# Distribution Network Planning Enhancement via Network Reconfiguration and DG Integration Using Dataset Approach and Water Cycle Algorithm

Munir Azam Muhammad, Hazlie Mokhlis, Kanendra Naidu, Adil Amin, John Fredy Franco, and Mohamadariff Othman

*Abstract*—The integration of network reconfiguration and distributed generation (DG) can enhance the performances of overall networks. Thus, proper sizing and siting of DG need to be determined, otherwise it will cause degradation in system performance. However, determining proper sizing and siting of DG together with network reconfiguration is a complex problem due to huge solution search space. This search space mostly contains non-radial network configurations. Eliminating these non-radial combinations during optimization process increases computational overhead and may end up at local optimal solution. To reduce the searching complexity, this paper considers the discretized network reconfiguration via dataset approach. Water cycle algorithm (WCA) is used to obtain the near optimal solution of network reconfiguration, and sizing and sitting of DG. In addition, the power factor of DG is also optimized to reduce the power loss. The proposed method is tested on an IEEE 33-bus network and an IEEE 69-bus network considering different scenarios to show the effectiveness of simultaneous approach considering variable power factor. The results show that the discretization of reconfiguration search space avoids that WCA to get trapped in local optima. The proposed method outperforms other technique such as harmony search algorithm (HSA), fireworks algorithm (FWA), Cuckoo search algorithm (CSA) and uniform voltage distribution based constructive algorithm (UVDA) and improves the solution quality of IEEE 33-bus network and 69-bus network by 29.20% and 27.88%, respectively.

*Index Terms*—Reactive power injection, sizing and siting of distributed generation (DG), dataset approach, active distribution network, power system.

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## I. INTRODUCTION

PROGRESSIVE load growth has placed distribution companies in a challenging environment where the emphasis on efficient and reliable operation of distribution system is heightened. Operational efficiency of a distribution network is significantly affected by power loss. In particular, 70% of the total power system loss originates from distribution systems [1]. Therefore, the minimization of power loss is imperative to achieve an efficient and economical operation of the system. In this regard, many methods have been adopted to minimize power loss of distribution network. Prominent techniques such as distributed generation (DG) integration and network reconfiguration have been widely followed. This integration offers numerous benefits including capacity relief of distribution system, power loss reduction, voltage profile improvement, load balancing, and reliability improvement.

The deployment of DG units in distribution network is an effective method to minimize power loss [2]. However, it is essential to identify its appropriate sizing and siting in the network. Improper sizing and siting can lead to an increase in power loss and a reduction in system efficiency [3]. Therefore, careful planning is necessary to ensure system operation within its security and stability limits. Many researchers have targeted power loss minimization as one of the objectives to determine optimal sizing and siting of DG in the distribution network [4]. Recent studies have addressed the application of optimization techniques for finding optimal sizing and siting of single or multiple DG units. Reference [5] minimizes the network power loss by determining optimal coordination of DG using particle swarm optimization (PSO) algorithm. Reference [6] employs Cukoo search algorithm to minimize power losses for non-dispatchable DG units. Reference [7] optimally places DGs in distribution network using evolutionary programming (EP). Reference [8] utilizes Bat inspired algorithm for DG sizing and its allocation problem to minimize power losses in radial and meshed networks.

Apart from DG integration, a well-known grid strategy called distribution network reconfiguration (DNR) is also applied to optimize the operational performance of the distribu-

tion network. DNR leads to a new network topology by altering the open/closed status of line switches while maintaining the radiality. DNR is an important grid strategy which decreases active power loss, improves voltage profile and system reliability [9]. Furthermore, DNR can be used to avoid overloading by transferring load from one feeder to another.

Considerable amount of research has also been conducted on network reconfiguration using metaheuristic optimization algorithms in the last few years. Reference [10] solves DNR problem using binary PSO (BPSO) for loss minimization. Fireworks algorithm (FWA) and harmony search algorithm (HSA) are considered for DNR in [11],[12]. The aforementioned techniques have shown excellent performance in finding near optimal solutions.

The research works stated above mainly focus on a single optimization problem, i.e., either DG integration or DNR for network power loss minimization. Nevertheless, there are few studies dealing with simultaneous integration of both DG and DNR. Reference [13] proposes a systematic method for optimizing network power loss using PSO algorithm. Initially, DNR is applied by the identification of optimal sizing and siting of DG. Reference [14] uses HSA to simultaneously handle DNR and DG coordination problem. Reference [15] integrates DNR with DG location problem using firework algorithm. Optimal configuration and DG siting is determined based on minimum network power loss. Reference [16] simultaneously determines feeder configuration with DG sizing using EP and genetic algorithm (GA).

It is important for distribution utilities to seek efficient and economical operation of the system through optimal network reconfiguration, and active and reactive power injection from DG units. Nevertheless, the simultaneous optimization of network reconfiguration as well as sizing and siting of DG leads to a complex problem which is difficult to solve using mathematical approaches. To address this challenge, metaheuristic techniques can be used since it implements efficient strategies to explore the search space.

One of the challenges in exploring the possible solution is the huge numbers of non-radial configuration in the search space. Therefore, [17] proposes an explicit radiality constraint for mathematical optimization. Reference [18] proposes a technique to generate feasible combination using GA integrated with Prims algorithm. In this proposed technique, the initial combination is generated using the prims algorithm. Therefore, all the combinations generated in this stage are feasible. However, implicit validation of radiality is considered in the recombination stage to generate feasible combinations. Reference [19] proposes a technique to generate feasible combination for network reconfiguration (NR) based on loop vector. Loop vector is extracted by closing tie switches and based on this vector, prohibited vector and common vector are obtained. PSO is used to search for near optimal solution, and the population in PSO are initialized and updated based on these vector rules.

Most researchers in the past consider the implicit method to ensure radiality solution and the process of eliminating the non-radial configurations can be time-consuming during the optimization process. In this paper, to improve the efficiency by reducing the complexity of search space, water cycle algorithm (WCA) together with dataset approach is employed. Dataset approach provides only radial solutions for DNR, and WCA finds the near optimal solution. This work proposes a method to simultaneously deal with network configuration, sizing and siting of DG and its power factor to improve the effectiveness of distribution network. The impact of discretized reconfiguration search space integrated with unity and variable power factor for DG injection is also analyzed. The effectiveness of the proposed method has been tested on the standard IEEE 33-bus network and IEEE 69-bus network.

## II. Problem Formulation

An optimal network configuration together with DG coordination in an active distribution network reduces power loss, improves voltage profile as well as system efficiency and reliability. Objective function defined in (1) is considered to optimize network performance:

$$\min \sum_{ij=1}^{N_b} \left( \frac{P_{ij}^2 + Q_{ij}^2}{V_j^2} \right) R_{ij} \gamma_{ij} + \rho \tag{1}$$

$$\rho = \begin{cases} 0 & \text{if no constraint is violated} \\ a & \text{if constraint is violated} \end{cases} \tag{2}$$

where $P_{ij}$ is the active power flow; $Q_{ij}$ is the reactive power flow; $R_{ij}$ is the resistance of branch $ij$; $V_j$ is the voltage of the bus; $\gamma_{ij}$ is a state variable that defines opening/closing of the switch; $N_b$ is the total number of branches in the distribution network; $\rho$ is the penalty; and $a$ is the Big-M number.

### A. Constraints

To obtain an optimal configuration, the following conditions should be satisfied.

*1) Active and Reactive Power Flows*

Inward and outward power flows of $i^{\text{th}}$ bus must be balanced with the generated power and load demand at the particular bus.

$$P_g - P_d - \sum_{ij} P_{loss,ij} = \sum_{ij} P_{ij} - \sum_{ki} P_{ki} \qquad i \in \Omega_b, ij \in \Omega_l \tag{3}$$

$$Q_g - Q_d - \sum_{ij} Q_{loss,ij} = \sum_{ij} Q_{ij} - \sum_{ki} Q_{ki} \qquad i \in \Omega_b, ij \in \Omega_l \tag{4}$$

where $P_g$ and $Q_g$ are the active and reactive power generations at bus $i$, respectively; $P_d$ and $Q_d$ are the active and reactive loads at bus $i$, respectively; $P_{loss,ij}$ and $Q_{loss,ij}$ are the active and reactive power loss at branch $ij$, respectively; and $\Omega_b$ and $\Omega_l$ are sets of buses and branches, respectively.

*2) Voltage*

The voltage drops in branch $ij$ can be calculated considering the binary variable $\gamma_{ij}$ as shown in (5). Moreover, the voltage should be kept within nominal limits as defined by (7).

$$V_j^2 = V_i^2 - 2(R_{ij} P_{ij} + X_{ij} Q_{ij}) - I_{ij}^2 Z_{ij}^2 - \beta_{ij} \tag{5}$$

$$\beta_{ij} \leq \begin{cases} 0 & \gamma_{ij} = 1 \\ V_i^2 - V_j^2 & \gamma_{ij} = 0 \end{cases} \tag{6}$$

$$V_{min}^2 \leq V_i^2 \leq V_{max}^2 \tag{7}$$

where $\beta_{ij}$ is an auxiliary variable; $V_i$ is the sending bus voltage; $I_{ij}$ is the branch current; $X_{ij}$ is the reactance of a branch; $Z_{ij}$ is the impedance of the branch; $V_{max}$ and $V_{min}$ are the maximum and minimum bus voltages, respectively.

### 3) DG Capacity

The maximum apparent power capacity $S_{g_{max}}$ of a DG unit can be bounded as:

$$0 \leq P_g^2 + Q_g^2 \leq S_{g_{max}}^2 \tag{8}$$

### 4) Reactive Power Injection of DG Unit

The power factor of a DG unit is maintained above a minimum limit $p_f$. Therefore, reactive power limit must be controlled. Constraint (9) states the boundary condition of the DG unit.

$$\left| Q_g \right| \leq P_g \tan(\arccos(p_f)) \tag{9}$$

### 5) Maximum Power Flow of a Branch

The power flow and the current through a branch depends on its current carrying capacity $I_{max}$ and its state variable, as defined by (10)-(12).

$$I_{ij}^2 \leq I_{max}^2 \gamma_{ij} \tag{10}$$

$$-I_{max} V_{max} \gamma_{ij} \leq P_{ij} \leq I_{max} V_{max} \gamma_{ij} \tag{11}$$

$$-I_{max} V_{max} \gamma_{ij} \leq Q_{ij} \leq I_{max} V_{max} \gamma_{ij} \tag{12}$$

## III. Pdataset Development Using Spanning Tree Algorithm (STA)

To maintain the radiality of the distribution network, conventional meta-heuristic techniques employ implicit approach. In this approach, non-feasible solution generated during the optimization process is adjusted with feasible ones. To avoid the non-feasible solutions, a dataset approach based on STA is proposed in this work. The proposed method only generates all possible radial combinations which are stored in a database.

The topology of a distribution network can be represented

through graph $G$. A spanning tree is a subgraph $G'$ of a graph $G$ of a distribution network with $M$ edges, $N$ vertices and $N_s$ source (substation) vertices. $G$ contains $M - (N - N_s)$ independent loops and each subgraph has $N - N_s$ edges. The STA generates all possible trees in $G$ and each tree should satisfy the following conditions: ① Contain $N - 1$ edges; ② All nodes are connected without forming any loops.

The process of generating spanning trees is explained as follows.

Let $S_0 \subset G$ be the initial spanning tree and a transformation process generates a new tree $S$ such that $S \subset G$. This tree $S$ can be formed from $S_0$ by eliminating the edge $e_i \in S_0$ and adding an edge $e_j \in K$ ($K = G - S_0$ is a set of non-connected edges), as represented by the following equation.

$$S = S_0 - e_i - e_j \tag{13}$$

## IV. Application of WCA

In this research, WCA is used to simultaneously solve the DNR and DG coordination problems. WCA is nature-inspired algorithm and it is derived from the idea of flow of streams and river towards sea. It is based on hydrological cycle which includes vaporization, rainfall and runoff water. The vaporization causes rainfall which creates water streams and these streams are headed towards the river followed by the sea by run-off process [22]. The algorithmic flow of WCA is as follows.

### 1) Initializing the Population

In the initialization stage, the population in WCA is initialized with set of random solutions which is known as streams. Each stream in an initial population which has a potential to become the best solution. Streams are distributed randomly into solution landscape. A stream $X_{str}$ is arranged in $d$ dimensional solution space as shown in (14).

$$X_{str} = \begin{bmatrix} x_1 & x_2 & x_3 & \cdots & x_d \end{bmatrix} \tag{14}$$

A set of streams is called one population. $N_{pop}$ is randomly generated and is represented by $X_{str(N_{pop},d)}$ as shown in (15). $X_{str(N_{pop},d)}$ is the total streams with $N_{pop}$ population. $DG_{L,*}$, $DG_{S,*}$ and $DG_{pf,*}$ are the location, sizing of active power and power factor of DG, respectively.

$$X_{str(N_{pop},d)} = \begin{bmatrix} \overbrace{x_{1,1}}^{\substack{\text{Dataset}\\\text{index}}} & \overbrace{x_{1,DG_{L,1}} \quad \cdots \quad x_{1,DG_{L,N}}}^{\substack{\text{DG}\\\text{location}}} & \overbrace{x_{1,DG_{S,1}} \quad \cdots \quad x_{1,DG_{S,N}}}^{\substack{\text{DG}\\\text{size}}} & \overbrace{x_{1,DG_{pf,1}} \quad \cdots \quad x_{1,DG_{pf,N}}}^{\substack{\text{DG}\\\text{power factor}}} \\ x_{2,1} & x_{2,DG_{L,1}} \quad \cdots \quad x_{2,DG_{L,N}} & x_{2,DG_{S,1}} \quad \cdots \quad x_{2,DG_{S,N}} & x_{2,DG_{pf,1}} \quad \cdots \quad x_{2,DG_{pf,N}} \\ \vdots & \vdots & \vdots & \vdots \\ x_{N_{pop},1} & x_{N_{pop},DG_{L,1}} \quad \cdots \quad x_{N_{pop},DG_{L,N}} & x_{N_{pop},DG_{S,1}} \quad \cdots \quad x_{N_{pop},DG_{S,N}} & x_{N_{pop},DG_{pf,1}} \quad \cdots \quad x_{N_{pop},DG_{pf,N}} \end{bmatrix} \tag{15}$$

### 2) Evaluating Stream Fitness

After random generation of initial streams, each of the streams is evaluated based on their cost function, as defined in (16).

$$Y_i = f \left( x_{i,1}, x_{i,2}, x_{i,3}, \ldots, x_{i,d} \right) \tag{16}$$

where $Y_i$ is the fitness of $i^{th}$ stream and $i = 1, 2, \ldots, N_{pop}$.

### 3) Sorting Streams as Sea, River and Streams

After the evaluation of streams, they are sorted in ascending order. These potential best solutions are divided into three categories which are sea, river and streams. The best stream among them is termed as sea which represents the global best solution so far. Few streams which are relatively good are labelled as rivers and characterized as local best solutions, and the rest are named as streams [22].

$$X_{str(N_{pop},d)} = \left[ S_{ea} \ R_{iver,1} \ R_{iver,2} \ R_{iver,3} \ \cdots \ S_{tr,N_{sr}+1} \ S_{tr,N_{sr}+2} \ S_{tr,N_{sr}+3} \ \cdots \right] \tag{17}$$

Among the population of the streams, the number of streams $NX_{str}$ selected for sea and river are defined by $NX_{sr}$. And $NX_{sr}$ equals to the total number of rivers and seas.

$$NX_{str} = N_{pop} - NX_{sr} \tag{18}$$

### 4) Determining Intensity of Flow

The total number of streams can be computed using (17) and among them how many streams designated to river/sea are found from (19).

$$str_{nj} = round \left( \left| \frac{Y_j}{\sum\limits_{i=1}^{NX_{sr}} Y_i} \right| NX_{str} \right) \tag{19}$$

where $j = 1, 2, \ldots, NX_{sr}$ and $str_{nj}$ is the number of streams which flows into river or sea.

### 5) Run-off Process

The run-off process updates the streams and river so that they flow towards sea. The flow of the streams towards sea and river is defined by (20) and (21), and (22) determines the flow of river towards sea.

$$X_{iter+1}^{str} = X_{iter}^{str} + rand \cdot C(X_{iter}^{sea} - X_{iter}^{str}) \tag{20}$$

$$X_{iter+1}^{str} = X_{iter}^{str} + rand \cdot C(X_{iter}^{river} - X_{iter}^{str}) \tag{21}$$

$$X_{iter+1}^{river} = X_{iter}^{river} + rand \cdot C(X_{iter}^{sea} - X_{iter}^{river}) \tag{22}$$

where $X_{iter+1}^{str}, X_{iter+1}^{river}$ are the updated stream and river for next iteration, respectively; *rand* is the random number which is in the range of 0 and 1; and $C$ is the acceleration coefficient in the range of 1 and 2. Equations (20), (21) and (22) show that if the stream position is better than the joining river, its position is swapped accordingly, and the similar process repeats for sea and rivers.

### 6) Evaporation Process

To avoid WCA from converging locally, the concept of evaporation is considered in which the evaporated water from sea returns to landscape via rainfall. The water from the rain makes a new stream which again flows towards river/sea. This evaluation process ensures that the algorithm avoids the solution being trapped in local minima.

## V. RESULTS AND DISCUSSION

The performance of the proposed method is evaluated on the IEEE 33-bus network and IEEE 69-bus network. Three DG units have been placed with maximum generation of 3 MVA and 2 MW. Furthermore, four cases are considered for comparative analysis with results published in the literature.

1) Case 1: DG units are considered with initial system topology.

2) Case 2: DG units are considered along with optimal configuration.

3) Case 3: network reconfiguration after sizing and siting of DG.

4) Case 4: simultaneous network reconfiguration and siz-

ing and siting of DG.

### A. IEEE 33-bus Test System

The IEEE 33-bus test system is a 12.66 kV distribution system having a total of 3750 kW active and 2300 kvar reactive demand [23]. It includes 5 normally open switches and 32 normally closed switches. In this paper, it is assumed that all branches can be switched on or off. Therefore, the IEEE 33-bus test system has $^{37}C_{32}$ possible configurations. Out of 435897 possible configurations, only 50751 (11.64%) are radial configurations.

The power loss of the initial configuration is 208.459 kW and the minimum voltage is 0.9108 p.u. at bus 18. With optimal network reconfiguration, the power losses are reduced to 138.927 kW, which is around 33.35% improvement. The voltage magnitude is improved by 3.51%.

In Cases 1 and 2, when DG units are integrated in the distribution network, the system power losses are reduced to 71.919 kW (65.18%) and 58.580 kW (57.83%), respectively. The respective bus voltage improves by 7.14% and 3.4% for both cases accordingly. However, in Case 3, the system power loss decreases to 57.201 kW. This shows that configuration after sizing and siting of DG improves system performance compared to Cases 1 and 2.

In Case 4, simultaneous configuration of the network and sizing and siting of DG have been considered. In this case, the system voltage is improved by 6.92% and losses are reduced by 75.18% as shown in Table I, where CSA stands for Cuckoo search algorithm and UVDA stands for uniform voltage distribution based constructive algorithm.

From Table I, we can observe that when DGs inject both active and reactive power, the power losses in Cases 1-4 are reduced to 12.784 kW, 17.576 kW, 11.868 kW, and 9.9687 kW, respectively. There is a significant reduction in power loss as compared to active power injection. The power losses in each of the cases are reduced by 82.22%, 70%, 79.43%, and 80.73%, respectively. Similarly, the minimum bus voltage of the system is improved by 1.71%, 0.63%, 2.37%, and 2.04%, respectively.

The proposed method is also compared with other works in literature which uses HSA, FWA, CSA and UVDA. It can be observed that the proposed method outperforms other results from literatures. When unity power factor is considered, CSA outperforms the FWA, HSA and UVDA in obtaining near optimal solution of power loss except in Case 1 where UDVA obtains better solution. Besides, UVDA also considers DGs with reactive power injection. On the contrary, UVDA does not consider the power factor when sizing reactive power injection of DG. Based on Table I, it can be observed that UDVA attains higher power losses and lower power factor as compared to proposed method.

To verify the reconfiguration solution obtained by FWA and CSA in Case 3 of Table I, network reconfiguration is performed after the optimal sizing and siting of DG is obtained. DG units are located at buses 14, 18, and 32 with sizes of 0.5897 MW, 0.1895 MW and 1.0146 MW, respectively. The final configurations obtained by FWA are 7-8, 9-10, 9-15, 32-33, 28-29, and the power loss is 68.271 kW. On the

other hand, the configurations obtained by the proposed method are 7-8, 8-9, 9-10, 32-33, and 28-29, and the power loss is 67.859 kW. The results obtained from FWA is 0.6% higher than the optimal solution for power losses. The optimal configurations obtained by the CSA are 8-9, 9-10, 27-28, 21-8, and 18-33, and the power loss is 63.271 kW. On the contrary, the optimal configurations obtained by the proposed method are 7-8, 8-9, 9-10, 25-29, and 18-33, and the power loss is 61.0748. The result obtained by the proposed method is 3.43% less than that by CSA. Thus, the proposed method has managed to obtain optimal results while FWA and CSA converge at local optimum solutions.

TABLE I
ANALYSIS OF IEEE 33-BUS NETWORK WITH UNITY AND VARIABLE POWER FACTOR

| | Case | Unity power factor | | | | | Variable power factor | |
|---|---|---|---|---|---|---|---|---|
| | | HAS [14] | FWA [15] | UVDA [24] | CSA [25] | Proposed | UVDA [24] | Proposed |
| 1 | Tie line configuration | 33,34,35,36,37 | 33,34,35,36,37 | 33,34,35,36,37 | 33,34,35,36,37 | 33,34,35,36,37 | 33,34,35,36,37 | 33,34,35,36,37 |
| | DG configuration (MW) | 0.10 (18), 0.57 (17), 1.04 (33) | 0.58 (14), 0.18 (18), 1.01 (32) | 0.87 (11), 0.92 (29), 0.93 (24) | 0.78 (14), 1.12 (24), 1.35 (30) | 0.75 (14), 1.01 (24), 1.07 (30) | 0.87 (11), 0.92 (29), 0.93 (24) | 0.71 (14), 1.04 (24), 1.15 (30), |
| | DG configuration (Mvar) | | | | | | 0.41 (11), 0.95 (29), 0.45 (24) | 0.38 (14), 0.54 (24), 0.86 (30) |
| | Power loss (kW) | 97.306 | 89.084 | 74.573 | 74.625 | 71.919 | 17.684 | 12.784 |
| 2 | Tie line configuration | 7,9,14,32,37 | 7,9,14,28,32 | 7,9,14,32,37 | 7,9,14,28,32 | 7,9,14,32,37 | 7,9,14,32,37 | 7,9,1432,37 |
| | DG configuration (MW) | 0.27 (32), 0.16 (31), 0.66 (30) | 0.60 (32), 0.31 (33), 0.16 (18) | 1.12 (30), 0.59 (15), 0.53 (12) | 1.75 (29), 0.54 (12), 0.50 (16) | 0.93 (8), 1.07 (24), 0.95 (30) | 1.12 (30), 0.59 (15), 0.53 (12), 1.03 (30), 0.25 (15), 0.28 (12) | 0.92 (8), 1.00 (24), 1.04 (30), 0.42 (8), 0.55 (24), 0.78 (30) |
| | Power loss (kW) | 96.829 | 83.898 | 66.286 | 58.774 | 58.580 | 26.435 | 17.5768 |
| 3 | Tie line configuration | | 7,9,28,32,34 | | 8,9,27,33,36 | 7.8,9,32,37 | | 9,17,33,35,37 |
| | DG configuration (MW) | | 0.59 (14), 0.19 (18), 1.01 (32) | | 0.78 (14), 1.12 (24), 1.35 (30) | 0.75 (14), 1.10 (24), 1.07 (30) | | 0.71 (14), 1.04 (24), 1.15 (30), 0.38 (14), 0.54 (24), 0.86 (30) |
| | Power loss (kW) | | 68.271 | | 63.271 | 57.201 | | 11.8682 |
| 4 | Tie line configuration | 67,37,45,52,35 | 67,37,45,52,35 | 7.10,13,27,32 | 11,28,31,33,34 | 11,28,31,33,34 | 7,10,12,23,32 | 5,13,22,26,35 |
| | DG configuration (MW) | | | 1.55 (29), 0.65 (15), 0.49 (21) | 0.90 (18), 1.44 (25), 0.96 (7) | 0.96 (7), 0.75 (17), 1.28 (25) | 1.88 (29), 0.67 (15), 0.53 (21), 1.37 (29), 0.32 (15), 0.30 (21) | 1.05 (8), 1.26 (25), 0.82 (32), 0.54 (8), 0.89 (25), 0.57 (32) |
| | Power loss (kW) | | | 57.279 | 54.232 | 51.744 | 14.082 | 9.9687 |

Based on Fig. 1, it can be observed that the proposed method outperforms other techniques in terms of power loss reduction. Maximum power loss reduction is achieved in Case 4, when network reconfiguration has been performed simultaneously with sizing and sitting of DG.

Figure 2 shows the voltage profile of the 33-bus network. Fig. 2(a) shows that when only network reconfiguration is performed, the minimum bus voltage is below 0.95 p.u.. On the other hand, after integration of DG units in the distribution system, the minimum bus voltage has improved above 0.95 p.u.. When DG injects both active and reactive power, the minimum bus voltage is above 0.98 p.u., as shown in Fig. 2(b).

*B. IEEE 69-bus Test System*

The 69-bus test system is connected to a 12.66 kV substation with 3800 kW active load and 2690 kvar reactive load
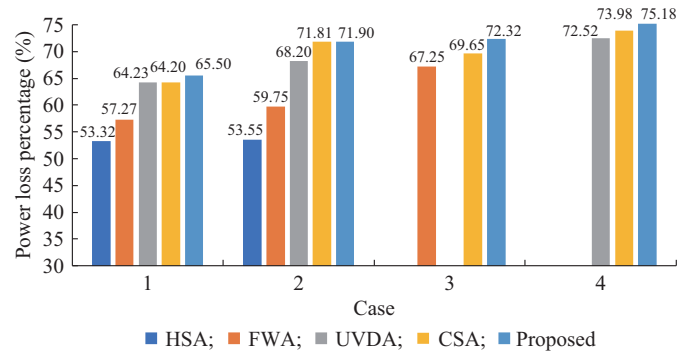


Fig. 1.   Power loss reduction percentage of IEEE 33-bus network.

[20]. The system has 68 normally closed sectionalized switches and 5 normally open tie switches. The total possible configurations are determined by $^{73}C_{68}$. Only 407924
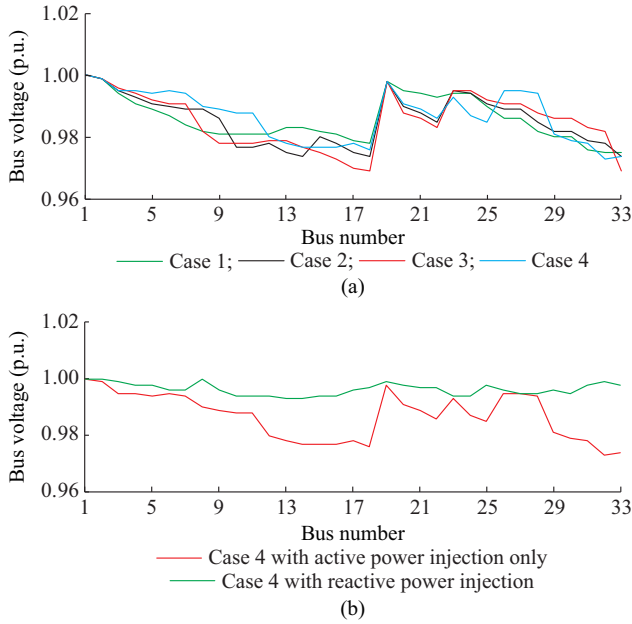
Fig. 2. Voltage profile of IEEE 33-bus network.

(2.71%) configurations from 15020334 are radial.

In Table II, similar case study has been performed to analyze the performance of the proposed methodology. For the initial configuration, the power loss of the distribution system is 224.975 kW with 0.909 p.u. minimum bus voltage. After network reconfiguration, the power loss reduces to 98.161 kW. Furthermore, in Cases 1-3, when DGs are integrated, the power losses further reduce to 69.431 kW, 35.044 kW and 38.962 kW, respectively. It can be observed that the simultaneous optimization of network reconfiguration and sizing and siting of DG provide better performance compared to their sequential optimization.

When unity power factor is considered as shown in Table II, CSA outperforms HSA, FWA and UVDA in terms of power loss reduction. The power loss obtained in Cases 1-4 is 72.47 kW, 37.105 kW, 40.901 kW and 36.895 kW, respectively. On contrary, the proposed method further reduces power loss by 4.19%, 5.55%, 4.74% and 2.58%, respectively. Similarly, when DGs are capable to inject active and reactive power, the losses obtained in Cases 1, 2 and 4 by UVDA with reactive power injection is 7.775 kW, 9.388 kW and 5.559 kW, respectively. In contrast to the proposed methodology, UVDA is trapped in local optima.

TABLE II
ANALYSIS OF IEEE 69-BUS SYSTEM WITH UNITY AND VARIABLE POWER FACTOR

| Scenario unity power factor | | Unity power factor | | | | | Variable power factor | |
|---|---|---|---|---|---|---|---|---|
| | | HAS [14] | FWA [15] | UVDA [24] | CSA [25] | Proposed | UVDA [24] | Proposed |
| Case 1 | Tie line configuration | 69,70,71,72,73 | 69,70,71,72,73 | 69,70,71,72,73 | 69,70,71,72,73 | 69,70,71,72,73 | 69,70,71,72,73 | 69,70,71,72,73 |
| | DG configuration (MW) | 0.10 (65), 0.36 (64), 1.30 (63) | 0.40 (65), 1.19 (61), 0.22 (27) | 1.41 (61), 0.60 (11), 0.41 (17) | 0.60 (11), 0.38 (18), 2 (61) | 0.52 (11), 0.38 (18), 1.71 (61) | 1.41 (61), 0.64 (11), 0.47 (17) | 1.41 (61), 0.64 (11), 0.47 (17) |
| | DG configuration (Mvar) | | | | | | 1 (61), 0.42 (11), 0.27 (17) | 1 (61), 0.42 (11), 0.27 (17) |
| | Power loss (kW) | 86.767 | 77.872 | 72.650 | 72.470 | 69.431 | 7.775 | 4.289 |
| Case 2 | Tie line configuration | 18,13,56,61,69 | 69,70,14,56,61 | 69,70,14,58,61 | 69,70,14,57,61 | 69,70,14,56,61 | 69,70,14,58,61 | 69,70,14,56,61 |
| | DG configuration (MW) | 1.06 (61), 0.35 (60), 0.42 (58) | 1.00 (61), 0.21 (62), 0.14 (64) | 1.37 (61), 0.62 (11), 0.72 (64) | 1.72 (61), 0.46 (64), 0.36 (12) | 0.53 (11), 1.43 (61), 0.49 (64) | 1.37 (61), 0.62 (11), 0.72 (64), 0.98 (61), 0.44 (11), 0.51 (64) | 0.53 (11), 1.41 (18), 0.48 (61), 0.38 (11), 1.01 (18), 0.34 (61) |
| | Power loss (kW) | 59.437 | 43.749 | 37.740 | 37.105 | 35.0442 | 9.388 | 5.326 |
| Case 3 | Tie line configuration | | 69,70,12,58,61 | | 69,70,14,58,64 | 13,55,64,69,70 | | 69,70,71,72,73 |
| | DG configuration (MW) | | 0.40 (65), 1.19 (61), 0.22 (27) | | 0.60 (11), 0.38 (18), 2 (61) | 0.52 (11), 0.38 (18), 1.71 (61) | | 0.49 (11), 0.38 (18), 1.74 (61), 0.35 (11), 0.25 (18), 1.19 (61) |
| | Power loss (kW) | | 39.572 | | 40.901 | 38.962 | | 4.289 |
| Case 4 | Tie line configuration | | | 14,58,63,69,70 | 69,70,14,58,61 | 69,70,14,56,61 | 8,12,70,58,64 | 13,20,24,42,57 |
| | DG configuration (MW) | | | 1.47 (61), 0.53 (11), 0.67 (17) | 0.54 (11), 0.55 (65), 1.72 (61) | 0.53 (11), 1.43 (61), 0.49 (64) | 1.66 (61), 0.62 (11), 0.39 (17), 1.87 (61), 0.44 (11), 0.26 (17) | 0.79 (11), 0.86 (49), 1.59 (61), 0.54 (11), 0.62 (49), 1.13 (61) |
| | Power loss (kW) | | | 37.000 | 36.895 | 35.0442 | 5.559 | 4.009 |

Furthermore, the proposed method improves the solution quality by 44.83%, 43.27%, and 27.88%, respectively. Similarly, the minimum bus voltage of the system has been maintained above 0.99 p.u., whereas UVDA achieves less power factor than the proposed method which is 0.663.

The proposed methodology outperforms other methodologies in each scenario of DGs with different power factors. It can be observed from Fig. 3 that the proposed method gives better power loss solution in each of the cases. The voltage profile of 69-bus test system is presented in Fig. 4. When DGs inject active power in the distribution system, the voltage of the buses in all cases is above 0.95 p.u. as shown in Fig. 4(a). When DGs operate in reactive power mode, the voltage at all buses is above 0.99 p.u. as shown in Fig. 4(b).
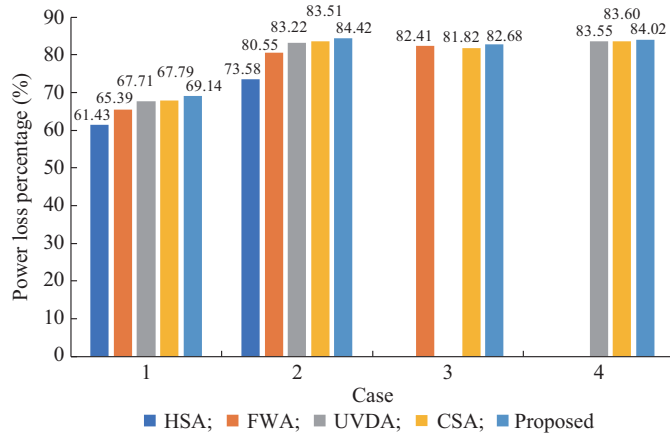


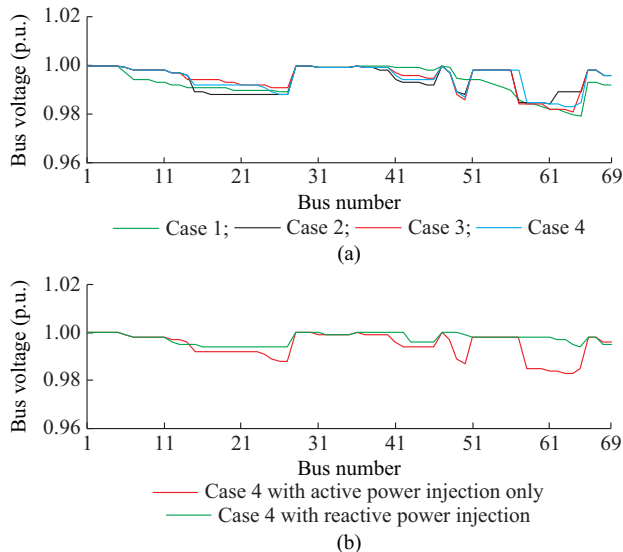Fig. 3. Power loss percentage of IEEE 69 Bus System.



Fig. 4. Voltage profile. (a) Voltage profile of IEEE 69-bus system. (b) Comparison between voltage profile of DGs operating in active power and reactive power mode.

## VI. Conclusion

With limited grid capacity, the enhancement in the network performance to address the growing load demand is a challenging task for the utilities. This paper presents simultaneous network configuration with optimal sizing and siting of DG and power factor to improve the effectiveness of dis-

tribution network. It can be observed that when DG injects active and reactive power, power loss has been reduced sufficiently. In the case of active power injection in IEEE 33-bus and 69-bus networks, the power loss is reduced by 75.16% and 84.42% respectively. After evaluation through various scenarios, it can be seen that the proposed method enhances the solution quality from the previous results obtained in the literature. Moreover, the optimal power factor (i.e., injection of active and reactive power) is more effective as compared to unity power factor. The result shows that there is 80.72% and 88.56% improvement in IEEE 33-bus and 69-bus networks, respectively, when optimal power factor is considered. Based on the evaluation from the investigation results, we can conclude that the integration of discretized reconfiguration search space with simultaneous reconfiguration, sizing and siting of DG and its power factor, significantly improves the effectiveness of distribution network.

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