Distribution network planning with DG units considering the network reconfiguration and reliability

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Abstract. The failure statistics of most utilities show that distribution networks (DN) make the most considerable individual contribution to the lack of supply to consumers. There are several advantages to optimizing distributed generation (DG) allocation in DNs, including loss reduction, voltage profile improvements, and reliability. A traditional objective function of optimal DG allocation is to minimize the total power loss and improve the voltage profile. Due to their ability to supply loads locally, DG units enhance the load-carrying capability of lines and, therefore, serve the same purpose as redundant lines. A DN's reliability indices can also be improved by optimal DG allocation. As such, it is interesting to investigate how network reconfiguration (NR) may be further enhanced to improve the achievement of these critical objectives and ensure the system's efficient operation in this context. The purpose of this paper is to present an intensive investigation of the reliability and performance improvement that NR can achieve when using DG units in modern DNs. An efficient metaheuristic rider optimizer algorithm (ROA) is applied to the complex combinatorial NR and DG allocation problem with stringent constraints. Analyses are conducted on benchmark IEEE 33-bus test DNs with explicit presentation of results.

1 Introduction

Planning distribution networks (DNs) with distributed generation (DG) units is a critical task in power systems engineering. As the electricity demand continues to grow and the integration of renewable energy sources (RES) becomes more prevalent, efficient and reliable DNs are essential for meeting the power needs of consumers. In this context, distribution network reconfiguration (NR) and reliability are crucial in ensuring optimal performance and minimizing power disruptions [1,2].

NR involves strategically altering the topology and configuration of the DN to optimize its operation, minimize power losses and improve reliability. By considering the placement and sizing of DG units, NR aims to improve the system's overall efficiency, voltage stability, and power quality. The planning process considers various factors, such as load profiles, generation capacity, and DN constraints, to determine the optimal configuration that maximizes the benefits of DG integration.

Reliability is another key aspect in the planning of DN with DG units. It refers to the ability of the system to deliver power consistently and without interruptions to consumers. The presence of DG units can enhance the reliability of the DN by reducing dependence on a centralized power source and providing localized generation close to the load centers. However, DG units' optimal placement and operation must be carefully considered to ensure a reliable and resilient power supply under normal and contingency conditions.

Due to simple protection and control mechanisms and lower short circuit current, DNs typically operate in radial topology [3]. There is only one source of supply per consumer in a radial topology. However, DNs are frequently the main reason for power system outages [4]. According to technical literature, issues in DNs account for 80% of consumer interruptions [5]. According to North American Electric Reliability Corporation records, 22% of power outages are caused by system equipment failures [6]. Overloaded systems can also cause outages. The frequency and severity of these power outages have increased in recent years. According to [7], from 2000 to 2013, the average number of grid failure events in the United States grew from 2.5 to 14.5 per month. According to [8], power outages could become more frequent and more severe in the future. Both electricity customers and electric utilities may also be affected by power outages. Consumers are primarily affected financially by an unpredictable power supply, which might also disrupt other operations that depend on electricity [9]. However, electrical utility firms experience a loss in energy sales and must cover additional operating and maintenance costs for service
restoration [10]. Distribution utilities invest in switching and protecting equipment to avoid prolonged outages and minimize the number of customers isolated by faults. With each outage, the quality of the power supply is degraded, so it's critical to measure and avoid them accurately. Reliability indices can quantify a network's ability to sustain continuous steady-state operation over a specific period. A system average interruption frequency index (SAIFI), a system average interruption duration index (SAIDI), and an energy not supplied (ENS) index are the most commonly used indices by utilities.

It was suggested in [11] to minimize load cost loss and average interruption indices by using a reliability-based NR technique. Switch exchange is based on the minimum path method, whereas the best configuration is found using meta-heuristic methods, including Tabu Search (TS), Evolution Strategies (ES), and Differential Evolution (DE). Simulating annealing (SA) redesigned the DN to increase reliability [12]. One needs to determine the optimal network topology to achieve the lowest disruption cost for customers. The cost of customer interruption is calculated using the reliability indices of the load points and the damage functions of customers, which correlate customer class with outage duration. A non-dominated sorting genetic algorithm (NSGA II) has been used to solve the reconfiguration problem of a large system containing DG units [13]. An ant colony optimization (ACO) approach combined with fuzzy multi-objective optimization has been used to minimize power loss and improve voltage profile by optimal simultaneous allocation of the distribution static synchronous shunt compensator (DSTATCOM), DG units, and NR in a DN [14].

It is important to note that when DG units are connected to a distribution feeder, they alter both the active power flow and the reactive power flow within the feeder, whereas when NR units are connected to a distribution feeder, they alter both the active and reactive power flows. DN's reliability and performance are directly affected by current flow since failure chances are primarily determined by current flow. Thus, it is essential to study how the simultaneous execution of NR and DG units affects DN performance, reliability, and efficiency. It has not yet been thoroughly explored in literature. The present research assesses whether NR and DG allocation can increase DN reliability and performance. To analyse the impact of DGs and NR on the reliability indexes, the failure statistics of feeders are proposed to be a function of feeder currents. This study uses a metaheuristic rider optimizer algorithm (ROA) to solve the complex combinatorial NR and DG allocation problem. The algorithm considers multiple reliability and performance enhancement objectives separately. An exhaustive analysis of DG allocation and NR in the IEEE 33-bus test DN is carried out by simulating some scenarios. The study's results and analyses are presented and analyzed extensively.

The remainder of this paper will be organized as follows: The problem formulation is presented in Section II. A detailed overview of the solution method is presented in Section III. The simulation results are presented in Section IV. Conclusion of the paper given in Section V.

2 Problem formulation

Due to increasing load demands, DNs suffer from power losses, low voltage levels, high currents, and low reliability. The optimal DG unit allocation considering optimal NR in the DN has been proven to improve reliability, reduce power loss, and improve voltage profile. As a result, to make the DN function effectively, it is essential to determine the optimal radial topology and the locations and sizes of the DGs to maintain a proper radial topology.

2.1 Objective function

The proposed technique has been used to perform four single-objective function optimizations. ENS, SAIFI, SAIDI, and power loss are four conflicting objectives. Through the use of suitable DG allocation and NR, the conflicting objectives have been minimized. The first objective is power loss minimization, and it is formulated as:

$$\text{Minimize } F = P_{\text{loss}} = \sum_{i} \sum_{j} \frac{P_i^2 + Q_i^2}{V_i^2}$$  (1)

where, $P_i$ and $Q_i$ are active and reactive power of bus $i$. $V_i$ is voltage magnitude of bus $i$. $R$ is resistance of branch $i$. $N_{i_b}$ is number of branch in test system.

The second objective is system average interruption frequency index (SAIFI) minimization, and it is formulated as:

$$\text{Minimize } F = \text{SAIFI}$$  (2)$$
$$\text{SAIFI} = \text{The total number of user outages} \over \text{total number of users} = \frac{\sum_{i} \lambda_i N_i}{\sum_{i} N_i}$$  (3)

where, $\lambda_i$ is the average failure rate of load point $i$. $N_i$ is the number of users of load point $i$.

Minimization of SAIDI has been considered as the third objective, and it is formulated as:

$$\text{Minimize } F = \text{SAIDI}$$  (4)$$
$$\text{SAIDI} = \text{The sum of user outage duration} \over \text{total number of users} = \frac{\sum_{i} U_i N_i}{\sum_{i} N_i}$$  (5)

where, $U_i$ is the annual average outage time of load point $i$.

The fourth objective is the minimization of expected energy not supplied EENS and its formulated as:

$$\text{Minimize } F = \text{ENS}$$  (6)$$
$$\text{ENS} = \text{Total energy not supplied by the system} = \sum_i L_i$$  (7)

where, $L_i$ is the average load of load point $i$.

2.2 Constraints

a) Power balance constraints

...
There must be a balance between the total power supplied to the network and the total power demand with loss [15].

\[ P_{\text{system}} = \sum_{i=1}^{N_{\text{bus}}} P_{\text{bus},i} + \sum_{j=1}^{M} P_{\text{gen},j} \]  
\[ Q_{\text{system}} = \sum_{i=1}^{N_{\text{bus}}} Q_{\text{bus},i} + \sum_{j=1}^{M} Q_{\text{gen},j} \]

where, \( P_{\text{system}} \) and \( Q_{\text{system}} \) are active and reactive system power, \( P_{\text{bus},i} \) and \( Q_{\text{bus},i} \) are active and reactive power losses, \( P_{\text{gen},j} \) and \( Q_{\text{gen},j} \) are active and reactive power demand, \( M \) is total system bus number.

b) Bus voltage constraint

\[ V_{\text{min}} \leq |V_i| \leq V_{\text{max}} \]

where \( V_{\text{min}} \) and \( V_{\text{max}} \) represent the minimum and maximum voltage values, respectively.

c) Line current constraints

The line current at any \( n \) line must meet the following constraints:

\[ I_{\text{line},n} \leq I_{\text{line},n(\text{max})} \]

where, \( I_{\text{line},n(\text{max})} \) is maximum allowed current of line \( n \).

d) Installed DG power size and power factor (PF) constraints

The DG power size in the DN is restricted as [1]:

\[ P_{\text{DG}}^{\text{min}} \leq P_{\text{DG}}(n) \leq P_{\text{DG}}^{\text{max}} \]
\[ Q_{\text{DG}}^{\text{min}} \leq Q_{\text{DG}}(n) \leq Q_{\text{DG}}^{\text{max}} \]

where, \( P_{\text{DG}}^{\text{max}}, Q_{\text{DG}}^{\text{max}} \) and \( P_{\text{DG},\text{max}}, Q_{\text{DG},\text{max}} \) represent maximum active, maximum reactive, and maximum PF of DG units. \( P_{\text{DG}}^{\text{min}}, Q_{\text{DG}}^{\text{min}} \) and \( P_{\text{DG},\text{min}}, Q_{\text{DG},\text{min}} \) represent minimum active, minimum reactive and minimum PF of DG units.

e) Constraints of radial topology

No insulated buses should exist in the DN topology, and the topology should be radial.

\[ \text{det}[\text{BusInM}] = 1 \text{ or } -1 \quad (\text{for radial network}) \]
\[ \text{det}[\text{BusInM}] = 0 \quad (\text{for nonradial network}) \]

where, \( \text{BusInM} \) is network incidence matrix.

### 3 Overview of solution technique and proposed algorithm

To solve the optimal planning of DG and NR problem, this study applies a recently developed metaheuristic rider optimizer algorithm (ROA).

#### 3.1 Network reconfiguration method

NR is one of the feasible methods in which power flow is varied by ON or OFF the switches on the feeders. It is incorporated by opening a sectionalizing switch and closing a tie switch to protect the feeder radial structure. The proposed algorithm searches for better-switching combinations that further improve reliability indexes, voltage stability and minimize losses by considering a tie switch and its neighboring sectionalizing switches one at a time. It continues the search process until there is no further improvement in voltage stability, active power losses and reliability. NR affects only tie/sectionalized switches but not other equipment’s location, properties, or status. Only feeder section failures are simulated for reliability evaluation in this study.

#### 3.2 Feeder failure rate model

For reliability calculations, failure statistics must be available for all network components. Component failure statistics are mainly based on their historical behavior, but they remain valid as long as the components are subjected to similar working conditions. Unlike the conventional DN in which the utility grid supply is distributed to end customers, there are now several DG sources in addition to the utility grid supply available in the modern deregulated and competitive energy market [16]; therefore, the current derived from the grid has decreased significantly. In addition to localized generation, NR is also contributing to a reduction in the magnitude of the feeder current, thus changing the operating conditions of the switches. In underground cables, the operating lifetime of insulation reduces at an exponential rate with a rise in temperature with current flowing through it [16]. This is quite important since a conductor’s current has a significant relationship with its temperature [16-17]. As a result, conductors that generate less heat are expected to last longer and be less prone to failure due to their reduced heat generation. Therefore, feeder failure statistics must account for this change in the current through feeders. According to the model presented in this paper, the feeder failure rate of an \( i^{th} \) feeder is calculated as a linear function of how much current flowed through it \( (I_i) \). As an example, if \( \lambda_{\text{base}} \) is the failure rate of a feeder carrying \( I_{\text{base}} \) before any compensation and it changes to \( \lambda_{\text{compensated}} \) after full current compensation, then its failure rate \( (\lambda_i) \) for any arbitrary current \( I_i \) flowing through and its formulated as follows [16]:

\[ \lambda_i = m \cdot I_i + \lambda_{\text{compensated}} \]  

where, \( m \) is the compensation degree and defined by the following formula:

\[ m = \frac{\lambda_{\text{base}} - \lambda_{\text{compensated}}}{I_{\text{base}}} \]

As a result of this relationship, network reliability is affected because feeder conductors that carry lesser current limit the temperature of the conductor, increasing
its lifespan and as the probability of failure is higher for an older conductor, reducing the current reduces the likelihood of failure.

3.3 Reliability evaluation in the integration of DG units

In recent years, the DNs have become more self-sufficient due to the integration of DG units that add to the system's reliability. These DG units supply the local demand during emergency periods. During a fault on a particular feeder, a small downstream segment of the network may be isolated from the grid based on the location and type of protection devices [16]. A faulty feeder in an isolated network bus may cause an outage for a duration equal to the repair or maneuver time of the feeder, depending on whether the supply can be restored after fault clearance by NR [16,18]. It is possible to form an island if a DG unit capacity $S_{DG}$ is located in an isolated network segment consisting of d buses, each of which exhibits a demand of $S_d$ and thus the condition must be satisfied for that island to form.

$$S_{DG} = \sum_{i=1}^{d} S_d + S_{inter}$$  \hspace{1cm} (18)

Due to the localized nature of the generation, losses in the island ($S_{loss}$) are negligible. A minimal number of loads are shed if localized generation is insufficient to sustain the island under condition (18) and prevent unstable operations.

3.4 Rider optimizer algorithm (ROA)

In recent years, metaheuristic optimization techniques such as the rider optimizer algorithm (ROA) have gained popularity. The ROA is inspired by a group of riders [19]. There are four groups based on the total group number. There are equal numbers of riders in each group. To arrive at a final solution, the groups take different approaches.

This algorithm can be summarized in the following way in terms of its basic steps:

Step 1. Randomly initialize group position and rider parameters (steering angle, brake, acceleration, gear).

$$X_i^0 = U(X_{min}, X_{max})$$  \hspace{1cm} (3.27)

where, $X_{min}$ and $X_{max}$ are the lower and upper limits of the optimization dimension.

Step 2. The success rate of riders is calculated as follows:

$$R_i = \frac{1}{|[X_i - I]|}$$  \hspace{1cm} (3.36)

where, $X_i$ is position of $i^{th}$ rider. $I$, is target position.

Step 3. Finding the leader rider according to the maximum rider’s success rate.

Step 4. Update positions of riders.

Bypass rider updates its position as follows:

$$X_{i+1}^{bypass} (i,n) = \delta \left[ X_i (\eta,n) \ast \beta (n) + X_i (\zeta,n) \ast [1 - \beta (n)] \right]$$  \hspace{1cm} (3.37)

where, $\delta$ and $\beta$ are random numbers within $[0,1]$, $\eta$ and $\zeta$ are random numbers within $[0,1]$, $G$ is riders’ total number.

The follower rider updates its position as follows:

$$X_{i+1}^{follower} (i,j) = X_{leader} (l,j) + \left[ \cos(T_{ij}) \ast X_{leader} (l,j) \ast d_i' \right]$$  \hspace{1cm} (3.38)

where, $i$ is selector of coordinate, $X_{leader}$ is position of leader rider, $l$ is its index, $T_{ij}$ is steering angle in the $j^{th}$ coordinate, $d_i'$ is travelled distance of the $i^{th}$ rider.

The attacker rider updates its position as follows:

$$X_{i+1}^{attacker} (i,k) = X_{leader} (l,k) + \left[ \cos(T_{ij}) \ast X_{leader} (l,k) \right] + d_i'$$  \hspace{1cm} (3.40)

where, $X_{leader} (l,k)$ is the leader rider position in $k^{th}$ coordinate.

Step 5. According to the calculated objective function, the leader rider position is updated.

Step 6. This step updates riders’ parameters (steering angle, brake, acceleration, gear).

Riders’ parameters are updated following the success rate using the activity counter.

Step 7. Time to ride off. The rider determines a race winner in the lead at the end of the race.

A summary of the proposed method’s parameters and the study’s limitations is presented in Table 1 [1-2,15].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>33-bus DN</td>
<td></td>
</tr>
<tr>
<td>Total rider number</td>
<td>20</td>
</tr>
<tr>
<td>Iteration number</td>
<td>50</td>
</tr>
<tr>
<td>Buses voltage limits</td>
<td>$0.93 \leq V_m \leq 1.05pu.$</td>
</tr>
<tr>
<td>Power generation limits of DG units</td>
<td>$0.2MW \leq P_{DG,m} \leq 3MW$</td>
</tr>
<tr>
<td>DG units’ PF limits</td>
<td>$0.7 \leq PF_{DG,m} \leq 1$</td>
</tr>
</tbody>
</table>

4 Research results

The proposed method has been carried out using MATLAB R2021b software on a PC having a core i5-6200U CPU @ 2.30GHz processor and 8 GB RAM, and its effectiveness is evaluated for IEEE 33-bus DN. The single-line diagram of the test network is shown in
Figure 1. The power flow calculations were performed based on the forward-backward sweep (BFS) method. A DG unit is assumed to be 100% reliable regardless of the network configuration and operated at its maximum generation capacity. A 100% availability assumption is made for disconnects, substations, and fuses. The test network’s feeder failure rates and repair/maneuver time can be found in [20]. When DG units are integrated or NR performed, the failure rates will be modified following equations (16) and (17), and performance and reliability indices will be evaluated, as described in equations (1–7). An 85% reduction in feeder failure rate is assumed with total current compensation. The extent of support provided by DGs in the event of feeder faults is determined by equation (18) and the location of the protection devices within the network (Fig. 1). The test DN is expected to perform under balanced load conditions. A constant power is expected in nature for all loads. Bus and line data of DN are taken from [21].

The following scenarios are used to demonstrate the effectiveness of the proposed approach:

Scenario 1: DG placement, Network Reconfiguration, and Simultaneously Reconfiguration with DG placement carried out for power loss reduction when compared to a Base configuration.

Scenario 2: Base configuration, DG placement, and Simultaneously Reconfiguration with DG placement carried out for reliability improvement when compared to Base configuration.

4.1. Scenario 1: Power loss reduction

Optimal DG allocation: In Table 2, the obtained results of the proposed technique for identifying the optimal size, location, PF, and simultaneously NR with DG allocation for single and multiple DG units in a 33-bus system are presented. According to this table, active power loss reductions for one, two and three PV-based DG units and simultaneously NR with one, two and three WT-based DG allocation in the test DN, active power loss reductions are 67.83, 86.42, 94.43, 82.41%, 90.61%, and 95.07%, respectively. Due to the ability to generate reactive power, WT-based DG is also more efficient than PV-based DG in terms of power loss reduction. The impact of the DG integration and their simultaneous NR with DG allocation on voltage profile is shown in Figs. 2-4.

![Figure 1. IEEE 33-bus radial DN with disconnects, fuses, and load points.](image1)

![Figure 2. The voltage profile of 33-bus DN with optimal installing one DG unit, NR and simultaneously NR with one DG unit.](image2)

<table>
<thead>
<tr>
<th>Cases</th>
<th>Bus № (size (kW)/PF) and tie switch</th>
<th>Power loss (kW)</th>
<th>Loss reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case</td>
<td>s33, s34, s35, s36, s37</td>
<td>210.98</td>
<td>-</td>
</tr>
<tr>
<td>Network reconfiguration</td>
<td>s9, s7, s37, s14, s32</td>
<td>139.55</td>
<td>33.85</td>
</tr>
<tr>
<td>One PV</td>
<td>s33, s34, s35, s36, s37</td>
<td>111.02</td>
<td>47.37</td>
</tr>
<tr>
<td>One PV+DNR</td>
<td>30, [1628/1] s13, s15, s7, s9, s28</td>
<td>81.687</td>
<td>61.28</td>
</tr>
<tr>
<td>One WT</td>
<td>s33, s34, s35, s36, s37</td>
<td>67.83</td>
<td>67.83</td>
</tr>
<tr>
<td>One WT+DNR</td>
<td>30, [1594/0.82] s13, s9, s34, s33, s27</td>
<td>37.105</td>
<td>82.41</td>
</tr>
<tr>
<td>Two PV</td>
<td>s33, s34, s35, s36, s37</td>
<td>87.165</td>
<td>58.68</td>
</tr>
<tr>
<td>Two PV+DNR</td>
<td>30, [1572/1.855/1] s8, s14, s7, s25, s16</td>
<td>67.182</td>
<td>68.15</td>
</tr>
<tr>
<td>Two WT</td>
<td>s33, s34, s35, s36, s37</td>
<td>28.50</td>
<td>86.42</td>
</tr>
<tr>
<td>Two WT+DNR</td>
<td>10, [715/0.7,1725/0.7] s15, s33, s27, s34</td>
<td>19.792</td>
<td>90.61</td>
</tr>
<tr>
<td>Three PV</td>
<td>s33, s34, s35, s36, s37</td>
<td>72.786</td>
<td>65.50</td>
</tr>
<tr>
<td>Three PV+DNR</td>
<td>14, 25, 27, [1008/1, 1301/1, 707/1] s8, s9, s33, s28, s31</td>
<td>55.262</td>
<td>73.80</td>
</tr>
<tr>
<td>Three WT</td>
<td>s33, s34, s35, s36, s37</td>
<td>11.740</td>
<td>94.43</td>
</tr>
<tr>
<td>Three WT+DNR</td>
<td>8, [1265/0.7,1004/0.7,1220/0.7] s2, s15, s14, s11, s22</td>
<td>10.40</td>
<td>95.07</td>
</tr>
</tbody>
</table>
4.2. Scenario 2: Reliability improvement

Figure 1 shows the test network for this case. A set of links, namely s33-s37, represents the initial molecular structure, i.e., network configuration. In Table 3, the results obtained by NR are explicitly presented.

As shown in Table 1, by opening the switches s10, s15, and s27 and closing the tie switches s35, s36, and s37, the ENS decreased from 7097.95 kWh/year to 5057.0238 kWh/year, which can be reduced to 28.75% of the base case. As shown in Table 3, changing the radial structure appropriately will minimize SAIDI and SAIFI by 27.12% and 15.74%, respectively.

The test network is updated for this analysis by optimal allocation of three PV-based DG units’ size and location as mentioned in Table 8 (DG location and size table) and for minimizing the objectives (2, 4 and 6) separately. Under normal operating conditions, all DGs are assumed to have a unity PF. Table 4 summarizes the obtained results for this case.

All three reliability indices improved at base configuration when three PV-based DG units were integrated optimally. There is a significant reduction in SAIDI, SAIFI, and ENS, respectively, by 6.34%, 5.66%, and 6.1% as a result of optimally allocating three PV-based DG units.

<table>
<thead>
<tr>
<th>Objective minimized (optimal configuration)</th>
<th>Reliability indices</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SAIDI hours/customer year</td>
</tr>
<tr>
<td>Base case (s33, s34, s35, s36, s37)</td>
<td>2.0436</td>
</tr>
<tr>
<td>SAIDI (s10, s33, s34, s16, s27)</td>
<td>1.4893</td>
</tr>
<tr>
<td>SAIFI (s27, s17, s33, s14, s35)</td>
<td>2.2164</td>
</tr>
<tr>
<td>EENS (s10, s33, s34, s15, s27)</td>
<td>5063.315</td>
</tr>
</tbody>
</table>

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<tr>
<th>Objective minimized (optimal configuration)</th>
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<tr>
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<td>Base case (s33, s34, s35, s36, s37)</td>
<td>2.0436</td>
</tr>
<tr>
<td>SAIDI (s33, s34, s35, s36, s37)</td>
<td>1.914</td>
</tr>
<tr>
<td>SAIFI (s33, s34, s35, s36, s37)</td>
<td>2.2801</td>
</tr>
<tr>
<td>EENS (s33, s34, s35, s36, s37)</td>
<td>6687.3039</td>
</tr>
</tbody>
</table>

This analysis depicts the modern case analysis of DN by optimal integration of three PV-based DG units with...
NR simultaneously, as given in Table 8. Table 5 summarizes the obtained results for this case.

From the table, it can be seen that three PV-based DG units with NR significantly improve network reliability. When obtained results in Table 8 were placed in the test network, SAIDI, SAIFI and ENS were reduced by 33.08%, 20.26%, and 34.27%, respectively. As a result of the reduction in feeder failure rates and the real power support provided by PV-based DG units during emergencies, the index was reduced by 34.27% when using NR with three PV-based DG units simultaneously. NR with three PV-based DG allocations also significantly improves the other reliability indices.

<table>
<thead>
<tr>
<th>Objective minimized (optimal configuration)</th>
<th>Reliability indices</th>
<th>ENS (kWh/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAIDI (s33, s34, s35, s36, s37)</td>
<td>2.0436</td>
<td>2.4126</td>
</tr>
<tr>
<td>SAIFI (s33, s34, s35, s36, s37)</td>
<td>1.8293</td>
<td>1.8417</td>
</tr>
<tr>
<td>EENS (s33, s34, s35, s36, s37)</td>
<td>6429.5596</td>
<td>6373.4449</td>
</tr>
</tbody>
</table>

Following this case, the optimal integration of three WT-based DG units with NR was carried out simultaneously, as given in Table 8. Table 7 summarizes the obtained results for this case.

From the table, it can be seen that three WT-based DG units with NR significantly improve network reliability. When obtained results were placed in the test network at the base configuration, SAIDI, SAIFI and ENS were reduced by 40.18%, 27.11% and 40.20%, respectively. As a result of the reduction in feeder failure rates and the active and reactive power support provided by WT-based DG units during emergencies, the index was reduced by 40.20% when using NR with three WT-based DG units simultaneously. Additionally, NR with three WT-based DG allocations significantly improves the other reliability indices.

<table>
<thead>
<tr>
<th>Objective minimized (optimal configuration)</th>
<th>Reliability indices</th>
<th>ENS (kWh/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAIDI (s33, s34, s35, s36, s37)</td>
<td>2.1916</td>
<td>2.1804</td>
</tr>
<tr>
<td>SAIFI (s33, s34, s35, s36, s37)</td>
<td>1.9199</td>
<td>1.7585</td>
</tr>
<tr>
<td>EENS (s33, s34, s35, s36, s37)</td>
<td>4264.8434</td>
<td>4667.8849</td>
</tr>
</tbody>
</table>

The test network is updated for this analysis by optimal allocation of three WT-based DG units as mentioned in Table 8 (DG location and size table) and for minimizing the objectives (2,4 and 6) separately. Under normal operating conditions, all DGs are assumed to have an optimal PF. Table 6 summarizes the obtained results for this case.

All three reliability indices improved at base configuration when three WT-based DG units were integrated optimally. There is a significant reduction in SAIDI, SAIFI, and ENS by 10.48%, 9.62% and 9.61% respectively. Unlike three PV-based DG units, three WT-based DG units generated active and reactive power. Therefore, active and reactive currents are significantly reduced through feeder sections compared to three PV-based DG units.

<table>
<thead>
<tr>
<th>Objective minimized (optimal configuration)</th>
<th>Reliability indices</th>
<th>ENS (kWh/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAIDI (s33, s34, s35, s36, s37)</td>
<td>1.2223</td>
<td>1.3843</td>
</tr>
<tr>
<td>SAIFI (s27, s9, s7, s34, s16)</td>
<td>1.9199</td>
<td>1.7585</td>
</tr>
<tr>
<td>EENS (s10, s34, s7, s36, s27)</td>
<td>4264.8434</td>
<td>4667.8849</td>
</tr>
</tbody>
</table>

Table 5.

<table>
<thead>
<tr>
<th>Objective minimized (optimal configuration)</th>
<th>Reliability indices</th>
<th>ENS (kWh/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAIDI (s33, s34, s35, s36, s37)</td>
<td>2.0436</td>
<td>2.4126</td>
</tr>
<tr>
<td>SAIFI (s33, s34, s35, s36, s37)</td>
<td>1.8293</td>
<td>1.8417</td>
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<tr>
<td>EENS (s33, s34, s35, s36, s37)</td>
<td>6429.5596</td>
<td>6373.4449</td>
</tr>
</tbody>
</table>
Scenario Bus
to

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Bus location</th>
<th>Maximum generation capacity (MW/PF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three PV</td>
<td>24,30,14</td>
<td>1073/1,1058/1, 7961</td>
</tr>
<tr>
<td>Three PV+DNR</td>
<td>18,26,24</td>
<td>981/1, 747/1, 1384/1</td>
</tr>
<tr>
<td>Three WT</td>
<td>30,24,14</td>
<td>1176/0,7,982/0, 7,677/0,70113</td>
</tr>
<tr>
<td>Three WT+DNR</td>
<td>29,27,11</td>
<td>1743/0,7,356/0,7,719/0,70146</td>
</tr>
</tbody>
</table>

5 Conclusion

In this paper, an effective optimizer called ROA with the BFS method developed here for radial distribution NR with optimal DG allocation has been developed. To check the effectiveness of the proposed method, it is applied to standard 33 bus DN. The first scenario was carried out to minimize power loss of the test network with optimal integration DG units with NR and analyzed impact of size and locations of DG units and tie switches on the reduction of power loss and voltage profile has been obtained. NR, base configuration with DG installation and simultaneous NR with DG installation cases are analyzed with MATLAB programming. The results show that NR showed better results than the base configuration with the installations of DG. Then, the improvement of reliability from base case to NR case, base case to base with DG, and base case to simultaneously NR with DG has been observed.

As a result of this research, researchers can develop an algorithm and model that will reduce power loss and improve the voltage profile and reliability of DN.

References
