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Transforming distribution system into a sustainable isolated microgrid considering contingency

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Abstract. Currently, the distribution system has been adapted to include a variety of Distributed Energy Resources (DERs). Maximum benefits can be extracted from the distribution system with high penetration of DERs by transforming it into a sustainable, isolated microgrid. The key aspects to be addressed for this transformation are the determination of the slack bus and assurance of reliable supply to the prioritized loads even during contingency. This paper explores the possibilities of transforming the existing distribution system into a sustainable isolated network by determining the slack bus and the optimal locations and capacity of Distributed Generators (DGs) in the isolated network, taking into account the contingencies due to faults in the network. A combined sensitivity index is formulated to determine the most sensitive buses for DG placement. Further, the reliability based on the loss of load in the isolated system when a fault occurs is evaluated, and the modifications required in for reliability improvement are discussed. The supremacy of the transformed isolated network with distributed generators is comprehended by comparing the results from conventional IEEE 33-bus grid connected test system and modified IEEE 33-bus isolated test system having no interconnection with the main grid.

Key words: isolated microgrid, distributed generation, reliability, sustainability, prioritized load management, reconfiguration.

1. Introduction

Modern consumers demand reliable and quality energy supply for their loads. It is extremely challenging to facilitate this with the present infrastructure and can be achieved only by investing a significant amount of money for its modernization. An alternative to meet these requirements is to integrate small-scale, modular and highly efficient DGs in the distribution system. The security and reliability of such active distribution systems can be improved by transforming it into a sustainable isolated microgrid.

Over the past few decades, much research is being carried out in the optimal planning of DGs in distribution systems considering technical, economic, and environmental benefits. Depending on the technology used, DGs can supply real power alone, supply both real and reactive power, supply real power and consume reactive power, or supply only reactive power [1]. Renewable energy sources such as the wind, solar, biomass, and alternative sources such as diesel generators, and fuel cells are the available DG options.

In a distribution network, because of a high R/X ratio of the distribution lines, system losses are high. Hence, a loss minimum configuration is advantageous for the utility. A detailed review of DG planning in the distribution system is presented in [2] and an extensive survey on the uncertainty modelling methods is depicted in [3]. Various computational techniques used for planning a microgrid are reviewed in [4]. The methods proposed in literature can be broadly classified into analytical methods [1, 5–7], numerical methods [8–10], and intelligent search-based techniques [11–14].

In recent years, high penetration of DGs has evoked the possibility of transforming an existing distribution system into a sustainable, isolated microgrid. The feasibility of transforming an existing distribution system into an isolated microgrid, with the objective of loss minimization and voltage profile improvement is investigated in [15]. A methodology for finding the optimal location and capacity of DGs and the locations of the tie switches for reconfiguration are presented in [15]. However, for siting the DGs, the algorithm proposed in [15] is computationally intensive even for a system with a lesser number of buses, as it searches within all the permutations of buses and DG capacities possible. Also, the reliability of the microgrid in the event of a fault is not considered. In [16], both effective power flow-based and active power injection-based loss sensitivity factors of the system operating in non-autonomous mode are calculated and are used for identifying the optimal location of DGs. Further, Particle Swarm Optimization (PSO) is used to determine the size of the DG at these locations, considering that the system is operating in isolated mode. The probabilistic nature of the sources and loads are taken into account for the placement of DGs in [17]. A robust optimization approach for isolated network planning under load related uncertainty is proposed in [18]. However, the reliability of the isolated microgrid has not been analyzed in [17, 18]. A graph-partitioning and integer programming integrated methodology for the optimal planning of a loop-based microgrid topology considering the DGs and energy storage facilities is proposed in [19] for self-healing and protection coordination. In [20] planning of energy storage systems and controlling energy resources for

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energy balancing within planned community microgrid using decision tree approach is presented. In [21] the economic viability of microgrid deployment and the optimal generation mix of DGs with the objective of lowering the cost of unserved energy and DER investments is presented. In [22] planning of isolated community microgrid considering uncertainties associated with energy demands is suggested through optimal sizing and siting of tri-generation equipment, with the objective of minimising thermal losses and electrical losses. Determination of optimal location and size of the renewable based DGs for minimizing the microgrid power loss and increasing the loadability is proposed in [23]. Optimum location and size of DGs with the objective of minimizing the sum of the total investment, operational and maintenance costs is presented in [24]. An approach for transforming the distribution system into a set of microgrids for enhancing reliability and sustainability is proposed in [25].

From the literature review, it is clear that ample research has been done on the siting and sizing of DGs in the distribution system. However, the problem of identifying the slack bus, and the locations and capacity of DGs in an isolated microgrid has not been tackled yet. Further, little research has been done in the area of planning the DGs to increase the reliability of an isolated microgrid with multiple islands in the event of a fault. Besides, detailed analysis to evaluate the advantages of transforming the distribution system into an isolated microgrid has not been performed yet. In this context, the present study focuses on the planning of DGs in an isolated microgrid with the objective of minimizing losses, improving voltage profile, and maximizing the load served in the event of a fault. Also, the results obtained are compared with the non-isolated network to estimate the prospective advantages of this transformation.

This paper is organized as follows: In Section 2, the placement of DGs in an isolated microgrid and the sensitivity indices are elaborated. In Section 3, the objective functions for the planning and reliability analysis are presented. PSO techniques used for the optimization are discussed in Section 4. The algorithm for siting and sizing DGs is explained in Section 5. Reliability analysis performed in this study is detailed in Section 6, and the isolated microgrid management with prioritized loads is described in Section 7. Results and discussion on the various test cases are presented in Section 8 followed by conclusions in Section 9.

2. Placement of DGs in an isolated microgrid

For the isolated microgrid to be sustainable, DGs that can supply the total demand have to be integrated into the system. Unlike a non-isolated distribution system, it is necessary to determine the location of the slack bus in the network as it operates in isolation from the utility grid. Further, with N_g generators in a system with N_b buses, there are $P(N_g, N_b)$ permutations of locations to install the DGs. Because it is computationally intensive to try all such combinations in a practical system, an approach to reduce the search space for determining the candidate locations of DGs has to be deduced. Moreover, the optimum capacity of the DGs also has to be determined.

In the event of a fault, there may be multiple non-sustainable islands within the isolated microgrid resulting in reduced reliability of supply, which can be improved by load management and/or reconfiguration. In a microgrid, the loads have a definite priority. Moreover, for the stable operation, it is imperative to restore the system in a minimum possible time and serve the maximum load. To achieve these goals, it is necessary to decouple the load management and reconfiguration. Primarily, if there is a shortage of generation in the network, load management has to be done considering all the load priorities, ensuring that the high priority critical loads are served uninterruptedly. Secondly, in the event of a fault, islands with a shortage of power may exist within the isolated microgrid. In such cases, reconfiguration has to be done to interconnect these islands to the sections with surplus power to ensure continuity of supply. The assumptions and constraints used in the analysis are:

1. An isolated microgrid can accommodate any type of DG and hence, the type of DG and the cost of generation is not considered for optimization.
2. The DGs are controlled for constant real and reactive power.
3. A DG can be connected to any bus in the system.
4. The total generation from each bus (Sum of the power output of the generators connected to a bus) is considered to be from one source for the analysis.
5. The maximum DG capacity is total load plus losses.
6. The maximum and minimum bus voltage magnitudes are limited to 1.05 pu and 0.95 pu, respectively.

In the power system, load flow analysis needs to be performed to determine the adequacy of generation, losses, and voltage profile. In microgrids with radial structure, the Newton-Raphson method and other conventional approaches cannot be used because of the sparsity. Hence, for performing the load flow analysis, the backward-forward sweep algorithm is employed in this study [26].

The constraint that needs to be considered in network reconfiguration is to retain its radial topology.

2.1. Real Power Loss. The real power loss in the branch between bus p and bus q of a distribution system is given by (1).

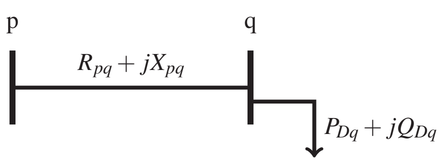

Fig. 1. Schematic of a branch between bus p and bus q

$$P_L(p, q) = \frac{P_q^2 + Q_q^2}{|V_q|^2} R_{pq} \tag{1}$$

where P_q and Q_q are the real and reactive power supplied beyond the bus q, V_q is the magnitude of the voltage at bus q and R_{pq} is the impedance of the branch between bus p and bus q.

The total real power loss (P_{LT}) in the distribution system with N_l branches is given by (2).

$$P_{LT} = \sum_{k=1}^{N_l} P_L(p, q) \tag{2}$$

2.2. Loss Sensitivity Index. Loss Sensitivity Index (LSI) of a bus can be used to identify the bus that provides maximum reduction in losses because of the power injection. The LSI of a bus because of the real power and reactive power injections are calculated using (3) and (4), respectively [27].

$$\frac{\partial P_L(p, q)}{\partial P_q} = \frac{2 \cdot P_q \cdot R_{pq}}{|V_q|^2} \tag{3}$$

$$\frac{\partial P_L(p, q)}{\partial Q_q} = \frac{2 \cdot Q_q \cdot R_{pq}}{|V_q|^2} \tag{4}$$

The bus that has the highest LSI provides maximum reduction in losses when a DG is connected.

2.3. Voltage Stability Margin. Radial distribution systems are prone to voltage collapse because of its network structure. The sensitivity of the buses to voltage collapse can be identified from the Voltage Sensitivity Index (VSI). Buses that have lesser VSI value are more sensitive to voltage collapse. The VSI of bus q in the network can be computed using (5) [28].

$$\begin{aligned} \mathrm{VSI}(q) = {} & |V_p|^4 - 4\left[P_q \cdot R_{pq} + Q_q \cdot X_{pq}\right]|V_p|^2 - \\ & - 4\left[P_q \cdot X_{pq} - Q_q \cdot R_{pq}\right] \end{aligned} \tag{5}$$

where P_q is the sum of the real power supplied beyond bus q and the real power demand at bus q, Q_q is the sum of the reactive power supplied beyond bus q and the reactive power demand at bus q.

The Voltage Stability Margin (VSM) is defined as the reciprocal of VSI and is given by (6).

$$\mathrm{VSM}(q) = \frac{1}{\mathrm{VSI}(q)} \tag{6}$$

2.4. Combined Sensitivity Index. In an isolated microgrid, the installation of DGs aims to reduce the losses and improve the voltage profile. Therefore, the sensitivity of a bus on real loss, caused by real power and reactive power injections and the VSM of the bus are combined to form a new sensitivity index called Combined Sensitivity Index (CSI) and is given by (7).

$$\mathrm{CSI} = \alpha \cdot \frac{\partial P_L(p, q)}{\partial P_q} + \beta \cdot \frac{\partial P_L(p, q)}{\partial Q_q} + \gamma \cdot VSM(r) \tag{7}$$

where α, β and γ are constants such that, $\alpha + \beta + \gamma = 1$ and $\alpha, \beta, \gamma \in (0, 1)$. The value of these constants is chosen after conducting the base case load flow. If more preference in the study is given for reducing the real power loss by real power injection, a higher value has to be allocated for α. Similarly, if the primary objective is to reduce the real power loss by reactive power injection, a higher value has to be provided for β, and if there are issues related to voltage stability, the greater value needs to be assigned to γ. Accordingly, based on the system requirements, the importance to be given for α, β and γ are decided by the expert power system planner, and appropriate values are allocated.

The buses having the highest value of CSI are the candidate locations for connecting DGs, which will provide maximum reduction in the distribution loss with improvement in voltage stability margin of the buses. Hence, the buses are arranged in the descending order of their CSI, and the top-ranked bus is selected for the installation of DG.

3. Objective Functions

3.1. Objective Function for Sizing DGs. The objective function for finding the optimal capacity of DGs in a radial isolated microgrid that minimizes the power loss in the system is given as:

$$\text{Minimize } f = P_{LT} \tag{8}$$

subject to

- Power Balance Constraints: Aggregate of the demand and losses in the system must be equal to the total generation in the system.

$$\sum_{i=1}^{N_b} P_{Di} + P_{LT} = \sum_{j=1}^{N_g} P_{DGj}$$

  where P_{Di} is the total demand at the i^{th} bus, N_b is the total number of buses in the system, P_{DGj} is the total real power output of the j^{th} DG, and N_g is the total number of DGs in the system.
- Generation limit of sources: Real and reactive power output of DGs must be within the specified minimum and maximum limits.

$$P_{DGj\,min} \le P_{DGj} \le P_{DGj\,max}$$
$$Q_{DGj\,min} \le Q_{DGj} \le Q_{DGj\,max}, \qquad j = 1, 2 \ldots N_g$$

  where Q_{DGj} is the total reactive power output of the j^{th} DG.
- Voltage limit of buses: Magnitude of the voltage at each bus must be within the specified minimum and maximum limits.

$$|V_{min}| \le |V_i| \le |V_{max}|, \qquad i = 1, 2 \ldots N_b$$

- Current limit in branches: Maximum power flow in a branch must be less than the thermal limit of the branch.

$$I_k \le I_{k\,max}, \qquad k = 1, 2 \ldots N_l$$

  where, I_k is the magnitude of current through the k^{th} branch and N_l is the total number of branches in the system.

3.2. Objective Function for Maximizing the load Supplied. In an isolated microgrid, the maximum load must be supplied at any point of time by load management and/or reconfiguration, considering the load priorities and the islands within the microgrid. Priority based load management for dynamically changing loads was first proposed in [29], where the load priorities could be given in chronological order, and the issues associated with different load magnitude-priority combinations is addressed. In this approach, based on the mismatch between generation and demand, the lower priority loads are immediately shut down. Further, an optimization technique is used to identify the maximum load that can be supplied, from the loads having priority next to the highest priority of load shed. Besides, all the loads having a priority greater than the optimized priority continues to get supply. Hence, the search space for optimization is limited to loads with only one priority leading to a solution in lesser time.

For priority based load management, the objective function is defined as:

$$\text{Maximize } f(x) = \sum_{n=1}^{N_{di}} x_{Ln} L_n \tag{9}$$

subject to

$$\left(\sum_{j=1}^{N_g} x_{DGj} P_{DGj} - \sum_{m=1}^{N_{dk}} x_{Lm} L_m \right) \geq \sum_{m=1}^{N_{di}} x_{Ln} L_n \tag{10}$$

where N_{di} is the total number of loads with priority 'i', N_{dk} is the total number of loads with priority greater than 'i' (priority: 1 to $i-1$), N_g is the total number of generators, x_{Ln} and x_{Lm} are the breaker status of n^{th} and m^{th} load, respectively, L_n and L_m are the magnitudes of n^{th} and m^{th} load, respectively, x_{DGj} is the j^{th} generator breaker status, and P_{DGj} is the real power generation of the j^{th} generator.

The objective function for reconfiguration, with a minimum number of tie/sectionalizing breaker operations, is defined as [29]:

$$\text{Minimize } f(x) = \sum_{r=1}^{N_s} y_r \tag{11}$$

where N_s is the number of tie/sectionalizing breakers and y_r is '1' if the r^{th} tie/sectionalizing breaker status has changed and '0' otherwise.

4. Application of Particle Swarm Optimization

In this study, the sizing of DGs and the determination of the breaker status for the management are done using Particle Swarm Optimization (PSO) [30].

4.1. PSO for Sizing DGs. The continuous version of PSO is used for determining the optimal capacity of distributed generators that minimizes losses in the system [30]. The position of particles (DG capacity) is updated using (12).

$$x_i^d(k+1) = x_i^d(k) + v_i^d(k+1) \tag{12}$$

where $x_i^d(k)$ and $x_i^d(k+1)$ are the positions of the i^{th} particle with dimension d at instant k and $k+1$, respectively, and $v_i^d(k+1)$ is the velocity of the i^{th} particle with dimension d at the instant $k+1$.

4.2. PSO for Isolated Microgrid Management. The parameters to be optimized in the isolated microgrid management are the status of load breakers for the load management, and tie/sectionalizing breakers for the reconfiguration. The breaker status takes only '0' or '1' and hence, binary version of PSO is used.

In binary PSO, the position updation means switching between '0' and '1', which has to be accomplished based on the velocity of the particles. As velocity is a continuous variable, a transfer function is used to map the velocity values to probability values for updating the positions [29]. In this study, a V-shaped transfer function (13) is utilized for the transformation. Further, this probability value is used to update the position of the particle (breaker status) using (14).

$$S\left(v_i^d(k)\right) = \left| \frac{2}{\pi} arctan\left(\frac{\pi}{2} v_i^d(k) \right) \right| \tag{13}$$

$$x_i^d(k+1) = \begin{cases} compliment\left(x_i^d(k)\right) & \text{if rand} < S\left(v_i^d(k+1)\right) \\ x_i^d(k) & \text{if rand} \geq S\left(v_i^d(k+1)\right) \end{cases} \tag{14}$$

The velocity of the particle in PSO is updated using (15).

$$x_i^d(k+1) = w(k) v_i^d(k) + c_1 r_1 \left(pbest_i^d - x_i^d(k) \right) + c_2 r_2 \left(gbest^d - x_i^d(k) \right) \tag{15}$$

where p_{best} is the best position of the particle, g_{best} is the global best position of the swarm, $w(k)$ is the inertia weight, c_1 is the cognitive acceleration constant, c_2 is the social acceleration constant and *rand* is a random number ranging between 0 and 1.

5. Optimal Siting and Sizing of DGs

Algorithm 1 presents the proposed computational procedure for determining the optimum location of the slack bus and the locations and capacity of DGs in a sustainable, isolated microgrid.

The computational procedure proposed in the algorithm can be explained in three stages. The first stage comprises of the selection of the prospective slack bus. For this, load flow using the backward-forward sweep algorithm is performed, considering each bus in the network as a slack bus. The total system loss and the bus voltages in each case are computed and tabulated. The bus that gave minimum loss is selected as the prospective slack bus.

In the second stage, the locations and capacity of DGs are determined using Iterative Procedure (IP). Load flow is performed with the selected slack bus, CSI of each bus is computed, and the buses are arranged in the descending order based on

Algorithm 1. To determine the locations and capacity of DGs

Input: *Number_of_DGs_Available*, *System Data*
Output: Location of slack bus, optimal locations, and capacity of DG

for $(k = 1 : No.\_of\_Buses)$ **do**
  Run load flow with the bus k as slack bus and compute *Total_System_Loss*
  $Loss[k] \leftarrow Total\_System\_Loss$
end for
$Pros\_Slack\_Bus \leftarrow$ Bus k which resulted in minimum loss
Run the base case load flow with *Pros_Slack_Bus* as the system slack bus and compute *Total_System_Loss*
$Old\_Loss \leftarrow Total\_System\_Loss$
while (No. of DGs installed $<$ *Number_of_DGs_Available* $-\ 1$) **do**
Calculate the CSI using equation (7)
  Locate the bus which is having the highest CSI value and place the DG
  Run load flow and compute *Total_System_Loss*
  $New\_Loss \leftarrow Total\_System\_Loss$
  while $[(New\_Loss < Old\_Loss)$ and (No constraint violation)$]$ **do**
    Update the DG capacity by an incremental value
    Run load flow and compute *Total_System_Loss*
    $Old\_Loss \leftarrow New\_Loss$
    $New\_Loss \leftarrow Total\_System\_Loss$
  end while
end while
while $[(New\_Loss < Old\_Loss)$ and (No constraint violation)$]$ **do**
  $Pros\_Slack\_Bus \leftarrow$ Bus next to *Pros_Slack_Bus* having a lower voltage magnitude
  Run load flow and compute *Total_System_Loss*
  $Old\_Loss \leftarrow New\_Loss$
  $New\_Loss \leftarrow Total\_System\_Loss$
end while
Resize the capacity of DGs at selected locations using PSO

the magnitude of CSI. The bus with the highest CSI is selected for placing the DG. Then, DG capacity in the selected bus is increased in incremental steps, losses are computed by running load flow, and constraint violations are checked. If there is any constraint violation, then the capacity obtained in the previous iteration is fixed as the size of DG for the selected bus. The second stage procedure is repeated until all the available DGs are placed.

The third stage involves re-fixing both the location of the slack bus and the capacity of DGs for maximizing loss reduction. For this, the DG in the prospective slack bus is moved to the nearby bus with lower voltage magnitude, losses are computed by running load flow, and constraint violations are checked. If there is any constraint violation, then the slack bus location in the previous iteration is fixed as the optimum location. Further, PSO is used to resize the DGs at the selected locations to ensure a maximum reduction in the value of the objective function for DG placement.

6. Reliability analysis

Determination of optimum locations and capacity of DGs is followed by the assessment of system reliability after the DG placement. In this study, the reliability of the microgrid is assessed by determining the magnitude of the load in the network that cannot be supplied, in the event of a fault. When a fault occurs in the i^{th} bus, the associated breakers trip to isolate the faulty bus from the rest of the network, which will result in loss of both load and DG in that bus. Moreover, certain sections of the microgrid may get isolated resulting in the formation of non-sustainable islands within the microgrid. Hence, it is mandatory to identify such sections in the network for proposing solutions for reliability improvement. Algorithm 2 presents the methodology for determining the solutions for improving the reliability.

Algorithm 2. Proposed Algorithm for Reliability Improvement

Input: *System_data*, *DGs_for_Reliability_Improvement*
Output: Location and capacity of DGs and Tie line details for reliability improvement

for $i = 1$ to N_b **do**
  Introduce fault at bus i
  Determine the islands even after possible reconfiguration.
  for (each island) **do**
    Determine the total demand.
  end for
end for
Determine the number of unique islands (N_U) and the demand in each.
Determine the optimum alternative for reliability improvement.

Three possible alternatives for reliability improvement are proposed in this study. The first alternative is by adding an additional DG in the appropriate bus of each isolated section. The second possibility is by adding a new branch (tie line) between the identified bus and a nearby loadable bus to feed the isolated section, and the third one is the combination of first two alternatives based on the economic and practical viability. In this study, the addition of one DG is chosen as the option for reliability improvement.

6.1. Additional DG: If the reliability improvement is attempted by adding additional DGs, then the total number of DGs required for 100% reliability is N_U, and the capacity of each of these DGs is the total demand in the corresponding island. If DGs of appropriate capacity are installed at N_U locations, each isolated section operates as an island in the isolated microgrid during a fault.

6.2. Using Tie Lines: In the case where the alternative selected is by adding tie lines, the nearby bus in the active network that can handle the additional load of the island is identified by assessing its loadability and is interconnected to that bus by adding a new branch.

Once the number of unique islands and their power demand during a fault are assessed, solutions for improving the reliability have to be identified.

7. Management of an Isolated Microgrid with Prioritized Loads

When radial distribution network with prioritized loads is operated in an isolated mode, there is a possibility of mismatch between generation and demand. In such cases, maximum demand in the network must be met, considering the load priority. Priority-based load management and reconfiguration of the microgrid proposed in [29] is used to determine the amount of load served in the network when a fault occurs. Algorithm 3 gives a brief description of the procedure adopted for load management and reconfiguration in the event of a fault.

Algorithm 3. Isolated microgrid management

```
Input: Current status of load breakers and tie/sectionalizing
    breakers
Output: Updated status of tie/sectionalizing breake
Determine the islands in the microgrid after fault
    isolation using tie/sectionalizing breaker status.
Determine Negative Power Island (NPI), where the
    demand is more than generation.
if (NPI exists) then
    if (NPIs can be interconnected with other islands) then
        for (Each island combination) do
            if (Power mismatch exists) then
                Perform priority based load management in
                Algorithm 4.
            else
                Identify the optimum combination of
                tie/sectionalizing breakers using PSO.
                Reconfigure the network by switching the
                tie/sectionalizing breakers.
            end if
        end for
    end if
end if
```

In a power system without sufficient generation, power mismatch between generation and demand is alleviated by load management. Further, in a microgrid, generally loads are given priority, and this needs to be adhered to when performing load management. Algorithm 4 describes the procedure for priority-based load management, where load priority is given in chronological order, and multiple loads have the same priority.

Algorithm 4. Algorithm for priority based load management

```
Input: Total load to be shed, load magnitude, load priority
Output: Updated status of load breakers
Prepare a load aggregate table based on priority.
Determine the index in the load aggregate table having
    aggregate less than or equal to the magnitude of the load
    to be shed.
if (Index exists) then
    if (aggregate < load to be shed) then
        Index = Index + 1
    end if
else
    Index = 1
end if
Determine the priority of the load corresponding to the
    index.
Shed the loads having priority less than the obtained priority.
Determine the no. of loads having priority equal to the
    obtained priority
if (no. of loads > 1) then
    Use PSO to identify the optimum load to be shed
else
    Shed the corresponding load
end if
```

For the successful implementation of the isolated microgrid management algorithm, generator breakers, load breakers, tie breakers, and sectionalizing breakers have to be controllable. The status of these breakers, generation and load magnitudes acquired using sensors are the inputs to the algorithm. In the event of any change in breaker status, the algorithm is executed, and the status of the breakers for load management and reconfiguration are determined.

8. Results and Discussion

The modified IEEE 33-bus, isolated, radial network topology, assumed to be operating in isolated mode, is used to test the proposed algorithm. The system is having tie lines with tie switches that are normally open. These tie switches are operated in the event of a fault to maintain continuity of supply, which results in the increased reliability of the system. In this study, the analysis is carried out considering that the system is operating at their peak demand and the base MVA and base voltage chosen are 100 MVA and 12.66 kV respectively.

8.1. Case Study. The following case studies were carried out to demonstrate the effectiveness of the proposed methodology.

- **Case 1.** One source: One DG in the slack bus.
- **Case 2.** Two sources: One DG in the slack bus and one DG in the network.
- **Case 3.** Three sources: One DG in the slack bus and two DGs in the network.

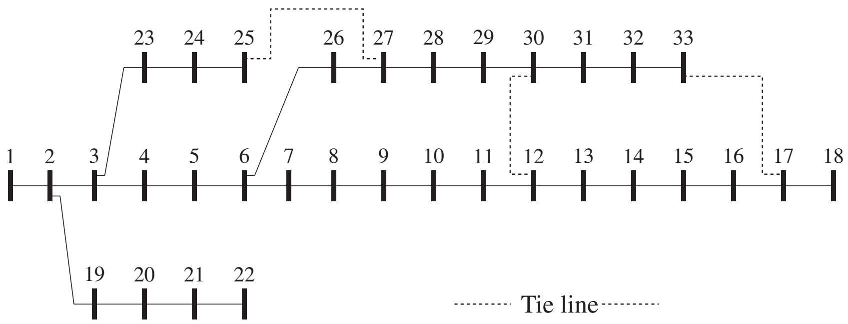

Fig. 2. One line diagram of the modified IEEE 33-bus isolated microgrid test system

8.2. Modified IEEE 33-bus Isolated Test System. The single line diagram of the modified IEEE 33-bus, isolated, radial distribution system [15] with 33 buses, 3 laterals, 3 tie lines, the total real power demand of 3.715 MW and reactive power demand of 2.3 MVAr is shown in Fig. 2. The only difference between this system and the conventional IEEE 33-bus test system is that this system is considered to be operating in isolation from the main grid.

Table 1 presents the simulation results of placing DG in the 33-bus isolated test system by IP and PSO for the three test cases. The results by PSO approach are same or better concerning loss reduction for all the studied test cases. The values of α, β, and γ used in this analysis are 0.7, 0.2, and 0.1 respectively.

In Table 2, the loss reduction with a different number of sources in isolated and conventional modes are compared to evaluate the advantages of transforming the existing distribution system into an isolated microgrid. From the results obtained it can be seen that, by installing a DG at bus 6 in the isolated test system, there is a loss reduction of 55.3% in the distribution network. It is worth noting that, when the network is operating in the conventional mode, taking power from the central generating plants, there will be transmission loss in the power system. However, in the isolated mode of operation, the transmission loss does not exist as the power is generated locally. Hence, a substantial improvement in the overall efficiency of the utility grid is achieved by the transformation of the existing distribution system into a sustainable, isolated microgrid.

Table 1
DG placement for the modified IEEE 33-bus isolated test system

Case	Method	Bus	DG Capacity		Distribution Loss	
			MW	MVAr	MW	MVAr
1	–	6*	3.8000	2.3695	0.0906	0.0695
2	CSI-IP	6*	2.5500	1.5925	0.0525	0.0423
		24	1.2100	0.7500		
	CSI-PSO	6*	2.5600	1.6000	0.0525	0.0423
		24	1.1976	0.7422		
3	CSI-IP	13	0.6800	0.4214	0.0304	0.0234
		24	1.9500	1.2080		
		29*	1.1100	0.6935		
	CSI-PSO	13	0.7894	0.4892	0.0246	0.0192
		24	1.5519	0.9618		
		29*	1.3900	0.8681		

*Slack bus

Table 2
DG for the IEEE 33-bus conventional and modified IEEE 33-bus isolated test system

No. of Sources	Conventional				Isolated			Loss Reduction %
	Bus	Utility Grid (MVA)	DG (MVA)	Real Loss (MW)	Bus	DG (MVA)	Real Loss (MW)	
1	1*	4.6090	–	0.2027	6	4.4835	0.0906	55.30
2	1*	1.3401	–	0.0617	6*	3.019	0.0525	14.86
	6	–	3.103		24	1.4089		
3	1*	1.2393	–	0.0384	13	0.9287	0.0246	35.89
	6	–	2.118		24	1.8258		
	30	–	1.0590		29*	1.6388		

*Slack bus

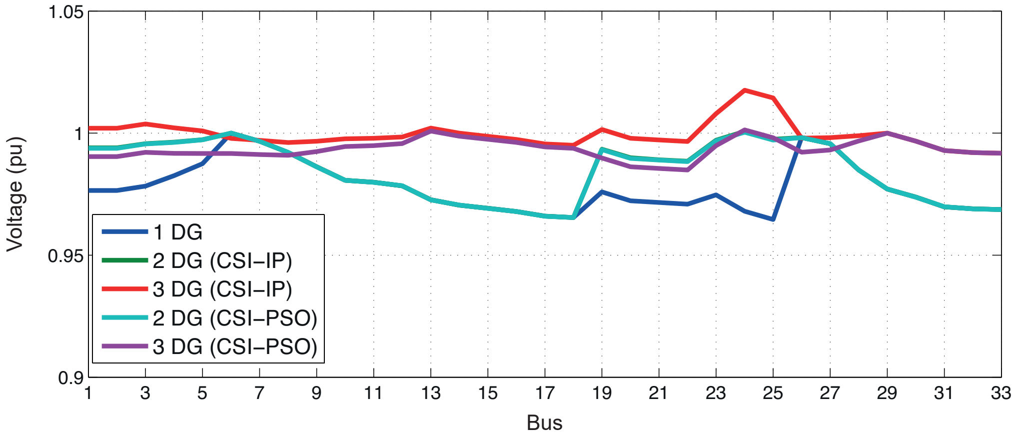

Fig. 3. Voltage profile in the modified IEEE 33-bus isolated microgrid test system after DG placement

8.3. Voltage Profile. Voltage profile of the modified IEEE 33-bus isolated test system for all the test cases are shown in Fig. 3. The minimum and maximum values of voltages in the modified IEEE 33-bus isolated test system for all the test cases are listed in Table 3. It can be observed that there is an improvement in the voltage profile with the increase in the number of DGs, and a relatively flat voltage profile is obtained with three sources.

Table 3
Bus voltages under different Cases for of the modified IEEE 33-bus isolated test system

Case	Method	Min voltage @ bus	Max voltage @ bus
1	–	0.9646 @ 25	1.0000 @ 6
2	CSI-IP	0.9654 @ 18	1.0007 @ 24
	CSI-PSO	0.9654 @ 18	1.0004 @ 24
3	CSI-IP	0.9918 @ 33	1.0176 @ 24
	CSI-PSO	0.9849 @ 18	1.0013 @ 24

8.4. Effect of α, β and γ on DG Placement. In the proposed approach, a CSI, which depends on the values of the constants α, β, and γ, is used to determine the optimal locations of DGs in an isolated microgrid. To assess the effect of these constants on the solution, a detailed analysis is conducted in the modified IEEE 33-bus isolated test system considering bus 1 as the slack bus. To contextualize the results obtained, the values of distribution losses and bus voltages with different combinations of α, β, and γ are compared with the base case load flow results. Table 4 and Table 5 shows three typical test cases indicating the effect of these constants on the distribution losses and the voltages at five buses having least voltage in the base case analysis respectively.

From the results, it can be seen that a higher value of α and β will identify DG locations that lead to increased loss reduction. Similarly, a higher value of γ gives prominence to improvement in voltage at the voltage sensitive buses compared to loss reduction. Further, it is observed that, by giving

Table 4
System losses for different combinations of α, β and γ for modified IEEE 33-bus isolated test system (Case 3)

α	β	γ	Bus	DG (MVA)	Real Loss (MW)	Loss# Reduction (%)
0.85	0.1	0.05	1*	2.0073	0.0510	74.75
			6	1.7694		
			13	0.6565		
0.3	0.2	0.5	1*	2.6855	0.0530	73.76
			18	0.0619		
			33	1.1301		
0.7	0.2	0.1	1*	2.4378	0.0386	80.89
			13	0.8357		
			31	1.1427		

* Slack bus; # with respect to the base case loss of 0.202 MW

Table 5
Bus voltages for different combinations of α, β and γ for modified IEEE 33-bus isolated test system (Case 3)

Bus	Bus Voltage (pu)			
	Base Case*	$\alpha = 0.85$, $\beta = 0.1$, $\gamma = 0.05$	$\alpha = 0.3$, $\beta = 0.2$, $\gamma = 0.5$	$\alpha = 0.7$, $\beta = 0.2$, $\gamma = 0.1$
18	0.9131	0.9942	1.0282	1.0163
17	0.9137	0.9948	1.0287	1.0169
16	0.9157	0.9967	1.0171	1.0187
33	0.9166	0.9783	1.0038	1.0008
32	0.9169	0.9786	0.9997	1.0010
Average System Voltage	0.9484	0.9963	0.9972	1.0011

*With bus 1 as slack bus

appropriate importance to the sensitivity factors by prudently choosing the values of α, β, and γ, contemplating the base case system losses and voltage profile, the optimum locations with a maximum reduction in losses and improvement of the bus voltages can be obtained.

8.5. Reliability Analysis. Detailed reliability analysis is conducted in the isolated test system with three DGs of optimum capacity installed at optimum locations. A fault is introduced at each bus to determine the number of islands at the instant of a fault and after possible reconfiguration. The cases where there are two or more islands within the isolated microgrid after possible reconfiguration are tabulated.

The simulation results obtained when introducing a fault in the modified IEEE 33-bus isolated test system are shown in Table 6. From this, it can be seen that, when a fault occurs at bus 2, there are two islands without any sources, island1 with bus 1 alone and island2 with buses 19, 20, 21, and 22. As island1 does not have any load, it can be ignored. Island2 has a total load of 360 kW and has to be supplied by connecting a DG or by interconnecting it with other parts of the network using tie lines. Further, when a fault occurs at bus 3, an island with buses 1, 2, 19, 20, 21, and 22 with a total load of 460 kW is isolated from the rest of the network and does not have any source. Similarly, on further analysis of other test cases, it can be concluded that by connecting a DG of 460 kW at bus 22 or by interconnecting bus 22 to another section of the network, reliability can be improved. The bus to which bus 22 needs to be interconnected can be determined by analyzing the loadability of the buses and the geographic distance between them. Also, it can be seen that, if the tie line 33–17 is changed to 33–18, the entire load is connected to one source or the other in the event of a fault.

Table 6
Number of islands during fault and after possible reconfiguration in the modified IEEE 33-bus isolated test system

Faulted Bus	No. of islands during fault	No. of islands after possible reconfiguration	Islands without sources	Loss of Load (kW)
2	3	2	Island1 : 1	0
			Island2 : 19-20-21-22	360
3	3	3	Island1 : 1-2-19-20-21-22	460
17	2	2	Island1 : 18	90
19	2	2	Island1 : 20-21-22	270
20	2	2	Island1 : 21-22	180
21	2	2	Island1 : 22	90

In the present study, it is assumed that addition of one DG is the only option available for attempting reliability improvement in the system. Hence, a DG of 460 kW is connected to bus 22 in the modified IEEE 33-bus isolated test system for reliability improvement.

The loss of load before and after the placement of one additional DG for reliability enhancement in the modified IEEE 33-bus isolated test system is compared in Table 7. It is seen that, by adding a single additional DG of appropriate capacity, the loss of load during most of the fault cases can be avoided, thereby ensuring high reliability. Hence, the potential of the proposed methodology in reliability improvement is reiterated from these results.

Table 7
Loss of load before and after DG placement for reliability improvement in the modified IEEE 33-bus isolated test system

Faulted bus	Loss of load (kW)		% Reduction in loss of load
	Before DG placement	After DG placement	
2	360	0	100
3	550	0	100
17	90	90	0
19	270	0	100
20	180	0	100
21	90	0	100

8.6. Management of an Isolated Microgrid. To further investigate the performance of an isolated microgrid with prioritized loads, single and multiple faults are introduced at various buses in the system after the placement of DGs. In the event of a fault, the isolated microgrid management algorithm is executed to alleviate mismatch between generation and demand by priority-based load management.

In the modified IEEE 33-bus isolated system, priorities from 1 to 12 are assigned to various loads as shown in Table 8. In this analysis, three DGs are located at buses 13, 24, and 29 with capacities listed in Table 1. An additional DG of capacity 460 kW is connected to bus 22 for reliability improvement.

Table 8
Load priority in the modified IEEE 33-bus isolated test system

Connected Bus	2	3	4	5	6	7	8	9
Priority	1	1	2	2	3	5	4	6
Connected Bus	10	11	12	13	14	15	16	17
Priority	7	3	5	4	4	7	6	5
Connected Bus	18	19	20	21	22	23	24	25
Priority	1	8	9	10	11	12	1	9
Connected Bus	26	27	28	29	30	31	32	33
Priority	5	5	12	10	9	1	3	5

Table 9 presents the results for seven typical fault cases when the isolated microgrid management algorithm is implemented in the modified IEEE 33-bus isolated test system. In case 1, when the fault occurred on bus 2, the entire network is divided into two islands. But each island has sufficient gen-

Table 9
Results of load shedding and reconfiguration during fault in the modified IEEE 33-bus isolated test system

Case	Faulted Buses	Load Disconnected (kW)	Load Shed (kW)	Reconfig-uration	Average Computing Time (sec)
1	2	100	–	No	0.161
2	13	60	240	Yes	0.247
3	17	60	90	No	0.181
4	24	420	650	Yes	0.292
5	29	120	840	Yes	0.285
6	2,13	160	270	Yes	0.307
7	5,14	180	–	Yes	0.233

eration within itself to meet the demand. Since, the only load disconnected from the system is the 100 kW load connected to bus 2, load management or reconfiguration is not required. In case 2, when a fault occurred on bus 13, in addition to the 60 kW load in bus 13, a load of 240 kW is shed to alleviate the power mismatch. In this test case, reconfiguration is required to serve maximum highest priority loads in the network. In case 3, the fault in bus 17 resulted in the disconnection of 60 kW load from bus 17 and shedding additional load of 90 kW from the network. In this case, reconfiguration is not required to meet the demand and hence not done. In test cases 4 and 5, both load management and network reconfiguration are done to serve the highest priority loads.

In case 6, simultaneous faults in buses 2 and 13 resulted in the formation of three islands. Island1 with bus 1 alone does not have any load and can be ignored. Island2 consisting of buses 19, 20, 21, and 22 has sufficient generation to meet the demand. Island3 with remaining buses has a shortage of generation, and hence a total load of 270 kW having lower priority is shed to mitigate the power mismatch. Further, in case 7, simultaneous faults in buses 5 and 14 resulted in the reconfiguration of the network, without load management to serve the maximum load.

From this study, it is evident that transformation of an existing distribution system into an isolated microgrid by optimally placing DGs results in a significant reduction of distribution losses and improvement in voltage profile as compared to the addition of DGs in a conventional distribution network. Further, it can be seen that by implementing priority-based load shedding and reconfiguration algorithm, the system can be operated safely and reliably by serving maximum higher priority loads. Moreover, the interconnection of the transformed system to the utility grid needs to be made only during emergency situations.

9. Conclusions

In this paper, a methodology for transforming the radial distribution network into an isolated microgrid is proposed. A systematic approach for determining the slack bus and the optimal locations and capacity of DGs, with the objective of minimizing losses, improving voltage profile, and reliability, considering contingency is suggested. Detailed analysis has been done to demonstrate the effectiveness of the proposed methodology. From this analysis, it is proved that such a configuration has lesser losses and better voltage profile than adding distributed generators in the existing distribution network. To further minimize the losses in the system, PSO is used to determine the optimum size of the DGs. However, this improvement is at the cost of degrading the voltage profile by a marginal amount.

The reliability of the system after placing DGs is evaluated in this study. The possible modifications that can be incorporated to improve the reliability proposed in the event of a fault are by adding DGs in the islanded sections, interconnecting the islanded sections with the active part of the network, or by the combination of both according to practical and economic viability. Also, the priority-based load shedding and reconfiguration algorithm are employed to evaluate the loss of load in the system when a fault occurs, which is an indicator of the system reliability.

Further studies can be done to determine the capacity and locations of DGs considering the probabilistic nature of the renewable-based sources and loads. Moreover, restriction on the type of DGs and the minimization of generation cost can also be considered for the optimization.

Appendix

The parameters used for PSO are: Population size = 50, Number of iterations = 50, Inertia weight: Min = 0.2 & Max = 0.9, $c_1 = 1.2$, $c_2 = 1.2$, Particle Velocity: Min = –0.3 & Max = 0.5.

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