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Voltage Profile Enhancement and Loss Minimization Using Optimal Placement and Sizing of Distributed Generation in Reconfigured Network

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Abstract: Power loss and voltage instability are major problems in distribution systems. However, these problems are typically mitigated by efficient network reconfiguration, including the integration of distributed generation (DG) units in the distribution network. In this regard, the optimal placement and sizing of DGs are crucial. Otherwise, the network performance will be degraded. This study is conducted to optimally locate and sizing of DGs into a radial distribution network before and after reconfiguration. A multi-objective particle swarm optimization algorithm is utilized to determine the optimal placement and sizing of the DGs before and after reconfiguration of the radial network. An optimal network configuration with DG coordination in an active distribution network overcomes power losses, uplifts voltage profiles, and improves the system stability, reliability, and efficiency. For considering the actual power system scenarios, a penalty factor is also considered, this penalty factor plays a crucial role in the minimization of total power loss and voltage profile enhancement. The simulation results showed a significant improvement in the percentage power loss reduction (32% and 68.05% before and after reconfiguration, respectively) with the inclusion of DG units in the test system. Similarly, the minimum bus voltage of the system is improved by 4.9% and 6.53% before and after reconfiguration, respectively. The comparative study is performed, and the results showed the effectiveness of the proposed method in reducing the voltage deviation and power loss of the distribution system. The proposed algorithm is evaluated on the IEEE-33 bus radial distribution system, using MATLAB software.

Keywords: distributed generation; voltage deviation; power loss minimization; particle swarm optimization; network reconfiguration; voltage stability enhancement

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1. Introduction

1.1. Background

Responding to rising electricity demands is a significant challenge for all energy utilities. The combustion of fossil fuels provides 75% of global energy demand. Increased greenhouse gas emissions, global warming, decreased fossil fuels, and increased fuel prices have demanded a potential energy strategy with regard to renewable resources. Providing renewable technologies for producing power has been a major concern in many countries over the past decade. A major challenge encountered by electrical distribution companies concerns the power losses and voltage instabilities arising from their respective networks. Owing to these problems, their operating costs increase, and their profits are subsequently decreased. The utilities have a great interest in the reliability of the system, voltage regulation, and active and reactive power (PQ) problems owing to the high degree of penetration of intermittent renewable energy sources (RES) into the distribution networks. That may pose a danger to the system. Therefore, distributed generation (DG) units are expected to follow strict technological and regulatory requirements to ensure the safety, stability, and efficiency of the distribution network [1].

The current distribution networks face numerous challenges. A voltage profile has great importance to customers, as it is a primary requirement for quality voltage-controlled electrical equipment. DGs can provide voltage support at the end of a feeder to increase the voltage [2]. Owing to the existence of DGs, network reliability, power flow, relay safety, voltage profile, and stability may have major impacts on distribution grids. The primary advantages of DG integration in power systems are power stability and enhanced distribution network reliability, as well as a variety of operational and cost-effective benefits. The benefits for both utilities and customers include better voltage profiles, lower power loss, peak load shaving, decreased transmissions, and expansion of the distribution network [2–4]. However, the increased injection of DG units into a network may cause several technical challenges, such as overvoltage, undervoltage, overloading, system protection, reverse power flows, power quality problems, and thermal overloading of the distribution lines. Microturbines, fuel cells, and photovoltaic (PV) systems are the core technologies that have been explored for distributed energy generation. Other DG technologies include engines for combustion, diesel, and wind. In areas with high energy costs and low reliability (including developing countries), DG technology has greatly increased the market potential [5]. In the United States alone, nearly 679 power loss incidents occurred from 2003 to 2012 [3]. The Electric Power Research Institute determined that by 2010, DGs would represent approximately 25% of new power generation, whereas a national gas foundation survey suggested that DGs would represent approximately 30% of new power generation [6].

1.2. Literature Review

Researchers are working on incorporating DGs into networks to minimize power loss, improve power efficiency, minimize line current, improve voltage profiles, improve system stability, and boost load performance. They use different algorithms and optimization techniques to integrate DGs into the network [7]. They have investigated different algorithms for DG placement in a radial distribution system, including approaches based on a heuristic optimization [8], and metaheuristic algorithms [9]. Moreover, the location and sizing were determined by nature-inspired algorithms [10], genetic algorithm (GA) from the array of artificial intelligence [11], whale optimization algorithm [12,13], particle swarm optimization (PSO) [14], unified PSO [15], and PSO for optimal placement of STATCOM [16]. A multi-objective optimization problem based on a Pareto frontier differential evolution algorithm [17], a hybrid method based on the imperialist competitive algorithm and GA [18], in addition to analytical approaches [19] and simplified analytical approaches [20], are presented. A salp swarm algorithm [21], sensitivity methods and quadratic curve-fitting technique [22], and ant lion optimization, such as a novel metaheuristic algorithm [23], are used for placement and sizing of DGs. A continuation power flow and modal analysis [24], analytical technique [25], optimal power flow algorithm [26], and clonal selection algorithm [27] were used to optimal allocation and sizing of DGs in the distribution system. Some authors have used a smart inverter for voltage control in a distribution system [28]. Reference [29] measured the voltage stability of buses in a system based on a novel voltage stability factor. RES will allow regulating the voltage challenges owing to their high penetration into grids. The voltage should be within the ANSI C84.1 limit [30], which allows a ±5% voltage deviation from the nominal value at the customer connection.

The power production of DG units faces considerable uncertainty owing to their intermittent nature and unreliability [31,32]. In [33], both grid-connected and off-grid scenarios, planning and control schemes have been developed for allocating surplus PV energy according to variable ratios. A novel fuzzy-PID controller is introduced to enhance the frequency stability of the power system. It utilized a novel nature algorithm called multi-verse optimizer to tackle the optimal frequency regulation [34]. Blockchain technology was used to improve cyber security, physical safety of energy networks and provide clean energy for customers [35]. A smart cyber physical multi-source device is implemented for applications in electric vehicles. This model is designed to improve the vehicle's charge efficiency along with self-energy dispatch system [36]. In Ref. [37], the internet of things system was used to monitor the power grid system. In [38], the authors described an economic evaluation of smart solar PV inverters with a unique control system (based on watt-var) to improve PV penetration into distribution networks in Taiwan, including a study of cost advantages and sensitivity. In [39], the authors proposed new DG size and location approaches for autonomous microgrids and structural changes. High power losses in a distribution network are generally reduced by an optimal network reconfiguration (NR), and by improving the voltage profiles in the electrical distribution networks. Researchers have investigated and implemented novel algorithms for solving problems related to NR with DGs. They have aimed to reduce the true power loss and boost the distribution network voltage profile by using a harmony search algorithm (HSA) [40], GA [41], a hybrid algorithm of PSO and ant colony optimization [42], and the firefly algorithm (FA) [43,44] to obtain near-optimal solutions for the network reconfiguration.

In this paper, a multi-objective PSO-based approach has been applied for the placement and sizing of multi-DG units to obtain maximum power loss reduction, limiting branch current, and voltage stability improvement before and after reconfiguration of the distribution network. The integration of multi-DGs enhances the performance of the network to a certain level in terms of the bus voltage magnitude, limiting of line current, minimize voltage deviation, and energy losses. Further reconfiguration of the distribution system can increase the performance of an autonomous microgrid. The factor named as the penalty factor is also taken into account in case of voltage and power loss violation occurs in the system. It compels the voltage from violating the limits so as to the voltage stability and minimize power loss of the system. The major constraints voltage profile, voltage deviation, current, and power losses are considered for investigating the impacts of the DG units. The standard IEEE-33 bus distribution system is used for validation of the proposed methodology, developed and implemented by MATLAB coding.

The rest of the paper is arranged as follows. Section 2 provides the problem formulation. In Section 3, the system description and constraints are presented. In Section 4, a description is provided of the PSO and a procedure for selecting suitable locations for DGs using the PSO method. In Section 5, the simulation results are investigated, and different scenarios are presented. Finally, conclusions are drawn.

2. Problem Formulation

The major concern of this study is the optimal integration of distributed energy resources (DER) and NR in microgrids to optimize energy losses and reduce voltage drops. A PSO algorithm is proposed to solve the multi-objective optimization problem. The distribution network is usually radial, and the ratio of R/X is extremely high in comparison to that for a transmission system. The Newton–Raphson load flow method is suitable for resolving the load–flow problems of the distribution system. The main objective of the load flow is to calculate the bus voltage, line current, and PQ losses at each bus. Our proposed methods managed DG sizing and placement to improve voltage profile and loss minimization in base and reconfigured distribution system. Considering the penalty factor to find more accurate and actual results of the voltage profile and power loss. For example, one can assume a line section between k and k + 1 with an impedance of $R_k + jX_k$ and loads at bus k and k + 1, as shown in Figure 1. P_k and Q_k are the real and reactive power flows from bus k to k + 1, respectively, and V_k and V_{k+1} are the complex voltages. The power loss in the feeder section between buses k and k + 1 can be computed as follows [40]:

$$P_{Loss}(k, k+1) = R_k \frac{\left(P_k^2 + Q_k^2\right)}{|V_k|^2} \tag{1}$$

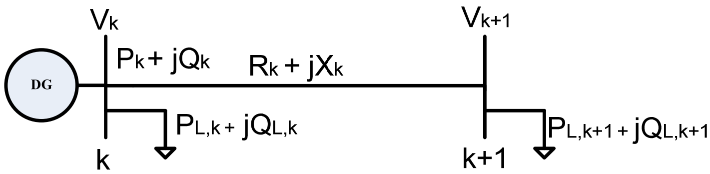

Figure 1. Two-bus distribution system for load flow analysis.

The total active power losses of the distribution network $P_{T,Loss}$ can be calculated by summing all losses of the line segments of each, as follows [40]:

$$P_{T,Loss} = \sum_{k=1}^{n} P_{Loss}(k, k+1) \quad (2)$$

2.1. Reconfiguration of Distribution System

The distribution system comprises sectionalizing switches. This makes the best utilization of network resources for a specific loading state. We proposed an active and reactive power loss minimization in the reconfigured network by placing and sizing DGs through restructuring the feeder. The feeder makes the decision to keep the switch states open or closed. The process of altering the topology of the distribution network using different states of switches is known as NR. It changes the switching states to transform a network from its original configuration into an optimal form. Therefore, the aim of NR is to reduce the total power losses and voltage deviation of the distribution system. The optimal configuration of this system, shown in Figure 2, is obtained by opening switches, such as 07–9–14–28–32. However, in switching, the radial nature of the distribution system must be maintained. During NR and DG placement, our proposed method attempts to reduce voltage deviations to near zero and enhance the voltage stability and network performance. A single-line diagram of the IEEE-33 bus reconfigured distribution network is shown in Figure 3. The active power losses from previous research on NR, such as those based on a refined genetic algorithm (RGA) at 139.55 kW [45], improved tabu search at 145.11 kW [46], HSA at 146.39 kW [47], and fireworks algorithm (FWA) at 139.98 kW [48]. The distribution system is reconfigured to optimize the issue in which the variables are considered as a switch. The main objective of the NR for the distribution network is to reduce power losses, and the operating constraint should remain within limits. P'_k and Q'_k are the real and reactive power flows from bus k to $k + 1$, respectively, and V'_k and V'_{k+1} are the complex voltages of the reconfigured system. The power loss of the reconfigured system in the feeder section between buses k and $k + 1$ can be computed as follows [47]:

$$P'_{Loss}(k, k+1) = R_k \frac{\left(P'^2_k + Q'^2_k\right)}{|V'_k|^2} \quad (3)$$

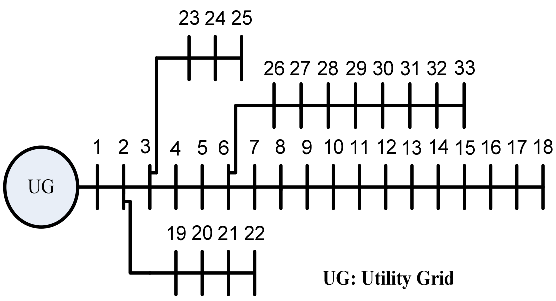

Figure 2. Schematic of IEEE-33 bus test system.

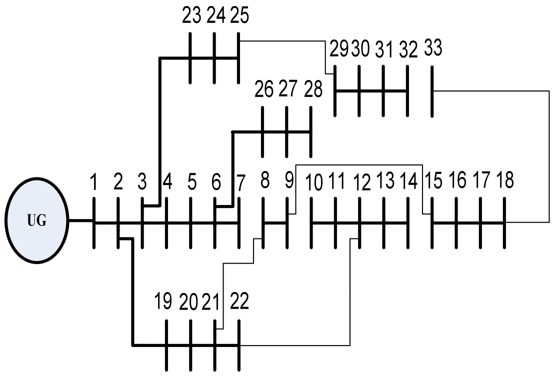

Figure 3. Schematic of IEEE-33 bus reconfigured test system.

The total active power losses of the reconfigured distribution system $P'_{T,Loss}$ can be calculated by summing the losses of all of the line sections of each feeder, as follows [47]:

$$P'_{T,Loss} = \sum_{k=1}^{n} P'_{Loss}(k, k+1) \tag{4}$$

2.2. Percentage Loss Reduction

The total net power loss reduction in the entire distribution network ΔP^R_{Loss} is the difference in total power loss before and after reconfiguration [40].

$$\Delta P^R_{Loss} = \sum_{k=1}^{n} P_{Loss}(k, k+1) - \sum_{k=1}^{n} P'_{Loss}(k, k+1) \tag{5}$$

2.3. Voltage Deviation

Minimizing the bus voltage deviation is one of the most important security and power-quality indices, and can be stated as follows:

$$V_D = \sum_{k=1}^{n} \frac{|V_i - V_k|}{V_i}, \qquad k = 1, 2, \ldots, n \tag{6}$$

In the above, V_D is the voltage deviation, n is the number of buses, V_i is the nominal voltage, and V_k is the real voltage up to the kth bus.

3. System Description

The IEEE-33 bus radial system examined in this study has 33 nodes, total 37 lines, 32 loads, 32 PQ buses, 1 feeder, and 1 slack bus. Normally, 32 closed switches and 5 open switches are used. The source of supply in the network is substation bus 1, with a constant voltage of 12.66 kV. The line and load data of the 33-bus test system are taken from [49]. The IEEE-33 bus network before and after reconfiguration is shown in Figures 2 and 3, respectively. All loads are considered a constant load of active and reactive power at 3715 kW and 2300 kVAr, respectively. Four factors (voltage profile, voltage deviation, current, and power losses) are considered for investigating the impacts of the DGs.

3.1. DG Units Placement

The reduction of energy resource assets, increments in load demand and need for clean power generation are the prime inspirations behind the integration of DER into distribution networks. DGs could play a crucial role in the transformation of the traditional distribution network into active distribution networks [50]. The transformation of a traditional radial distribution system into an autonomous microgrid network involves the optimal sizing and placement of DGs. Simultaneously, the operating constraints to minimize the network power loss and regulate the voltage deviations in each bus (within defined limits), current capacity of the feeder, and voltage profile of the system should be satisfied. When a DG unit is allocated to bus k in the form of a binary variable μ_k, the value will be 1, otherwise, it is zero, as defined by (7).

$$\mu_k = \begin{cases} 1, & \text{if DG is integrated at bus k} \\ 0, & \text{otherwise} \end{cases} \tag{7}$$

3.2. Voltage Profile Improvement

The voltage variance at each bus should have been within the upper and lower limits to ensure voltage stability and power quality. Voltage limits are considered, within ±5% of the rated voltage for the load buses, as follows:

$$V^{min} \leq V_k \leq V^{max} \tag{8}$$

Here, V_k is the V^{th} node voltage, and V^{min} and V^{max} are the minimum and maximum voltage limits, respectively. Thus, we need to enhance the voltage stability level and reduce the power loss in the distribution system by using DG units. The voltage drops per unit are calculated using (9), (9) is modified to (10) when a DG injects power at node k, whereas R and X are resistance and reactance of line connecting bus k and bus $k + 1$.

$$V_k - V_{k+1} = P_{(k,k+1)} R_{(k,k+1)} + Q_{(k,k+1)} X_{(k,k+1)} \tag{9}$$

$$V_k - V_{k+1} = (P^{load}_{k+1} - P_{DG\ k+1}) R_{(k,k+1)} + (Q^{load}_{k+1} - Q_{DG\ k+1}) X_{(k,k+1)} \tag{10}$$

3.3. Power Loss Minimization

The total active power loss $P^{loss}_{(k,\ k+1)}$ and reactive power loss $Q^{loss}_{(k,\ k+1)}$ of the network are calculated using (11) and (12), respectively. The total power loss of the network $S^{loss}_{(k,k+1)}$ is evaluated by summing up the active $P^{loss}_{(k,\ k+1)}$ and reactive $Q^{loss}_{(k,\ k+1)}$ losses as given by (11) and (12), respectively.

$$P^{loss}_{(k,\ k+1)} = \sum_{k=1}^{n} \sum_{k+1=1}^{n} (\alpha_{(k,k+1)} (P_k P_{k+1} + Q_k Q_{k+1}) + \beta_{(k,k+1)} (Q_k P_{k+1} - P_k Q_{k+1})) \tag{11}$$

$$Q^{loss}_{(k,\ k+1)} = \sum_{k=1}^{n} \sum_{k+1=1}^{n} (\gamma_{(k,k+1)} (P_k P_{k+1} + Q_k Q_{k+1}) + \delta_{(k,k+1)} (Q_k P_{k+1} - P_k Q_{k+1})) \tag{12}$$

$$S^{loss}_{(k,k+1)} = P^{loss}_{(k,\ k+1)} + jQ^{loss}_{(k,\ k+1)} \tag{13}$$

3.4. Line Current

The current capacity limits of all branches are considered as 200 A, except for branches 1–9, which have a capacity of 400 A. Every branch should have a current flow below the thermal permissible limits, as follows:

$$I_k \leq I^{max} \tag{14}$$

In the above, I_k is the k^{th} branch current, and I^{max} is the limit of the maximum current flows.

3.5. Fitness Function

In this study, we focused on voltage regulation, power loss minimization, and a penalty cost is also considered during a constraint violation. Violations of voltage limitations and total power losses are considered in the fitness function. The penalty factor compels the voltage from violating the limits so as to the voltage stability and minimize power loss of the system. Multi-objective PSO algorithms have been used for the optimal siting and sizing of DGs with objective function (15), with constraints based on Equations (5)–(8), (13), (14), and (16).

$$\min \mathrm{F} = \sum_{k}^{n} C_k^{DG}\mu_k + \sum_{k}^{n}\sum_{k+1}^{n} C_{(k,k+1)}^{loss}\, S_{(k,k+1)}^{loss} + \sum_{k}^{n} C_k^{viol} V_k \tag{15}$$

The penalty cost for violating voltage limits is high as compared to the penalty cost of the total power loss, as given by (16). Therefore, our voltage values are more accurate and efficient. A fitness function includes the total power losses and the voltage drop limit penalty values and current limit violation. The main purpose of the proposed approach is to reduce the total DG deployment cost (C^{DG}), cost of the penalty for a total power loss of the system (C^{loss}), and costs of penalties for violations of limits in the distribution system (C^{viol}).

$$C_k^{viol} > C_{(k,k+1)}^{loss} \tag{16}$$

4. Particle Swarm Optimization

In [51], a brief overview was provided on using a particle swarm algorithm for the optimization and advancement of DG placement and sizing. The PSO algorithm is developed through an iterative process and results in swarming to find the best solution from a group of problems. Increasing the number of iterations corresponds to a better convergence of the problem (from experience). An individual is known as a particle, and the individual updates their position at each iteration. A fitness function that provides an interface between the problem of optimization and functional problems magnifies the correctness of a precise solution from a group of particles. We calculated the fitness function for each particle using (15). The control system variables are evaluated by calculating the fitness function of the problem given by (15), with the objective of attaining a reduced global optimum, i.e., g_{best}. The PSO algorithm starts with the random generation of particles in the search space within the function domain. The current position and velocity of the particle are denoted by x and v, respectively. The algorithm finds the personal best position in the search group for every individual particle i. We can represent the location of particle i in the N-dimensional space vector mathematically, as shown in (17). Likewise, the particle velocity V can be shown as in (18). The location and velocity of each particle will be changed after each iteration. The initial particle velocities and positions are generated randomly and modified in accordance with (17) and (18).

$$X_{\mathrm{i}} = (\mathrm{x}_{\mathrm{i},1}\,,\ \mathrm{x}_{\mathrm{i},2}\,,\ \ldots, \mathrm{x}_{\mathrm{i,N}}) \tag{17}$$

$$V_{\mathrm{i}} = (\mathrm{v}_{\mathrm{i},1}\,,\ \mathrm{v}_{\mathrm{i},2}\,,\ \ldots, \mathrm{v}_{\mathrm{i,N}}) \tag{18}$$

The particle locations initialized at random are based on the limits of the basic control parameters. In [52], the optimum six parameters of the PSO (c_1, c_2, ω_{max}, ω_{min}, N, and $iter_{max}$) are shown to be highly effective in the system during convergence. Therefore, we need to select apposite values to achieve better efficiency. In this study, the values of self and social accelerating coefficients c_1 and c_2 are taken as 2. The weights ω_{max} and ω_{min} for the particle velocities are taken as 0.4 and 0.9, respectively. The maximum number of iterations $(iter_{max})$ 100, with 100 number of particles (N) are used for PSO. PSO convergence criteria are iter = $iter_{max}$, or $X_i^{k+1} - X_i^k < \varepsilon$. PSO is implemented on IEEE-33 bus system in base and after NR to analyze their effects on minimizing power losses and voltage profile improvement. The flow chart of the PSO algorithm is shown in Figure 4. In the minimization problem, P_{best} is the personal best position in the search space, which will lead to the smallest error and can be calculated using (19). Likewise, the global best position g_{best} is the best particle in the search space among all of the particles in the group by using (20). The particle that provides accurate personal best results will show the minimum error.

$$P_{besti} = (P_{besti,1}\,,\ P_{besti,2}\,,\ \ldots, P_{besti,N}) \tag{19}$$

$$G_{besti} = (g_{besti,1}\ ,\ g_{besti,2}\ ,\ \ldots, g_{besti,N}) \tag{20}$$

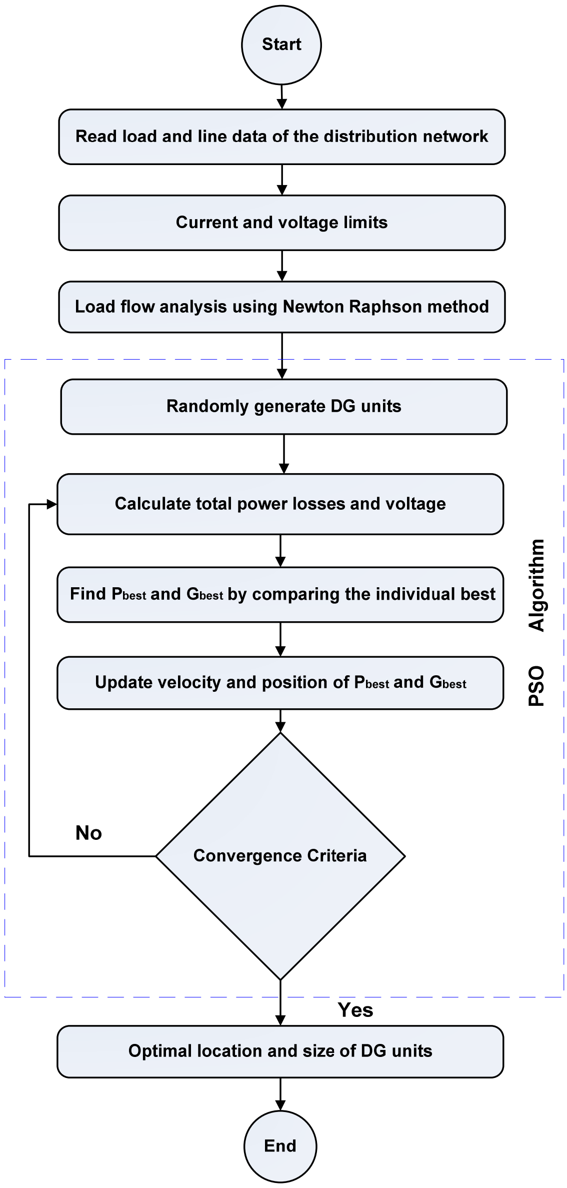

Figure 4. Flow chart of PSO algorithm for the distribution network.

Each particle in the swarm updates its location with its own P_{best}, g_{best}, and previous velocity vectors using (21), and the current position X_i^k of particle i can be changed based on (22). Additionally, c_1 and c_2 determine how fast a particle of the PSO proceeds towards P_{best} and g_{best}.

$$V_i^{k+1} = \omega_i V_i^k + c_1 r_1 \left(P_{besti} - X_i^k\right) + c_2 r_2 \left(g_{besti} - X_i^k\right) \tag{21}$$

$$X_i^{k+1} = X_i^k + \chi\left(v_i^{k+1}\right) \qquad k = 1, 2, \ldots, N \tag{22}$$

where, χ is the constriction factor, k is the iterative number. The inertia weights control the convergence behavior of PSO. A proper choice of the inertia weight provides a strong balance between global and local explorations, as shown in (23) [53].

$$\omega_i = \omega_{max} - \frac{(\omega_{max} - \omega_{min})}{iter_{max}}\, iter \tag{23}$$

The PSO showed a steady and fast convergence, with a global searching ability to provide P_{best} and g_{best}.

5. Results and Discussion

The development of DG systems plays a crucial role in power production. This allows the delivery system to withstand high loading, eliminate losses, and enhance the voltage profile. Even if DG units help to reduce losses, certain bus voltages do not reach the minimum voltage limit. Identifying the location and sizing of DGs to reduce the real power loss of a radial electric distribution system is a difficult task. These challenges can be mitigated by reconfiguring the network. The results show that the optimal placement and sizing of multi-DGs with reconfiguration can be identified. This gives the minimum power loss, while keeping the bus voltage magnitudes within acceptable limits. PSO algorithms are used to find suitable locations and sizes for multi-DG units placement. The PSO algorithm is tested on an IEEE-33 bus radial distribution system before and after reconfiguration. Four scenarios are investigated below.

Scenario 1: Base distribution system.
Scenario 2: Reconfigured distribution system.
Scenario 3: Base distribution system with DGs.
Scenario 4: Reconfigured distribution system with DGs.

5.1. Base Configuration

The standard IEEE-33 bus distribution system is considered as the base system for evaluation of this work. Newton–Raphson based power flow technique is used for power flow analysis. The total peak load consumption on the distribution system is 3715 kW and 2300 kVAr. In scenario 1, the total real and reactive power losses for the initial base configuration are computed by the Newton–Raphson load flow method as 203.17 kW and 135.17 kVAr, respectively. The minimum voltage on bus-18 is 0.9022 p.u. A significant reduction in power loss is observed when three DG units are placed into the base distribution system. The PSO algorithm is used to optimal locate and sizing of the multi-DG units.

In scenario 3, PSO algorithm is used to find optimal DG size and location in base system. DG1 is installed at bus 6, DG1 and DG2 at buses 6 and 16, and DG1, DG2, and DG3 at buses 6, 16, and 25, respectively. A DG rated at 2331 kW is installed in a single DG scheme in bus 6. In the 2 DG scheme, DG units with ratings of 3133.5 and 365.1 kW are installed in buses 6 and 16, respectively. For 3 DG units scheme, DG units with ratings of 2164.2, 365.1, and 738.6 kW are installed in buses 6, 16, and 25, respectively, as shown in Table 1. In scenario 3, when 3 DG units are installed in the distribution system, the active and reactive power losses are reduced to 82.77 kW (59.26%) and 58.39 kVAr (56.80%), respectively. The bus voltage is improved by 4.9% after the addition of the multi-DG units. The integration of a DG is used to inject active power into a system locally. As a result, the net power from a substation is decreased by multi-DGs integration. In this study, owing to the integration of the 3 DGs, the power losses are decreased to 82.77 kW, and the minimum bus voltage is 0.9464 p.u. at bus 33.

Table 1. Effects of DG units placement on power loss minimization and voltage profile enhancement.

Base System Configuration				
	Base System	**DG1**	**DG1 and DG2**	**DG1, DG2, and DG3**
Active power loss (kW)	203.17	110.2	105.7	82.77
Reactive power loss (kVAr)	135.17	79.43	74.81	58.39
Min. voltage magnitude (p.u.) and location	0.9022, 18	0.9484, 18	0.9573, 32	0.9464, 33
DGs size (MW) and location		3.1335, 6	3.1335, 6 0.3651, 16	2.1642, 6 0.3651, 16 0.7386, 25
After System Reconfiguration				
Active power loss (kW)	138.14	120.5	71.47	64.91
Reactive power loss (kVAr)	99.85	83.66	50.68	47.03
Min. voltage magnitude (p.u.) and location	0.9281, 32	0.9287, 32	0.9585, 32	0.9611, 32
DGs size (MW) and location		1.0641, 16	1.0641, 16 1.2155, 29	1.0641, 16 1.2155, 29 0.6745, 26

5.2. Reconfiguration with DGs

The PSO algorithm is implemented in the test system to find the optimal locations and sizing for the multi-DG units after reconfiguration. In scenario 2, after the optimal reconfiguration of the test system, the active power losses are reduced to 138.14 kW—an active power loss reduction of approximately 32%. The voltage magnitude is enhanced by 2.87%. Figures 5 and 6 show the voltage profile improvement and power loss reduction of the base and reconfigured test system, respectively. The lowest values of the voltage magnitude are measured as 0.9022 p.u. at bus-18 and 0.9281 p.u. at bus-32 for the system before and after reconfiguration, respectively.

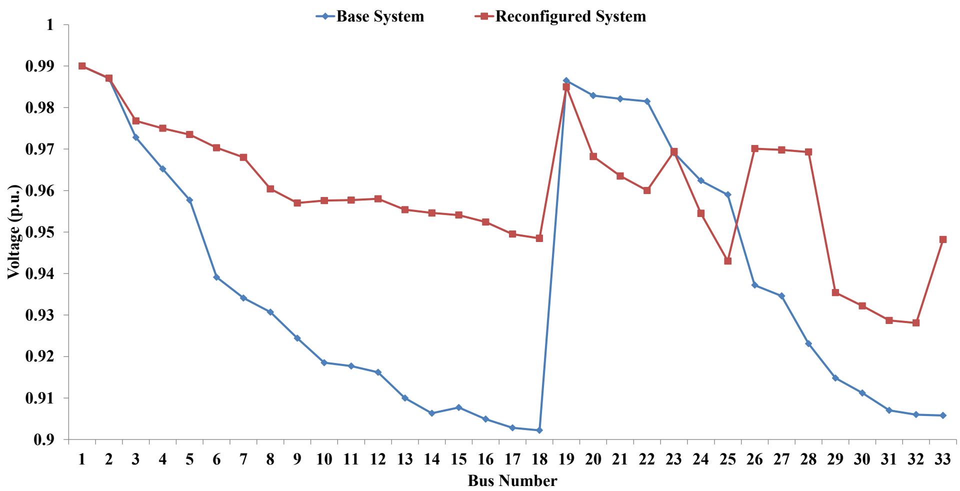

Figure 5. Voltage profile of base and reconfigured distribution system.

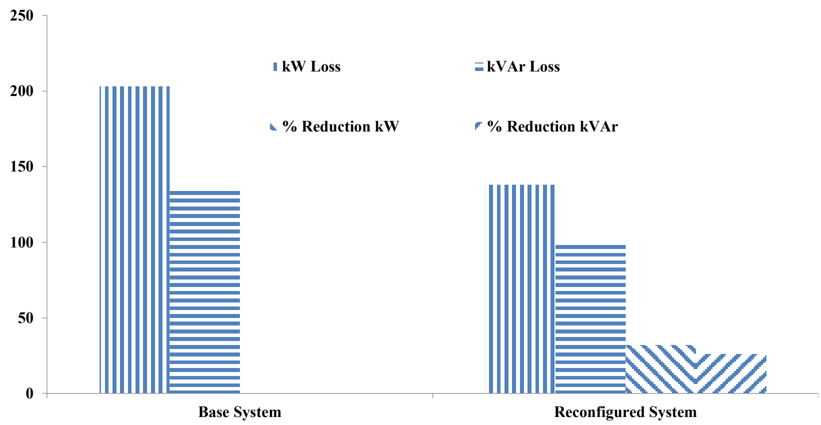

Figure 6. Losses of base and reconfigured distribution system.

In scenario 4, when the three DG units are placed in the reconfigured distribution system, an outstanding reduction in power loss is observed. Multi-DG units with different sizes are installed at different locations. DG1 (1064.1 kW) is installed at bus 16, and DG1 and DG2 (1064.1 and 1215.5 kW, respectively) are installed at buses 16 and 29, respectively. Likewise, DG1, DG2, and DG3 (1064.1, 1215.5, and 674.5 kW, respectively) are installed at buses number 16, 29, and 26, respectively, as shown in Table 1. Owing to the reconfiguration and DG installation in the network, the voltage profile increased by 6.53%, and the percent of loss reduction increased by 68.05%. The minimum voltage deviation is obtained by scenario 4. According to Table 2, four scenarios (1–4) for the IEEE-33 bus distribution system are presented.

Table 2. Performance of proposed method on IEEE-33 bus radial distribution network.

Methods	Base Network	Reconfigured Network	Base Network with DGs	Reconfigured Network with DGs
Active power loss (kW)	203.17	138.14	82.77	64.91
Reactive power loss (kVAr)	135.17	99.85	58.39	47.03
Min. voltage magnitude (p.u.)	0.9022	0.9281	0.9464	0.9611
Active power loss reduction (%)		32.00	59.26	68.05
Reactive power loss reduction (%)		26.13	56.80	65.20
Voltage deviation (V_D)	0.0878	0.0619	0.0436	0.0289
Voltage enhancement (%)		2.87	4.9	6.53

When we injected power, the active power losses were reduced in scenarios 1–4 by 203.17, 138.14, 82.77, and 64.91 kW, respectively, whereas the reactive power is also reduced from 135.17, 99.85, 58.39, and 47.03 kVAr, respectively. The percentage of active power loss reduction increased in scenarios 2–4 by 32%, 59.26%, and 68.05%, respectively. Similarly, the minimum bus voltage of the system in scenarios 2–4 improved by 2.87%, 4.9%, and 6.53%, respectively. This reveals that the NR and allocation of multi-DG units in scenario 4 are better than those in the other scenarios in terms of the voltage profile improvement and loss reduction. Figures 7–9 show the voltage profile improvement, line current reduction, and total power loss reduction, respectively, by using the PSO algorithm to locate and size for multi-DG units before and after reconfiguration of the test system.

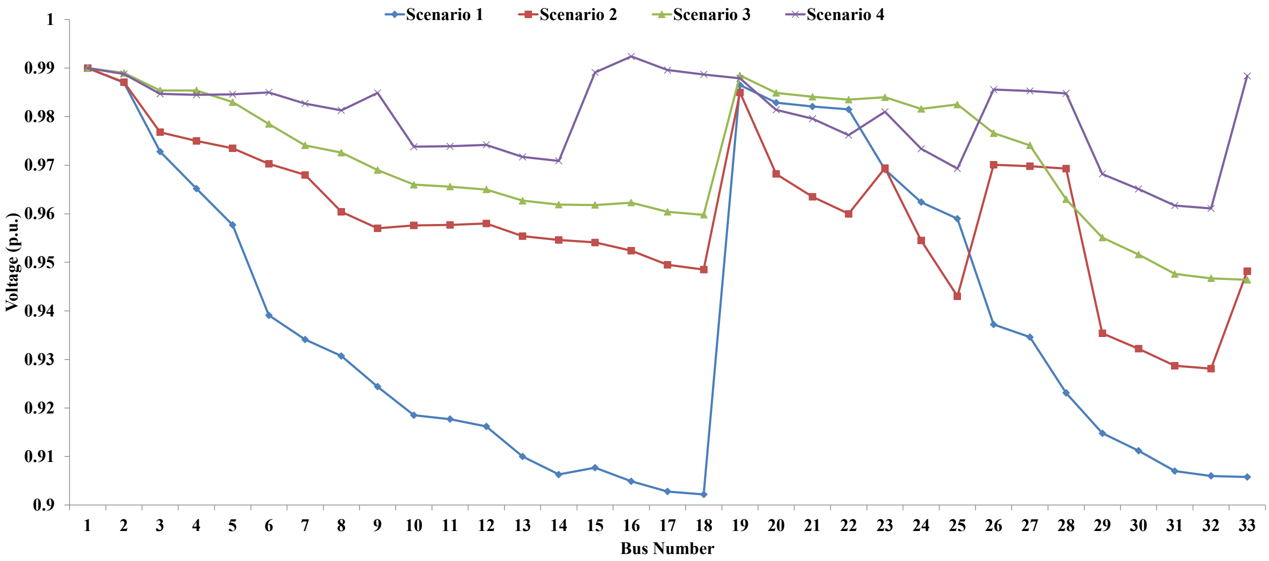

Figure 7. Voltage profiles of IEEE-33 bus system with different scenarios.

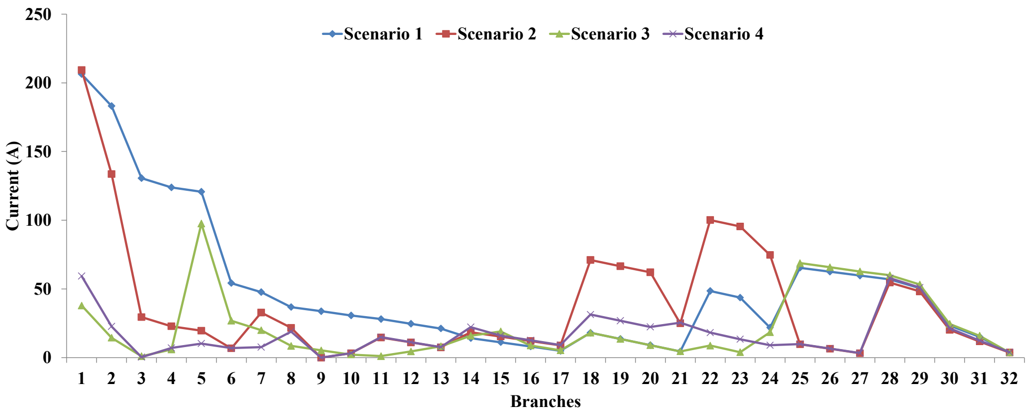

Figure 8. Current profile of the network with different scenarios.

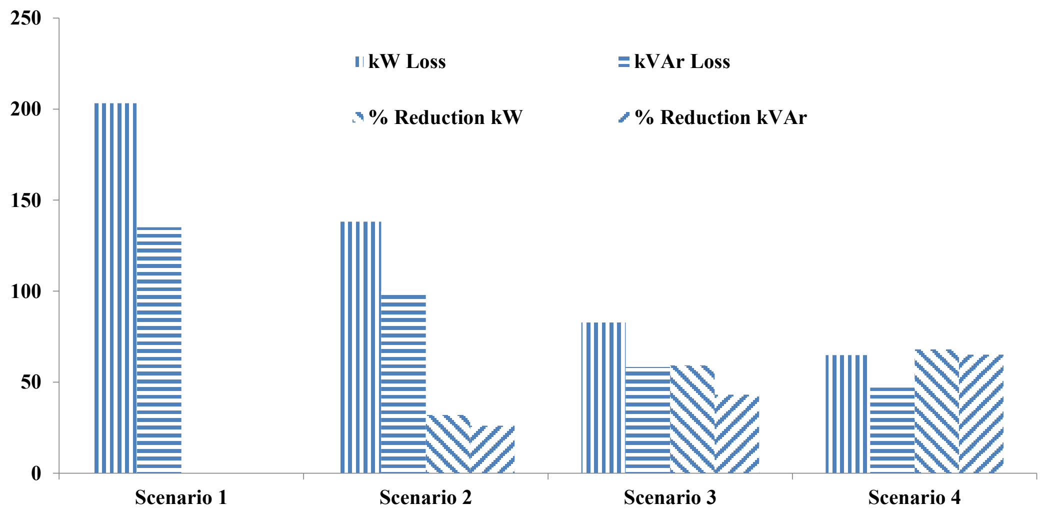

Figure 9. Active and reactive power losses of the network with different scenarios.

The performance of the proposed work is compared with that from the available literature in the form of active power loss, i.e., the HSA (73.05 kW) [40], GA (75.13 kW) [40], RGA

(74.32 kW) [40], FA (73.048 kW) [44], 2-stage algorithm (92.91 kW) [54], FWA (67.11 kW) [55], and direct graph (112.19 kW) [56]. Our proposed method provides 64.91 kW. Thus, our proposed method shows better results than those of previous research in terms of minimizing power loss and enhancing voltage stability, as shown in Table 3 and Figure 10.

Table 3. Comparative results for the configured IEEE-33 bus distribution system with DG units.

Methods	Active Power Loss (kW)	Min Voltage (p.u.)	Tie Switches	DGs (MW)	Buses
HSA [40]	73.05	0.9700	7, 14, 10, 32, 28	1.6684	
GA [40]	75.13	0.9766	7, 10, 28, 32, 34	1.9633	
RGA [40]	74.32	0.9691	7, 9, 12, 27, 32	1.774	
FA [44]	73.048	0.97352	8, 9, 28, 32, 33	0.8414	31
				0.3408	32
				0.5916	33
Two-stage algorithm [54]	92.91	0.9541	7, 9, 14, 30, 37	0.250	16
				0.250	17
				0.250	18
FWA [55]	67.11	0.9713	7, 14, 11, 32, 28	0.5367	32
				0.6158	29
				0.5315	18
Directed graph [56]	112.19	0.9465	7, 9, 14, 25, 32		
Proposed method	64.91	0.9611	7, 9, 14, 28, 32	1.0641	16
				1.2155	29
				0.6745	26

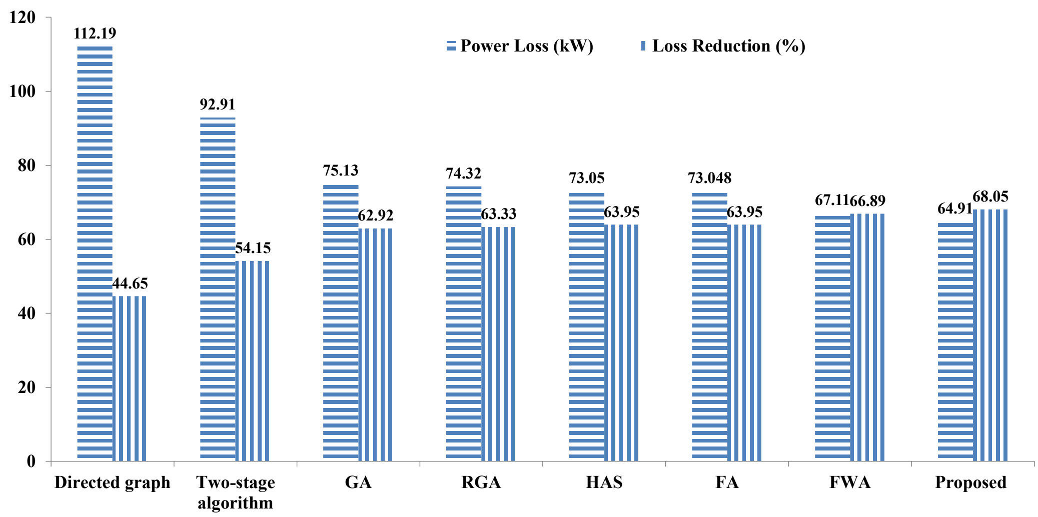

Figure 10. Comparison of active power loss reduction (%) by proposed method and other techniques.

6. Conclusions

In this study, the major issues investigated are the location and sizing of DGs to mitigate the total power loss, reduce line current, and boost the voltage profile of a radial distribution system. The multi-objective PSO algorithm is implemented to find the optimal locations and sizes for multi-DG units in an IEEE-33 bus radial distribution network before and after reconfiguration. In scenario 1, the power loss was 203.17 kW, and after the reconfiguration of the test system in scenario 3, the power loss decreased to 138.14 kW. PSO algorithm provided the best location and sizes for multi-DG units installation, and the active power losses were reduced from 82.77 to 64.91 kW before and after reconfiguration of the system, respectively. There were also significant improvements in the voltage profile and power loss reduction was achieved. The minimum voltage was 0.9022 p.u. at bus 18 for the base case. After adding 3 DGs with reconfigured system, the minimum voltage was enhanced to 0.9611 p.u. at bus 32. The overall simulation results showed that the proposed technique is comparatively efficient in terms of reducing the active and reactive power losses, voltage deviation, and boost-up voltage profile in the system.

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Future Work: In future: it would be more interesting to implement the proposed technique to "Enhancement of Hosting Capacity". We can achieve maximum DGs penetration and better power quality re-sults.

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