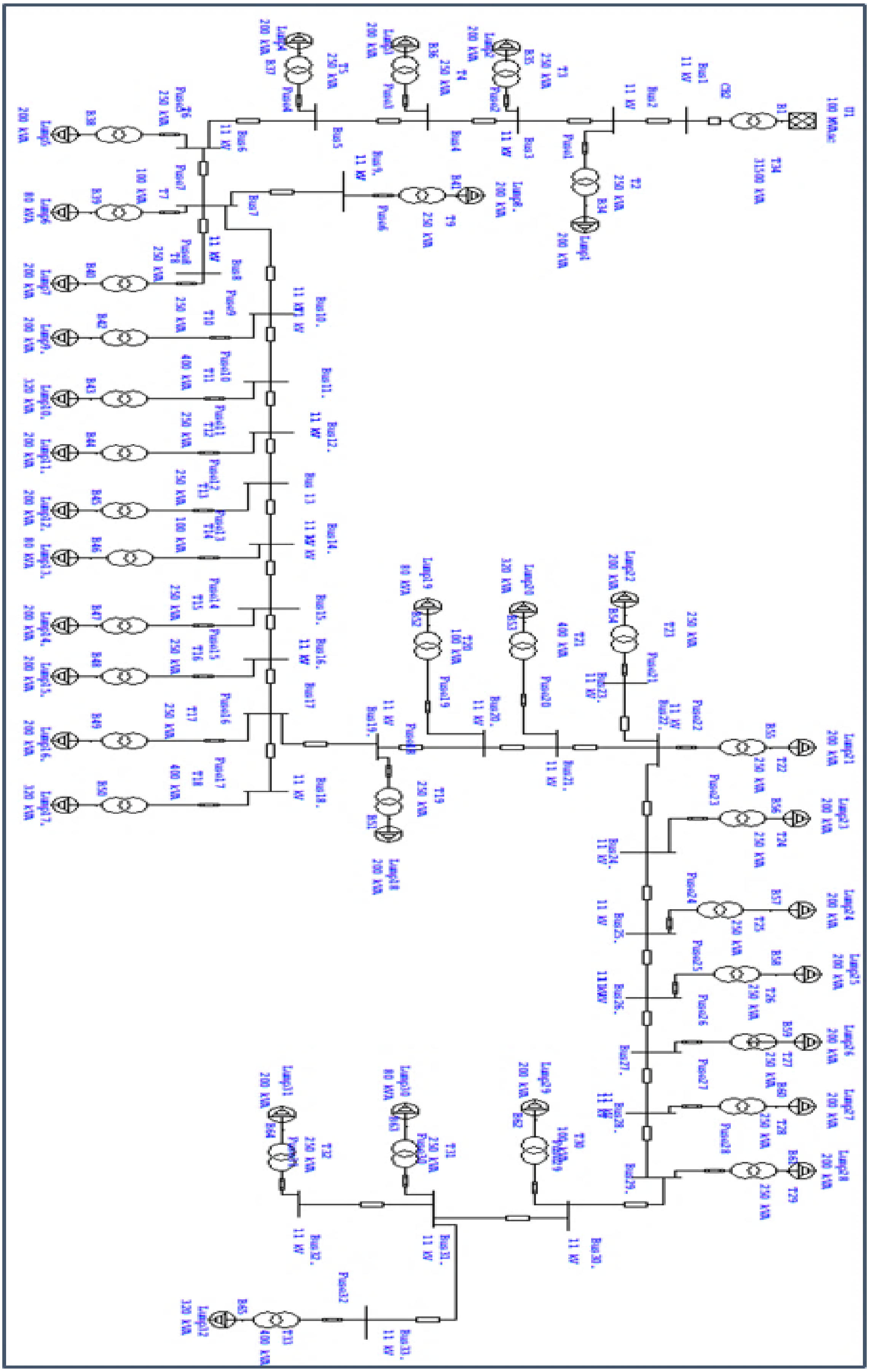
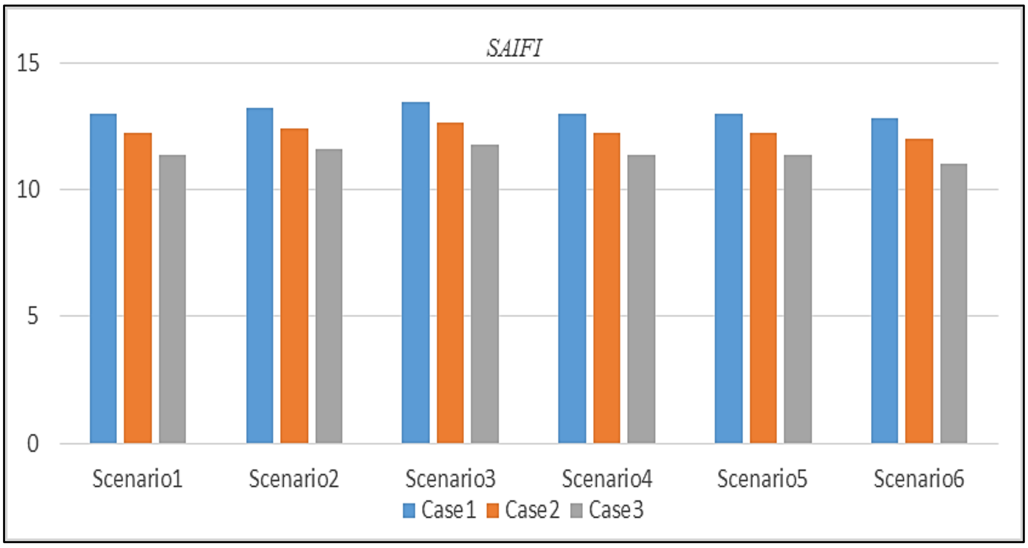
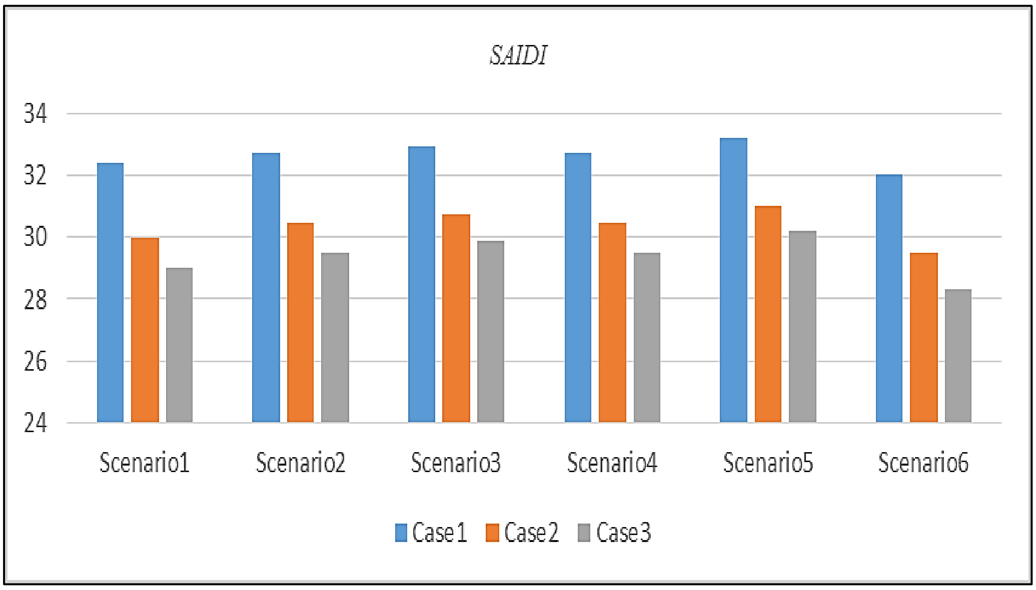


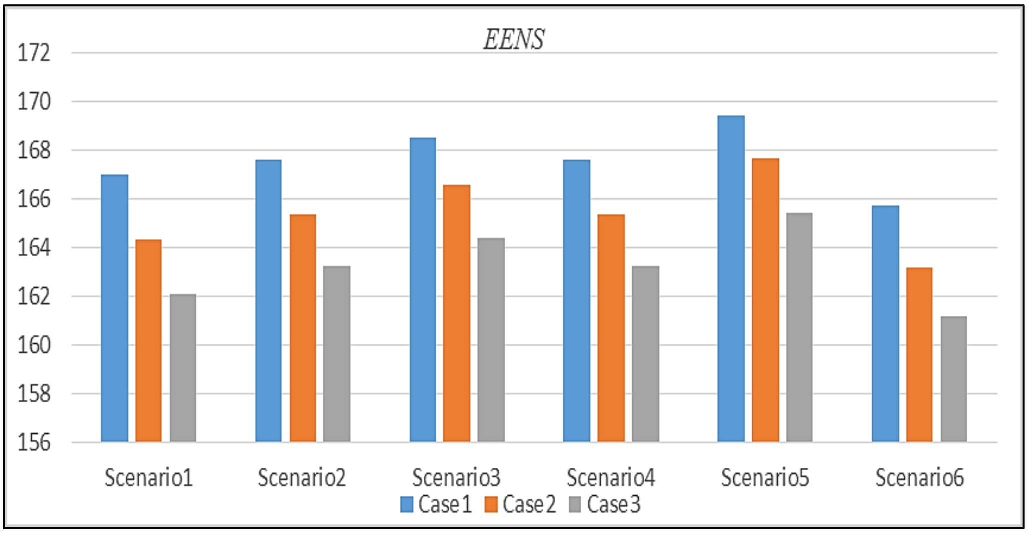
Figure 7: Feeder (F10) modeled in ETAP program



(a)SAIFI



(b)SAIDI



(c)EENS

Figure 8: Reliability indices for different DG units (λi ,r_i) reliability data in a, b and c

Future works

Some of the main features and ideas to develop and extend this work are summarized below:

1. A cost-benefit analysis of the DG unit's placement in the distribution system network.
2. Reliability analysis study with large radial distribution systems.
3. Influence study of large-scale electrical energy storage system on reliability.

Appendix A

Table A.1: Line and load data for AL-Abasia distribution network

Sec. NO.	From bus	To bus	Load (kW)	Load (kVAR)	R(Ω)	X(Ω)
1	1	2	160	120	0.055596	0.065517
2	2	3	160	120	0.02706	0.031889
3	3	4	160	120	0.113406	0.133644
4	4	5	160	120	0.142188	0.167562
5	5	6	160	120	0.127674	0.150458
6	6	7	64	48	0.079704	0.093928
7	7	8	160	120	0.005412	0.006378
8	7	9	160	120	0.005904	0.006958
9	7	10	160	120	0.073308	0.08639
10	10	11	256	192	0.020418	0.024062
11	11	12	160	120	0.037392	0.044065
12	12	13	160	120	0.04059	0.047834
13	13	14	64	48	0.00246	0.023192
14	14	15	160	120	0.014268	0.016814
15	15	16	160	120	0.035424	0.041746
16	16	17	160	120	0.090774	0.106973
17	17	18	256	192	0.028536	0.033628
18	17	19	160	120	0.257562	0.303525
19	19	20	64	48	0.070356	0.082911
20	20	21	256	192	0.193356	0.227861
21	21	22	160	120	0.015744	0.018554
22	22	23	160	120	0.00492	0.005798
23	22	24	160	120	0.144894	0.170751
24	24	25	160	120	0.04305	0.050733
25	25	26	160	120	0.010332	0.012176
26	26	27	160	120	0.113406	0.133644
27	27	28	160	120	0.095202	0.112191
28	28	29	160	120	0.171708	0.20235
29	29	30	160	120	0.209838	0.247285
30	30	31	64	48	0.139728	0.164663
31	31	32	160	120	0.07995	0.094218
32	31	33	256	192	0.087822	0.103494

Author contribution

All authors contributed equally to this work.

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Data availability statement

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

Conflicts of interest

The authors declare that there is no conflict of interest.

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