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Optimal Placement and Sizing of Distributed Generation (Dg) Units in Electrical Power Distribution Networks

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Abstract: *Researchers' attention has recently been on the best ways to integrate Distributed Generation (DG) into the conventional centralized electrical power distribution systems, particularly in the context of the smart grid idea due to its reputation as a viable remedy for the lack of electric power supply. To optimize the environmental, financial, and technological advantages of DG units' integration for distribution network operators, it is crucial to determine their ideal position and size. The main objective of this study was to develop and simulate an optimization system for the placement and sizing of distributed generation units in electrical power distribution networks for power losses reduction and voltage profile improvement. The specific objectives were to model and develop the load flow algorithm and codes; develop a meta-heuristic optimization algorithm and codes that selects the best location and size of the DG unit; simulate the nested load flow and optimization algorithms and codes on MATLAB and analyze the effectiveness of the developed algorithm via testing on the standard IEEE 33-bus radial electrical power distribution benchmark network. The Backward-Forward Sweep (BFS) technique was employed in the load flow modelling owing to its maximization of the radial structure of distribution systems. The optimization algorithm was developed based on the Multi-objective Particle swamp optimization (PSO) meta-heuristic technique due to its effective global searching characteristic. The line and load data for the IEEE 33-bus test network being a cutting-edge benchmark for contemporary power distribution networks; were obtained from the Power Systems Test Case Archive- a secondary data source. For this network fed by a synchronous generator, the chosen base MVA (Mega Volt Amp) was 10MVA and the base voltage was 12.66kV. The total active and reactive power demand were 3.715MW and 2.3Mvar* *respectively. The simulation was done on R2021a version of MATLAB/Simulink. The total real and reactive power losses obtained from base case simulation without the placement of any DG unit in the network were obtained as 201.8925kW and 134.6413kvar respectively while the per unit (p.u) average bus voltage was 0.948594 p.u. After the optimal allocation of one, two, three and four DG units, the total real power loss (in kW) in the network reduced by 140.89, 173.89, 189.89 and 195.89 respectively while the total reactive power loss (in kvar) reduced by 86.64, 114.64, 124,64 and 128.64 respectively. Likewise, the per unit average bus voltage improved by 0.0376p. u, 0.0458p.u, 0.0480p.u and 0.0498p.u respectively. Also, the decrease in the total real and reactive power losses and the improvement in bus voltage profiles varies proportionally with the number of DG units optimally placed. In conclusion, the results shows that the total real power loss and the total reactive power loss of the network, were significantly decreased; and the voltage profile of the system was drastically enhanced by incorporating DG units at predetermined buses. The developed algorithm is recommended for application in a real electrical power distribution network for more efficient integration of new distributed generation units in the current electrical power distribution networks.*

Keywords: Distributed Generation (DG); electrical power, distribution networks; optimization, algorithm, power losses; voltage profile

INTRODUCTION

Over the past few decades, the integration of Distributed Generation (DG) into the electrical power grid has grown significantly. The DGs have the potential to be a desirable energy source. They not only make the electricity system more secure and sustainable, but they also open the door to low-carbon technologies like wind or solar power. Generally speaking, Distributed Generation (DG) refers to small-scale power generating (typically 1kW to 50MW) that generates electricity at a location closer to clients than central generation plants [1]. Because of its capability to reduce power loss, better dependability, cheap investment cost, and most significantly, its capacity to utilize renewable energy resources, DG has recently experienced tremendous growth in the power sector. Installation of DG units in less-than-ideal sites may increase system losses, which would increase costs and have the reverse of the desired effect [2]. Centralized generation to dispersed generation, with distributed energy resources utilizing renewables are the main drivers of the modern power system. Hybridizing a number of the renewable energy sources (RESs) captures the best features of the sources [3]. In centralized distribution system structure, voltage is compromised, equipment stretched beyond operating limit, high power loss and generation failure and hence, Decentralized/Distributed distribution structure for robust power management is required.

A properly sized and located DG can have a variety of positive effects on the power system, including a decrease in overall power losses and an improvement in power quality characteristics including voltage profile, standard voltage wave, and frequency [4], [5]. The advantages depend on how well-installed the

DG units are in the distribution system. However, placing DG units in the wrong place and oversizing them might result in unanticipated problems with the power system, including voltage flicker, voltage sags, fault current, harmonic distortion, and power loss. Additional research on the distribution power network has revealed various effects of DG deployments on power systems. By installing the appropriate DG units, for example, overall power loss might be drastically cut and reduced to 13% [6].

The main goals of the majority of methods used to determine the best location and size for DG units have been voltage improvement and power loss reduction. One of the most effective and well-liked techniques is Particle swarm optimization (PSO). This technique (PSO) has been used in [7] to address the study's connection of DG units to the electricity grid. In this research, The Backward-Forward Sweep (BFS) technique was used for the load flow calculation and a very flexible adaptive multi-objective Particle Swarm Optimization (PSO)-based optimization system which was able to select the best size and location for the DG unit's placement has been developed. When simulated on MATLAB/Simulink and applied on a standard IEEE 33-bus radial electrical power distribution benchmark network, the developed optimization system was capable of decreasing the overall power losses while keeping the voltage at each bus within a predetermined range. Also, the optimal placement of single and multiple DG units was considered for performance comparison and the proposed algorithm could accommodate placement of three different types of DG discussed in the literature and also up to 4 DG units.

CRITICAL REVIEW OF RELATED WORKS

Over the past two decades, the distribution networks have faced significant issues and obstacles as a result of the ill-advised and unregulated installation of Distributed Generations. In contrast to unidirectional power flow from higher to lower voltages, bidirectional power flow in modern distribution networks is a necessary issue, as are the crucial issues of voltage drop and power losses [3], [8]. In an effort to improve the voltage profiles and reduce or even completely eliminate power losses in contemporary distribution networks with DG, researchers from all over the world are researching the aforementioned issues. They have presented a variety of techniques and methodologies for choosing the ideal sitting and sizing of DGs and the summary of a few of them critically reviewed are discussed below.

A genetic and particle swarm optimization methods have been used in [9] to determine where and how big a capacitor should be. The proposed methodology has been used to test the performance of these algorithms on a 12-bus radial distribution system. The outcomes demonstrated that the suggested methodology is more efficient and capable of producing superior outcomes than other analytical techniques.

Using two distinct approaches, "Parizad et al. [10]" attempted to establish the best location and size of DG in terms of lowering losses and stabilizing voltage. The initial strategy sought to reduce actual power losses by creating an exact loss formula that identified the ideal site for DG installation. The second method involved using a voltage stability index to place the DG at the best possible spot. By employing the forward-backward sweep method, power flow was calculated. The study made use of two distribution systems: a 30-bus loop and a 33-bus radial system. The suggested solutions significantly improved voltage profiles and reduced power losses.

Fuzzy logic was used in [11] to determine the best location for a single DG unit, and a novel analytical expression for DG scaling used in radial networks was also suggested. This study's objectives were to reduce actual and reactive power losses and enhance the voltage profile. To show that the suggested techniques may be used in radial distribution systems of various sizes and configurations, three distinct distribution systems (12-bus, 33-bus, and 69-bus) were used. The findings show that the proper installation of a DG unit has significantly reduced actual and reactive power losses and produced a notable voltage profile.

In order to reduce the system's actual power loss, “Mahat et al. [12]” established a methodology for determining the ideal size and position of wind type DG in primary distribution systems. Both a 33-bus and a 69-bus radial distribution system employed their approach and the precise loss formula to track system losses.

An analytical analysis was presented in [13] for the determination of the ideal DG unit size and placement. The aforementioned method applied a sensitivity index to determine the ideal location for the DG connection in order to decrease power losses in the distribution system and optimize voltage profiles. The key finding was that integrating a single DG unit of the ideal size at the ideal position, as opposed to integrating many DG units, can result in the lowest losses and an improved voltage profile. This was confirmed using the 13-bus IEEE radial distribution test system.

“Di Silvestre et al. [14]” have given a very intriguing study. The authors' goal is to increase the effectiveness of electricity distribution by lowering energy losses in an island-based medium voltage distribution network. The installation of distributed photovoltaic (PV) generation units was one of the suggested actions. In order to determine the ideal location and size of the PV units, the Non-Denominated Sorting Generic Algorithm-II (NSGA-II) multi-objective optimization technique has been employed. The fact that economic issues like utility costs and customer subsidies have been included makes this study significantly different from others in this field. The installation of PV generation units results in considerable improvements in terms of investment payback, voltage drop, and greenhouse gas emission reduction, as demonstrated by the application of the suggested approach on an existing medium voltage distribution network of Lampedusa Island.

Overview of Distributed Generation (DG) Allocation Methodologies

The placement and sizing of DGs have been optimized using a variety of methodologies, including analytical-based methods, heuristic algorithms, genetic algorithms, and tabu search. The best active power compensation can be used to model the ideal DG allocation. Contrary to capacitor allocation studies, which have been researched for a long time, DG allocation studies are relatively recent [15], [16]. The majority of traditional optimization techniques are derivative-based approaches that can address continuous or differentiable issues. These techniques, however, cannot ensure that the result is a global optimum. The main limitations of such techniques are the potential for getting stuck in local optima, inability to handle non-differentiable or non-continuous situations, and unnecessary calculations. Heuristic and meta-heuristic optimization techniques were developed to address these shortcomings. One of these techniques is particle swarm optimization (PSO), which is widely used [17], [18], [19]. The social behavior of swarms served as the inspiration for the stochastic population-based meta-heuristic optimization method known as PSO. It excels at handling power systems optimization issues like Optimal Power Flow (OPF), reconfiguration, capacitor placement, unit commitment, and economic dispatch as well as other single- and multi-objective constrained problems in many different domains. An extremely large-scale problem with a wide searching space, continuous variables, and discrete variables is the placement and sizing of DGs. Such issues can be handled using this algorithm. It contains less adjustable parameters and clear specifications when compared to other clever algorithms (such as Simulated Annealing-SA, Independent Component Analysis-ICA, and Generic Algorithm-GA). The application of this method to the DG allocation problem is made easier by its straightforward structure, good convergence characteristics, and great global searching capabilities.

Having attempted a critical review of previous works and their peculiar limitations, it was decided to develop a very flexible and improved decision-making algorithm based on adaptive multi-objective Particle Swamp Optimization (PSO) technique for optimal sizing and location of Distributed Generation (DG) units in electrical power distribution networks. The proposed optimization system which is very flexible to changes and modifications; can define the optimal location for a DG unit and can estimate the optimum DG size to be installed, based on the improvement of voltage profiles and the reduction of the power distribution network's total real and reactive power losses.

METHODOLOGY

Methodological Framework and Research Design

Quantitative method was used throughout the research process and the quantitative techniques that have been employed include modelling and simulation. The overall implementation steps involved problem formulation and modelling, load flow and optimization algorithms and MATLAB Codes development, Simulation and testing on standard IEEE 33-bus radial electrical power distribution system benchmark network for performance analysis. The two main parts of the overall optimization system are:

i. The Backward-Forward Sweep (BFS) Load flow algorithm and codes
ii. The main (overall) nested multi-Objective Particle Swamp Optimization (PSO)-based algorithms and codes incorporating the algorithms and codes stated in (i) above for the optimal placement and sizing of the DG units.

Research Population, Sample size, Software and Data Collection

The overall research population which is the case network where the optimization system is targeted for usage is radial electrical power distribution networks such as the 14-bus, 15-bus 30-bus, 31-bus, 33-bus, 69-bus, 85-bus etc., with increased penetration of grid integration of renewable energy sources. The benchmark network which constitutes the research sample size where the developed optimization algorithms has been tested is the standard IEEE 33-bus radial electrical power distribution network. The simulation software used was the R2021a version of MATLAB. For the IEEE 33-bus radial distribution system load flow modelling, analysis and simulation, the line data and load data were obtained from the Power Systems Test Case Archive- a secondary data source [20].

Problem Formulation and Modelling: Objective Functions and Constraints

The active power loss minimization and voltage stability enhancement objectives are taken into account while formulating the DG location and sizing problem as a multi-objective problem while observing system and unit limits. Power loss reduction and index enhancement for voltage stability are the two primary objective functions that are optimized. The analysis also takes into account the minimum and maximum voltage magnitudes as well as the power balance as constraints of the problem.

Optimization First objective function: Power losses reduction

According to "Hung et al. [21]", it is true that the electrical power distribution system has power losses of roughly 13% of the total power generated. Therefore, the first objective function of the optimization is to cut down on power losses. The diffident electrical parameters are computed using a backward-forward power flow [22]. Figure 1 below illustrates how each receiving bus in radial electrical power distribution networks is served by a single transmitting bus.

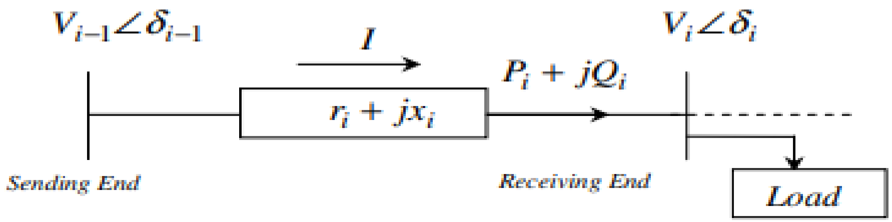

Figure 1: One line diagram of a two-bus system

From figure 1, the line losses between the receiving and sending end buses P_{loss} (i), can be calculated using equation 1 below:

$$P_{loss}(i) = r_i \frac{Pi^2+Qi^2}{Vi^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(i)}$$

According to "Kothari and Dhillon [23]", given the operational conditions of the system, equation (ii) below can be used to calculate the value of actual and reactive power losses in an electrical power distribution network. It should be noted that the precise formula for calculating power losses can be simply derived from the fundamental relation.

$$P_L = \sum_{i=1}^{n} 1 \sum_{j=1}^{n} [Aij(PiPj + QiQj) + Bij(QiPj - PiQj)] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(ii)}$$

Where;

$A_{ij} = \frac{Rijcos(\delta i-\delta j)}{ViVj}$

$B_{ij} = \frac{Rijsin(\delta i-\delta j)}{ViVj}$

Where;

P_i & Q_i = Net real and reactive power injections at bus ‘i’
R_{ij} = The line resistance between bus ‘i’ and ‘j’
V_i & δ_i = The voltage and angle at bus ‘i’
(r_i+jx_i) = The impedance of the line connecting buses i−1 and i

The first objective of the DG placement technique is to minimize the total power losses. Mathematically, this objective function can be written as:

$$f_1 = \text{Minimize } P_L = \sum_{i=1}^{Nbus}[Ploss(i)] \quad \text{(iii)}$$

Subject to the power balance constraints:

$$\sum_{i=1}^{N}(PDGi) = \sum_{i=1}^{N}(PDi + PL) \quad \text{(iv)}$$

Each DG unit must produce active and reactive power that is less than the system's combined active and reactive loads. This restriction is defined mathematically as follows:

$$P_{DG} \leq \sum Pload \quad \text{(v)}$$

$$Q_{DG} \leq \sum Qload \quad \text{(vi)}$$

Voltage constraints:

$$|V_i|^{min} \leq |V_i| \leq |V_i|^{max} \quad \text{(vii)}$$

Current limits:

$$|I_{ij}| \leq |I_{ij}|^{max} \quad \text{(viii)}$$

Where;

$P_{loss}(i)$ = Distribution power loss between the receiving and sending end buses ‘i’
N_{bus} = Total number of buses
P_L = The real power loss in the system
P_{DGi} = The real power generation DG at bus ‘i’
P_{Di} = The power demand at bus ‘i’

Optimization Second objective function: Voltage profile improvement

The IEEE Power System Engineering Committee's definition of voltage stability is as follows [22]: "Voltage stability is the ability of a system to maintain voltage such that load power will rise as load admittance increases and such that both power and voltage are regulated." As the goal for improving voltage stability, Chakravorty and Das's fast indicator of voltage stability (SI Index) is chosen [24].

From figure 1,

$V_{i-1} < \delta_{i-1} - V_i < \delta_i = I.(r_i + jx_i)$ …………………………………………………… (ix)

$(V_i < \delta_i)^* .\ I = P_i - jQ_i$……………………………………………………………… (x)

where ‘I’ is the current amplitude and ‘*’ symbolizes the complex conjugate operator.

From equation (ix) and (x), we get:

$Vi^2 - Vi.Vi - 1 + [(Pi^2 + Qi^2).(\mathrm{ri}^2 + \mathrm{xi}^2)]^{\frac{1}{2}} = 0$ ……………………………… (xi)

Roots of Equation (11) are real if:

$V(i-1)^2 - 4.[(Pi^2 + Qi^2).(\mathrm{ri}^2 + \mathrm{xi}^2)]^{\frac{1}{2}} \geq 0$…………………………………… (xii)

From this, the voltage stability index for bus i (SI_i) is derived as:

$\mathrm{SIi} = \mathrm{V(i-1)}^4 - 4.(Pixi - Qiri)^2 - 4.(Piri + Qixi)^2.V(i-1)^2 \geq 0$………… (xiii)

The value of SI should be greater than zero for all buses during stable operation, i.e., SIi (i=2, 3...N_{bus}) >0. All buses grow more stable as the SI value approaches one. The bus that has the lowest SI value is the one that is most vulnerable to voltage collapse. Each bus in the network's network is given a SI value according to the proposed algorithm. Consequently, the following is the second objective function:

$f_2 = \frac{I}{I+SImin}$……………………………………………………………….... (xiv)

where sSI_{min} is the minimum SI value of all the buses.

Design Variables

From equations (i) through (viii), it is clear that the decision variables include both the capacities and locations of the DGs to be installed at the candidate buses, which can be denoted as [P_{DG1}, P_{DG2}…., P_{DGNbus}], and that the state variables include the voltage, active power, and reactive power at each bus, all of which can be obtained by power flow computation.

P_{DGi}=0 (i=2, 3, ...N_{bus}) indicates that bus I cannot accommodate a DG unit. The decision variable for determining the ideal capacity of the DG at a predetermined location is one dimension, whereas the decision variable for determining the best location of the DG at a predetermined capacity is the location. It should be noted that the **per unit system** was employed in the load flow analysis coding.

The Per Unit System

The per-unit value for a given quantity (such as voltage, current, power, impedance, torque, etc.) is the value pertaining to a base quantity.

Usually, one of the two base values from the list below is used:

i. The base power is equal to the equipment's nominal power.
ii. The base voltage is equal to the equipment's nominal voltage.

These two base values serve as the foundation for all other base quantities. The natural rules of electrical circuits govern the base current and base impedance after the base power and base voltage have been selected.

Base current = $\frac{\textit{base power}}{\textit{base voltage}}$ …………………………………… (xv)

Base impedance = $\frac{\textit{base voltage}}{\textit{base current}}$ ………………………………… (xvi)

Reasons for Using the Per-Unit System

i. Irrespective of their overall size, similar equipment (generators, transformers, and lines) would have similar per-unit impedances and losses expressed on their individual ratings. As a result, per-unit data may be quickly examined for obvious mistakes. A per unit figure outside of the expected range merits investigation for possible mistakes.
ii. Manufacturers often provide per unit values for the impedance of the device.
iii. Three-phase calculations use the constant less frequently.
iv. Per-unit amounts, regardless of voltage level, are the same on each side of a transformer.
v. Calculations performed manually or automatically are made simpler by normalizing variables to a common base.
vi. It makes automatic calculation techniques' numerical stability better

The Backward-Forward Sweep (BFS) Load Flow Modelling, Algorithm and Coding

Load flow is one of the most crucial variables in planning and operation studies of power systems. For load flow analysis at the transmission level, either Gauss-Seidel or Newton-Raphson or their variants are used. Due to the distribution network's unique characteristics, such as its radial construction, high Resistance/Reactance (R/X) ratio, and unbalanced loads, the aforementioned approaches have been weak and have a very poor convergence characteristic. Branch-based and node-based procedures can be used to classify load flow techniques proposed for distribution networks [25]. In node-based techniques, the power or current of the node is utilized as a state variable to solve the power flow problem, whereas in branch-based approaches, the power or current of the branch is employed [26], [27]. Due to their low memory needs, high computing efficiency, and strong convergence properties, forward/backward sweep-based approaches have been the most extensively adopted techniques for distribution system load flow analysis. Each iteration of the BFS's core operating principle requires two calculation operations. Calculating node voltage from the sending end to the receiving end makes up the forward sweep. The branch current and/or total power from the receiving end to the sending end are calculated by the backward sweep. The voltage is maintained constant throughout the backward sweep, and the current or power value is maintained constant during the forward sweep. The convergence of the power flow is evaluated after each iteration [26], [27], [28].

Advantages of using the BFS Load Flow Technique

i. Compared to traditional methods, it is an effective iterative method for the quick convergence tendency in radial distribution networks.
ii. This strategy is still relatively simple to implement in a distribution management system.
iii. There is no need to sequentially number the branches which makes it considerably simpler in terms of computation. But in order to compute current and power, a branch identification

method must be used to count the number of connected nodes and subsequent linked branches.

iv. This approach maximizes the radial structure of distribution systems, resulting in high speed, reliable convergence, and little memory usage

BFS Load Flow Problem Formulation and Modelling

Calculating actual and reactive power losses that occur in the network is the goal. Hence, to determine the power flow:

$P_{n+1} = P_n - P_{loss,n} - P_{Ln+1}$ ………………………… (xvii)

$Q_{n+1} = Q_n - Q_{loss,n} - Q_{Ln+1}$ …………………………… (xviii)

Where:

$P_n = Real\ power\ flow\ out\ of\ bus,$

$Q_n = Reactive\ power\ out\ of\ bus,$

$P_{Ln+1} = power\ loss\ at\ n + 1\ bus,$

$Q_{Ln+1} = reactive\ power\ loss\ at\ n + 1,$

For the real and reactive power losses between n and n+1 bus:

$P_{loss}\ (n, n+1) = R_n \left(\frac{Pn^2+Qn\hat{}2}{Vn\hat{}2}\right)$ …………………………… (xix)

$Q_{loss}\ (n, n+1) = X_n \left(\frac{Pn^2+Qn\hat{}2}{Vn\hat{}2}\right)$ …………………………… (xx)

Where:

$P_{loss}\ (n, n + 1)$ is the $real\ power\ loss\ between\ n\ and\ (n + 1)$ buses and,

$Q_{loss}\ (n, n + 1)$ is the $reactive\ power\ loss\ between\ n\ and\ (n+1)$ buses

Therefore, the overall power loss will be:

$P_{loss}\ (n, n+1) = \sum_{n=1}^{t}[\mathrm{Ploss}\ (n, n + 1)]$ ……………………… ………. (xxi)

$Q_{loss}\ (n, n+1) = \sum_{n=1}^{t}[\mathrm{Qloss}\ (n, n + 1)]$ ……………………………… (xxii)

Algorithms for the BFS Load Flow Implementation

- **Assumptions**:

i. The initial voltage is 1 p.u

ii. The initial real and reactive power losses are both zero.

iii. A single line diagram can be used to depict the Radial Distribution Network (RDN) because it has a balanced nature.

- **To determine various network matrices:**

1. Start
2. Convert the voltages, power, resistance, and reactance into per unit form.
3. Calculate matrix [A]: (Matrix of Branch-Node Incidence):

$A_{i,j} = \{-1$ if $j = sending\ node$ and

$A_{i,j} = \{+1$ if $j = receving\ node$

4. Determine the number of end nodes in order to determine the number of possible pathways.
5. Determine how many nodes are along each potential path. The bus matrix [B] will have dimensions (l x m) if the lateral has as many as 'm' branches at most.
6. Create a next-linked node matrix [C] to determine linked branches that exist beyond a branch.

- **For the Load Flow**:

1. Consider a flat voltage start:

$V_i = 1 + 0j$, for $i = 1$ to n, $Pl_j = 0$, and $Ql_j = 0$, for $j = 1$ to b

Where, n = total nodes, m = total branches, Pl_j and Ql_j = actual and reactive power losses, respectively.

2. Set the iteration count IT = 1 to ITMAX as the maximum.

3. Determine the current from every branch:

$I_j = \{\frac{Si+1}{Vi+1}\}^* \; for \; i = 1 \; to \; b$ and,

S_{j+1} here equals $(P_{i+1} + jQ_{i+1})$.

4. **Backward Sweep**: Update current going backwards from the end nodes:

$I_k = \sum_j I_j \; for \; k = 1 \; to \; b$ and $where \; j \in C_j$

Here, C_j is the collection of linked nodes after the k branch.

5. **Forward sweep**: starting at the source node, update the nodal voltages using branch currents:

$V_{k+1} = V_k - (I_k * Z_k) \; for \; k = 1 \; to \; n$

6. Determine the Real and Reactive Power Losses:

$Pl_j = Il_j * R_j$ and
$Ql_j = Il_j * X_j$

Total real power loss = $\sum_{j=1}^{b}(Plj)$

Total reactive power loss = $\sum_{j=1}^{b}(Qlj)$

7. Examine the deviation between the real and reactive power losses data from the current and previous iterations.

If
Deviation is minimal ($\in$), move on to step.
Else
Move on to step 3.

8. Until IT=ITMAX, IT=IT+1
9. Return the total real and reactive power losses as well as Pl_j, Ql_j, and IT.

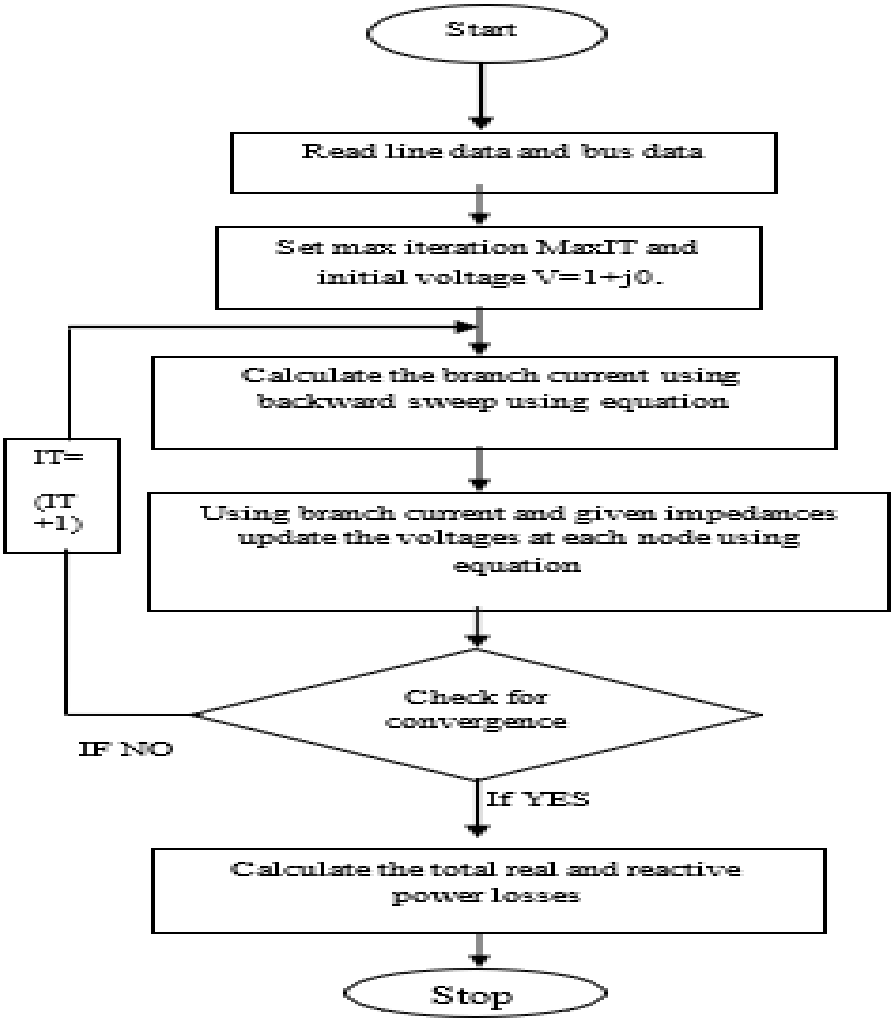

Figure 2: BFS Load Flow Implementation Algorithm Flow Chart

The Adaptive Multi-Objective Particle Swamp Optimization (PSO) Algorithm

The MPSO algorithm and codes start by initializing a collection of random particles, which can then iteratively discover the best solution. According to its own experience and the experience of the particles in its immediate vicinity, each particle modifies its position. The best location for each is denoted by the letters Pbest and Gbest, respectively.

Equations (xxiii) and (xxiv) below can be used to explain how the particle's location changes [45]:

$v_i^{k+1} = wv_i^k + c_1r_1 (Pbest_i - s_i^k) + c_2r_2 (Gbest - s_i^k)$ .... (xxiii)

$s_i^{k+1} = s_i^k + v_i^{k+1}$.. (xxiv)

Where;

c_1, c_2 = The weighting factor
r_1, r_2 = The random numbers between 0 and 1
w = The weighting function
v_i^k = The current velocity of particle i at iteration k
v_i^{k+1} = The modified velocity of particle i
s_i^k = The current position of particle i at iteration k
s_i^{k+1} = The modified position of particle i
$Pbest_i$ = The personal best of particle i
Gbest = The global best of the group

Equation (xxiii) represents the speed function, which is used in the iterative process to update each particle's speed in accordance with the Pbest and Gbest optimal solutions.

Equation (xxiv) is the location function, which indicates that after a certain number of iterations, particles update their positions to find the best solution.

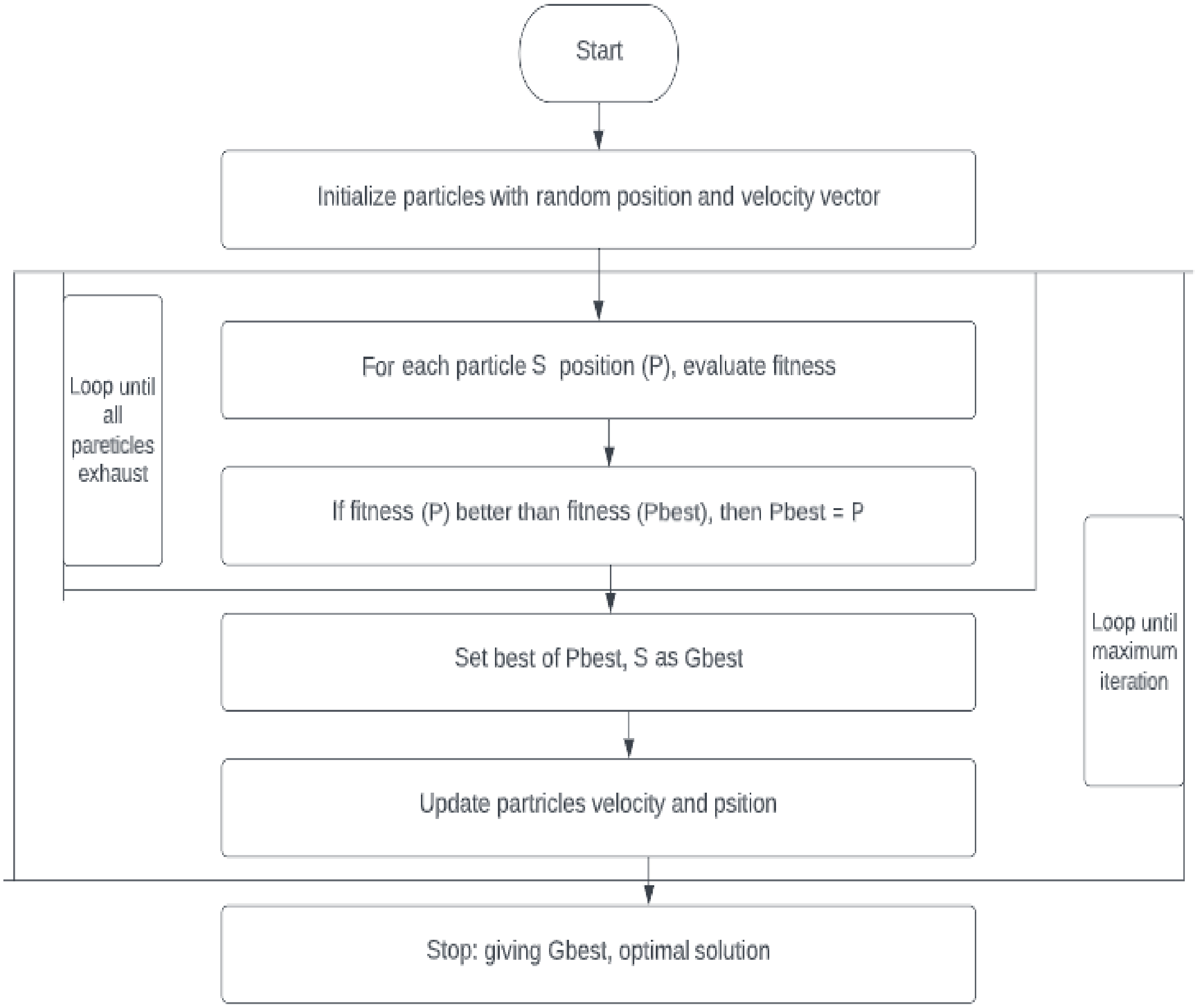

Figure 3: Algorithm Flowchart for the Particle Swamp Optimization (PSO) Implementation

Overall Multi-Objective PSO-Based Optimal Placement and Sizing of DG Optimization System Algorithm and Coding

The reduction of power losses, as given in equation (ii), serves as the first optimization's objective function. The optimization problem's core was established by the nested BFS load flow and MPSO algorithms and codes. The MATLAB M-File application was used to program these procedures. Figure 4 shows the overall flowchart of the optimization system. The following implementation steps were taken in order to put the overall algorithms for solving the problem of dispersed generation placement that minimizes power losses and improve voltage profile into practice:

Step 1: Input line and bus data and bus voltage limits.

Step 2: Utilizing a distribution load flow based on Backward-Forward Sweep (BFS), calculate the loss.

Step 3: The third step involves creating an initial population (array) of particles in the solution space at random, with random locations and velocities. Put k, the iteration counter, at 0.

Step 4: Determine the total loss for each particle using equation (ii) if the bus voltage is within the acceptable range. If not, that particle is impossible.

Step 5: Compare each particle's objective value to its best individual value. Set the objective value as the current P_{best} and note the related particle position if it is less than P_{best}.

Step 6: Pick the particle that has the lowest individual best P_{best} value among all particles, and make that value the current global best G_{best}.

Step 7: Using equations (xxiii) and (xxiv), update the particle's velocity and position.

Step 8: Proceed to Step 9 if the iteration count exceeds the allowed number. Otherwise, return to Step 4 and set iteration index $k = k + 1$.

Step 9: Print the ideal optimal response (optimal solution) to the target issue. The best position combines the ideal (optimal) DG sizes and positions (location) with the appropriate fitness value, which represents the minimum amount of power loss.

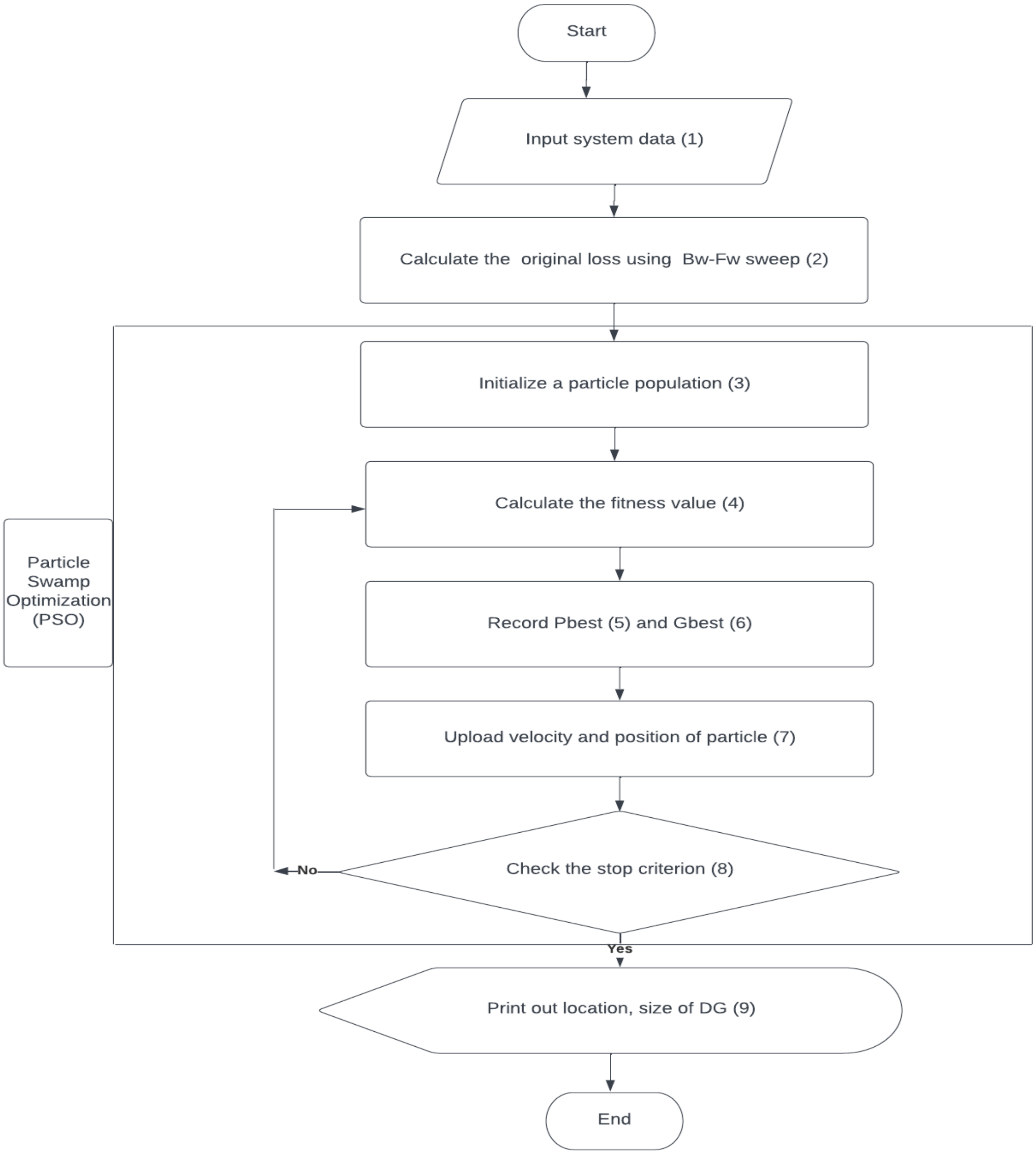

Figure 4: Overall flowchart for the multi-objective PSO-Based Optimal Placement and Sizing of DG optimization System

RESULTS AND DISCUSSION

Simulation Results and Analysis

As expected, when simulated on the MATLAB R2021a version, the overall nested multi-objective Particle Swamp Optimization (PSO)-based codes for the optimal placement and sizing of Distributed Generation (DG) units in electrical power distribution networks was able to reach a good solution by finite steps of evolution steps performed on a finite set of possible solutions. For the PSO parameters, population size is equal to 100 and maximum generation (k_{max}) is equal to 50. For a given DG penetration, the algorithm would take the real and reactive power and calculate the real and reactive power losses (P_{Loss} in kW and Q_{Loss} in kvar) which would then be compared with the original power losses. Th location of the bus for the DG placement will not be fixed initially but the algorithm will finally print the best location (bus number) and the optimum DG size for the placement. The size of the DG implies the amount of the real power and the reactive power. The simulated optimization system has the following salient features:

i. Flexibility to changes
ii. High convergence rate-reaches the optimum solution in just a matter of few seconds in less than 100 iterations and has a maximum iteration limit of 100
iii. Ability to accommodate three different types of DGs (Types 1-that generates real power only, Type 2-that generates reactive power only and Type 3-that generates both real and reactive powers). An embedded prompt command in the nested codes asks for the types of DG placement at the start of the simulation
iv. Ability to place up to four DG units in the IEEE 33-bus radial electrical power distribution network. An embedded prompt command in the nested codes asks for the number of DG units to be placed at the start of the simulation.

IEEE 33-Bus Radial Electrical Power Distribution System

Figure 5 below depicts the single line diagram of the IEEE 33-bus radial electrical power distribution system benchmark network where the nested overall algorithm was tested. There are thirty-three buses and thirty-two lines in it (branches). The base MVA is 10 MVA and the base kV is 12.66 kV (voltage level across all buses). For all buses, the maximum and lowest voltage limitations were taken into consideration at ±5%. A synchronous generator supplies electricity to the distribution network. The network is loaded with 3.715 MW (real power) which is the total active power demand and 2.3 Mvar (reactive power) which is the total reactive power demand, coupled to 32 branches with various power factors [20]. The 33-bus system has 32 lines with the original (base configuration) total real and reactive power losses equal to 201.8925 kW (5.44% of the total real power demand) and 134.6413 kvar (5.85% of the total reactive power demand) respectively. The upper bound size of DG is 3000 kW. Tables 1 2 present the line data and load data of the system, obtained from the Power Systems Test Case Archive, a secondary data source [20]

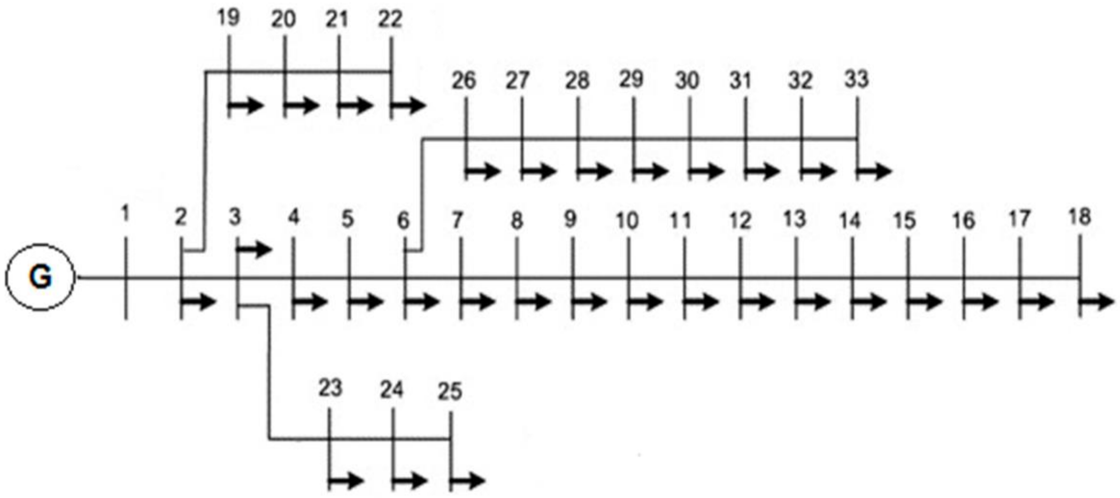

Figure 5: Single line diagram of the IEEE 33-bus radial electrical power distribution system [29].

Table 1: Line data of the IEEE 33-bus radial electrical power distribution system (Power Systems Test Case Archive, 2022) [20]

Line Name	From Bus	To Bus	Length (km)	Resistance (Ohm/km)	Reactance (Ohm/km)
BRANCH-1	1	2	1	0.0922	0.047
BRANCH-2	2	3	1	0.493	0.2511
BRANCH-3	3	4	1	0.366	0.1864
BRANCH-4	4	5	1	0.3811	0.1941
BRANCH-5	5	6	1	0.819	0.707
BRANCH-6	6	7	1	0.1872	0.6188
BRANCH-7	7	8	1	1.7114	1.2351
BRANCH-8	8	9	1	1.03	0.74

BRANCH-9	9	10	1	1.044	0.74
BRANCH-10	10	11	1	0.1966	0.065
BRANCH-11	11	12	1	0.3744	0.1238
BRANCH-12	12	13	1	1.468	1.155
BRANCH-13	13	14	1	0.5416	0.7129
BRANCH-14	14	15	1	0.591	0.526
BRANCH-15	15	16	1	0.7463	0.545
BRANCH-16	16	17	1	1.289	1.721
BRANCH-17	17	18	1	0.732	0.574
BRANCH-18	2	19	1	0.164	0.1565
BRANCH-19	19	20	1	1.5042	1.3554
BRANCH-20	20	21	1	0.4095	0.4784
BRANCH-21	21	22	1	0.7089	0.9373
BRANCH-22	3	23	1	0.4512	0.3083
BRANCH-23	23	24	1	0.898	0.7091
BRANCH-24	24	25	1	0.896	0.7011
BRANCH-25	6	26	1	0.203	0.1034
BRANCH-26	26	27	1	0.2842	0.1447
BRANCH-27	27	28	1	1.059	0.9337
BRANCH-28	28	29	1	0.8042	0.7006
BRANCH-29	29	30	1	0.5075	0.2585
BRANCH-30	30	31	1	0.9744	0.963
BRANCH-31	31	32	1	0.3105	0.3619
BRANCH-32	32	33	1	0.341	0.5302

Table 2: Load data of the IEEE 33-bus radial electrical power distribution system (Power Systems Test Case Archive, 2022) [20]

Load	Location (Bus Bar)	Real Load (kW)	Reactive Load (kvar)
L2	2	100	60
L3	3	90	40
L4	4	120	80
L5	5	60	30
L6	6	60	20
L7	7	200	100
L8	8	200	100
L9	9	60	20
L10	10	60	20
L11	11	45	30
L12	12	60	35
L13	13	60	35
L14	14	120	80
L15	15	60	10
L16	16	60	20
L17	17	60	20
L18	18	90	40
L19	19	90	40
L20	20	90	40
L21	21	90	40
L22	22	90	40
L23	23	90	50
L24	24	420	200
L25	25	420	200
L26	26	60	25
L27	27	60	25
L28	28	60	20
L29	29	120	70
L30	30	200	600
L31	31	150	70
L32	32	210	100
L33	33	60	40
	Total load	3715	2300

Base Case Load Flow Simulation Results and Analysis

The loads of all buses were maintained constant in all simulations with values that were equal to those shown in Table 2 above. Without attaching any DG to the network, the BFS load flow analysis was done on the investigated distribution system, yielding the data (bus voltages and line losses) shown in Table 4.3 below. The base case power losses in each branch (line) of the system were also estimated, along with the voltage profile for each bus.

Table 3: Bus voltages and line losses without DG placement (Base Case)

Bus No	Voltage (Pu)	Line No	Ploss (kW)
1	1.0000	1	12.1927
2	0.9970	2	51.5711
3	0.9830	3	19.7934
4	0.9755	4	18.5931
5	0.9682	5	38.0256
6	0.9498	6	1.9131
7	0.9463	7	4.8342
8	0.9415	8	4.1773
9	0.9352	9	3.5575
10	0.9294	10	0.5531
11	0.9286	11	0.8802
12	0.9271	12	2.6638
13	0.9210	13	0.7286
14	0.9187	14	0.3569
15	0.9173	15	0.2813
16	0.9160	16	0.2515
17	0.9140	17	0.0531
18	0.9134	18	0.1610
19	0.9965	19	0.8322
20	0.9929	20	0.1008
21	0.9922	21	0.0436
22	0.9916	22	3.1812
23	0.9794	23	5.1432
24	0.9727	24	1.2873
25	0.9694	25	2.5940
26	0.9479	26	3.3211
27	0.9453	27	11.2766
28	0.9339	28	7.8180
29	0.9257	29	3.8881
30	0.9222	30	1.5928
31	0.9180	31	0.2131
32	0.9171	32	0.0132
33	0.9168	Total power Losses	201.8925
Average bus voltage	0.948594		

Simulation Results and Analysis after the Placement of DG Units

Starting from the placement of one to four DG units, the voltage profiles and power losses before and after the optimal siting and sizing of the DG units in the standard IEEE 33-bus test system were compared and the results obtained are presented in both tabular and graphical forms in the following sections. Although, the developed algorithm is so robust and flexible that it can accommodate type 1-DGs, type 2-DGs and type 3-DGs, only type 3-DGs based on synchronous machines such as Small Hydro, Geothermal were considered in all the placement cases (1 to 4 DG units) in order to achieve the highest value of power loss reduction and superior voltage profiles than the other variants. This is because it has the capacity to produce real power (P) and reactive power (Q) simultaneously, which reduces the amount of current flowing through the branch and, as a result, lowers voltage drops.

Placement of One DG Unit

```
Please Enter Number of DG [1 to 4]:  1
Please Enter Type of DG (1: Real Power only, 2: Reactive Power Only 3: Real & Reactive Power):  3
```

Table 4a: Bus voltage profiles after the optimal installation of one DG unit in a standard IEEE 33-bus system

```
---------------
 |Bus| |V|
  No.   |Pu|
---------------
   1   1.000
   2   0.999
   3   0.996
   4   0.997
   5   0.999
   6   1.002
   7   0.999
   8   0.994
   9   0.988
  10   0.983
  11   0.982
  12   0.981
  13   0.975
  14   0.973
  15   0.971
  16   0.970
  17   0.968
  18   0.968
  19   0.999
  20   0.995
  21   0.994
  22   0.994
  23   0.993
  24   0.986
  25   0.983
  26   1.000
  27   0.998
  28   0.987
  29   0.979
  30   0.976
  31   0.972
  32   0.971
  33   0.971
```

Average bus voltage level= 0.986152
Minimum bus voltage level = 0.970

Table 4b: Line power losses and power flow after the optimal installation of one DG unit in a standard IEEE 33-bus system

```
--------------------------
 |Line| |Ploss| |Pflow|
  No.    |kW|     |kW|
--------------------------
   1   1.003   1192.300
   2   2.010    730.188
   3   0.262   -304.579
   4   0.553   -425.093
   5   1.544   -486.186
   6   1.711   1076.774
   7   4.319    951.023
   8   3.728    726.707
   9   3.174    672.574
  10   0.493    613.689
  11   0.785    561.209
  12   2.375    492.563
  13   0.649    426.590
  14   0.318    284.248
  15   0.251    224.417
  16   0.224    161.132
  17   0.047     97.682
  18   0.160    379.588
  19   0.829    272.807
  20   0.100    186.107
  21   0.043     93.638
  22   3.094    986.031
  23   5.003    862.263
  24   1.252    443.585
  25   2.317   1067.322
  26   2.965    799.313
  27  10.066    687.593
  28   6.978    541.343
  29   3.470    364.115
  30   1.420    311.301
  31   0.190    213.875
  32   0.012     45.883
```

Table 4c: Optimal DG size and location and total power losses before and after the optimal installation of one DG unit in a standard IEEE 33-bus system

```
---------------------------------------------
```

```
          Optimal Size & Location
---------------------------------------------
Power-Loss Before DG (kW):          201.89
Power-Loss Before DG (kvar):        134.64
Power-Loss After DG (kW):               61
Power-Loss After DG (kVAR):             48
Optimal Location DG (Num Bus):           6
Optimal Size Power-DG (kW):           2583
Optimal Size Power-DG (kvar):         1770
Total Active Power Demand (kW):       3715
Total Reactive Power Demand (kvar):  2300
--------------------------------------------->>
```

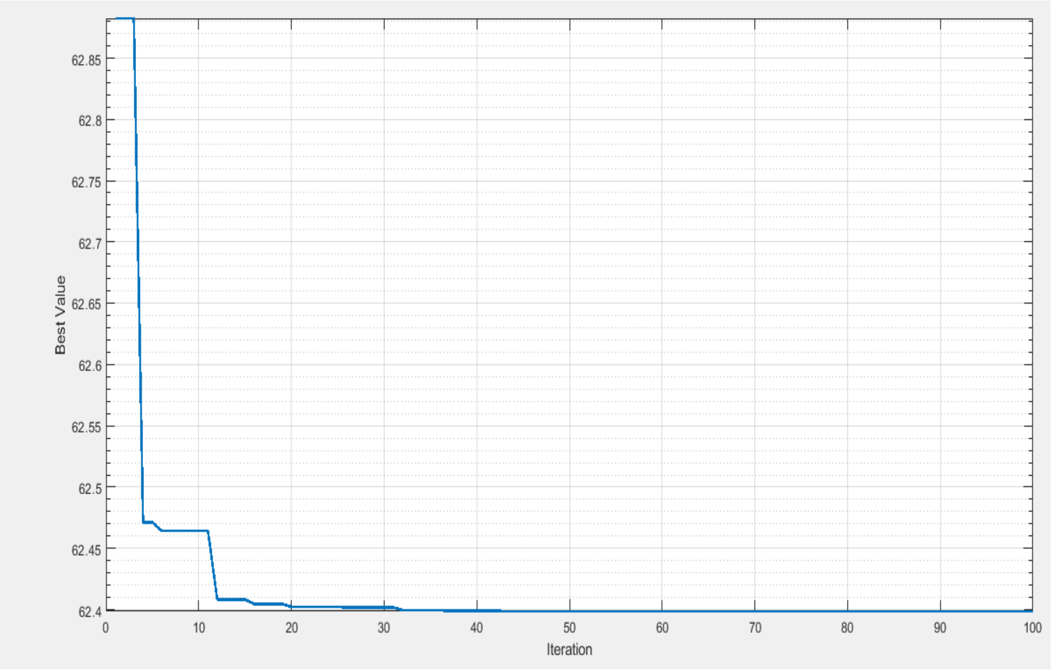

Figure 6: Best iteration values for the optimal placement of one DG unit

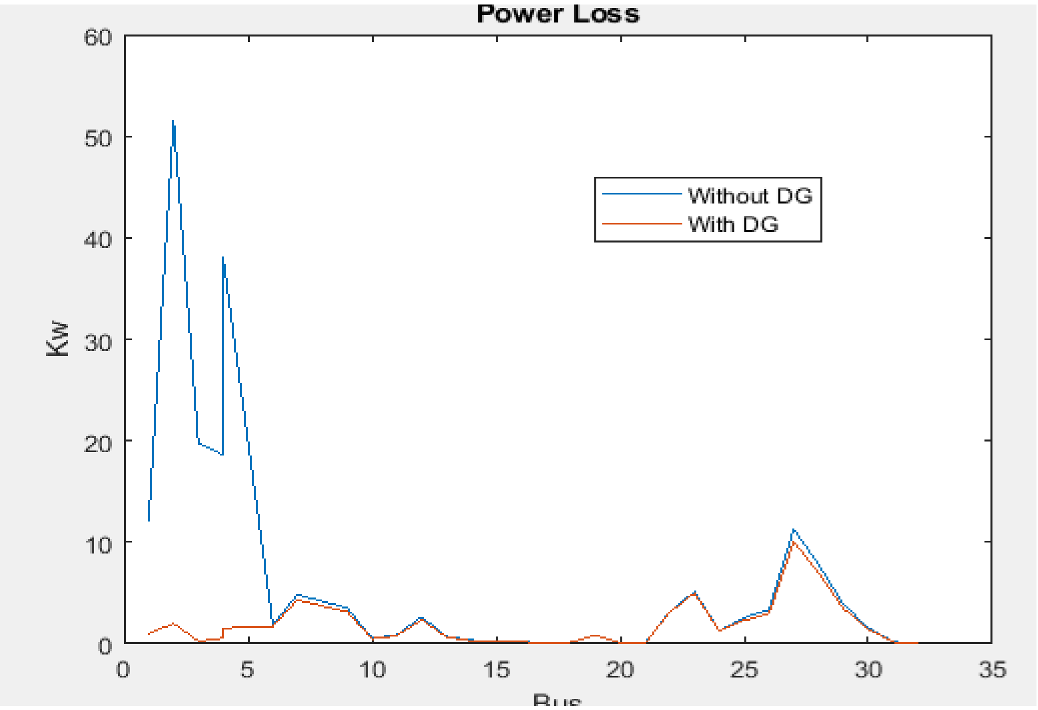

Figure 7: Power loss before and after the optimal placement of one DG unit in a standard IEEE 33-bus system

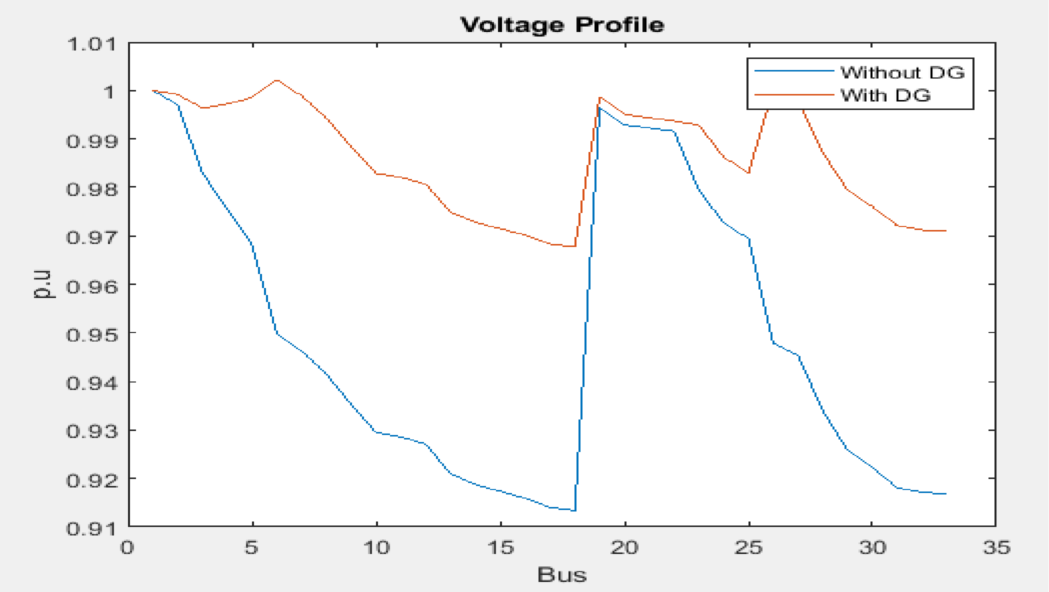

Figure 8: Bus voltage profiles before and after the optimal placement of one DG unit in a standard IEEE 33-bus system

When compared with the old system without DG units, the optimal installation of 1 DG unit results in better average bus voltage levels of (0.986152 per unit) as against (0.948594 per unit). Additionally, the lowest voltage level in the system without DG units is 0.9168 per unit, however the voltage level improves after one type 3-DG unit is installed, giving a minimum voltage level of 0.970. Likewise, the installation of the one DG unit brought about a reduction of 140.89 kW amounting to 69.79% and 86.64 kvar amounting to 64.35% in the overall real and reactive power losses respectively.

Placement of Two DG units

```
Please Enter Number of DG [1 to 4]:  2
Please Enter Type of DG (1: Real Power only, 2: Reactive Power Only 3: Real & Reactive Power):  3
```

Table 5a: Bus voltage profiles after the optimal installation of two DG units in a standard IEEE 33-bus system

```
---------------
  |Bus| |V|
  No.   |Pu|
---------------
   1   1.000
   2   0.999
   3   0.994
   4   0.993
   5   0.993
   6   0.992
   7   0.991
   8   0.991
   9   0.993
  10   0.995
  11   0.995
  12   0.996
  13   1.001
  14   0.999
  15   0.998
  16   0.996
  17   0.994
  18   0.994
  19   0.998
  20   0.995
  21   0.994
  22   0.993
  23   0.990
  24   0.984
  25   0.980
  26   0.993
  27   0.993
```

```
 28   0.996
 29   0.999
 30   1.001
 31   0.997
 32   0.997
 33   0.996
```

Average bus voltage level = 0.994375
Minimum bus voltage level = 0.980

Table 5b: Line power losses and power flow after the optimal installation of two DG units in a standard IEEE 33-bus system

```
---------------------------
 |Line| |Ploss| |Pflow|
 No.    |kW|     |kW|
---------------------------
  1   2.191   1757.747
  2   6.375   1294.959
  3   0.191    256.995
  4   0.051    136.208
  5   0.032     75.987
  6   0.082    238.284
  7   0.007     36.354
  8   0.225   -170.040
  9   0.407   -230.370
 10   0.120   -289.518
 11   0.315   -335.962
 12   1.745   -398.599
 13   0.616    388.678
 14   0.302    275.132
 15   0.238    216.488
 16   0.212    155.707
 17   0.045     95.492
 18   0.160    381.962
 19   0.829    272.837
 20   0.100    186.128
 21   0.043     93.648
 22   3.111    988.374
 23   5.029    862.924
 24   1.259    443.909
 25   0.079   -233.302
 26   0.176   -283.182
 27   0.955   -343.862
 28   0.986   -395.709
 29   1.072   -501.135
```

```
30   1.349    403.867
31   0.180    269.197
32   0.011     60.499
```

Table 5c: Optimal DG size and location and total power losses before and after the optimal installation of two DG units in a standard IEEE 33-bus system

```
---------------------------------------------
         Optimal Size & Location
---------------------------------------------
Power-Loss Before DG (kW):             201.89
Power-Loss Before DG (kvar):          134.64
Power-Loss After DG (kW):               28
Power-Loss After DG (kvar):           20
Optimal Location DG (Num Bus):        30      13
Optimal Size Power-DG (kW):            1146    845
Optimal Size Power-DG (kvar):         1065   396
Total Active Power Demand (kW):        3715
Total Reactive Power Demand (kvar):   2300
---------------------------------------------->>
```

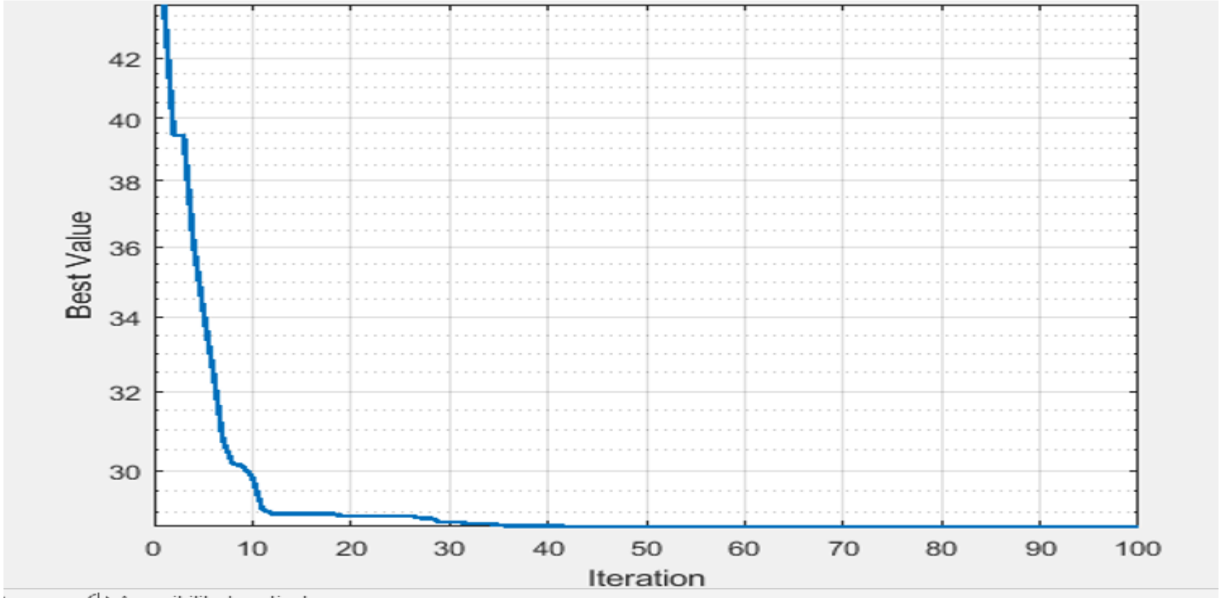

Figure 9: Best iteration values for the optimal placement of two DG units

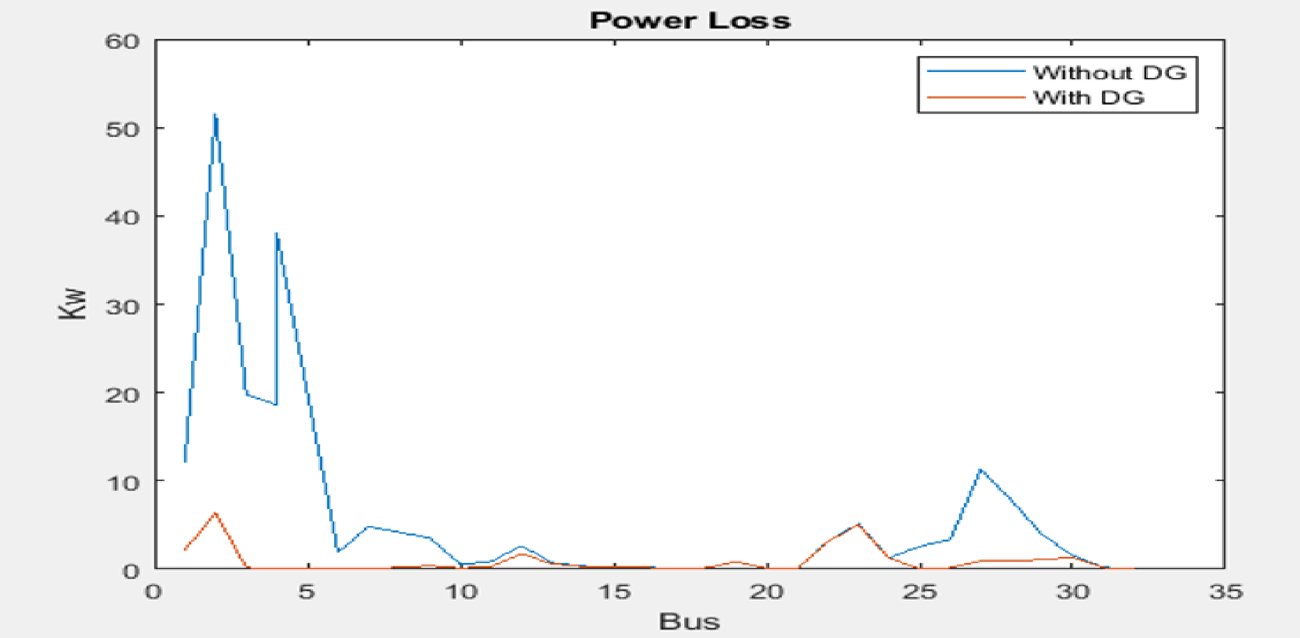

Figure 10: Power loss before and after the optimal placement of two DG units in a standard IEEE 33-bus system

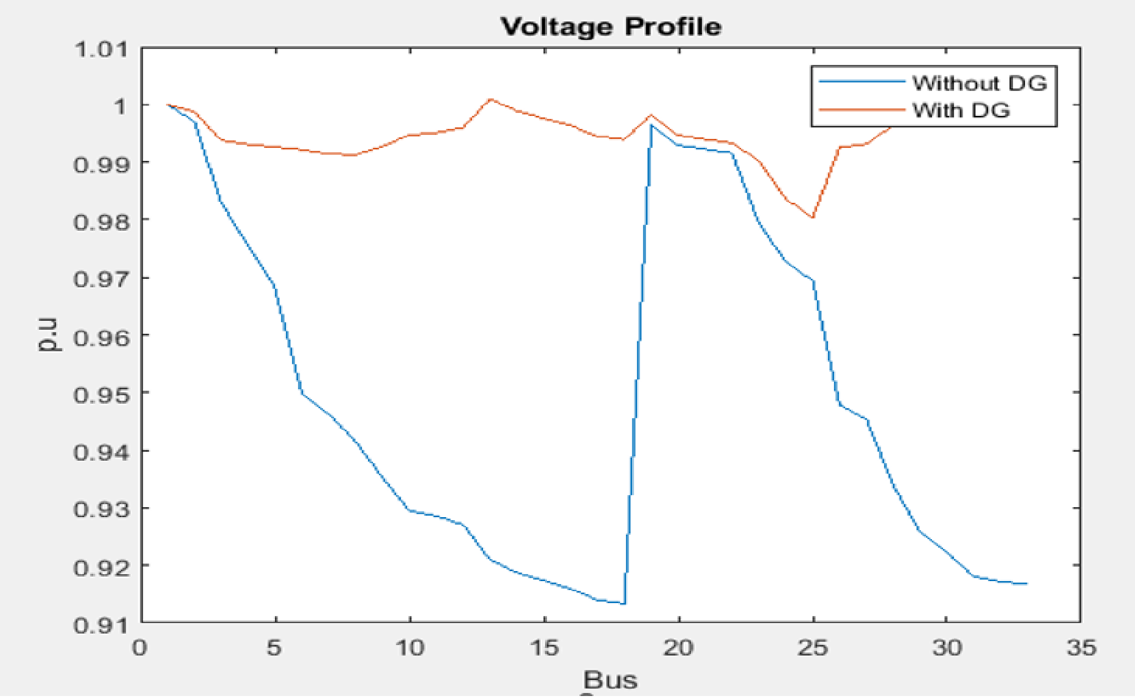

Figure 11: Bus voltage profiles before and after the optimal placement of two DG unit in a standard IEEE 33-bus system

By comparison with the old system without DG units, the optimal installation of two type 3-DG unit results in better average bus voltage levels of (0.994375 per unit) as against (0.948594 per unit) and also, the lowest voltage level in the system was increased from 0.9168 per unit to 0.980 per unit. Similarly, the optimal installation of the two DG units brought about a reduction of 173.89 kW representing 86.13% and 114.64 kvar representing 85.15% in the overall real and reactive power losses respectively.

Placement of Three DG units

```
Please Enter Number of DG [1 to 4]:  3
Please Enter Type of DG (1: Real Power only, 2: Reactive Power Only 3: Real & Reactive Power):  3
```

Table 6a: Bus voltage profiles after the optimal installation of three DG units in a standard IEEE 33-bus system

```
---------------
  |Bus| |V|
   No.   |Pu|
---------------
    1   1.000
    2   0.999
    3   0.998
    4   0.997
    5   0.996
    6   0.994
    7   0.993
    8   0.992
    9   0.993
   10    0.994
   11    0.994
   12    0.995
   13    0.999
   14    1.001
   15    1.000
   16    0.998
   17    0.996
   18    0.996
   19    0.999
   20    0.995
   21    0.995
   22    0.994
   23    0.998
   24    1.000
   25    0.997
   26    0.994
   27    0.995
   28    0.997
```

```
 29   0.999
 30   1.001
 31   0.997
 32   0.996
 33   0.996
```

Average bus voltage level = 0.996606

Minimum bus voltage level = 0.9920

Table 6b: Line power losses and power flow after the optimal installation of three DG units in a standard IEEE 33-bus system

```
---------------------------
 |Line| |Ploss| |Pflow|
  No.    |kW|     |kW|
---------------------------
   1   0.507    844.856
   2   0.562    382.916
   3   0.555    440.501
   4   0.291    319.890
   5   0.408    259.868
   6   0.157    333.391
   7   0.088    132.249
   8   0.046    -76.972
   9   0.142   -138.489
  10    0.055   -199.441
  11    0.163   -246.888
  12    1.022   -310.233
  13    0.550   -366.629
  14    0.300    269.266
  15    0.237    211.695
  16    0.212    152.291
  17    0.045     93.580
  18    0.160    375.117
  19    0.828    272.728
  20    0.100    186.061
  21    0.043     93.616
  22    0.076   -154.610
  23    0.400   -237.599
  24    1.217    416.288
  25    0.027   -130.147
  26    0.080   -192.259
  27    0.509   -253.287
  28    0.582   -309.542
  29    0.727   -422.150
  30    1.350    413.909
```

```
31   0.181    275.076
32   0.011     62.140
```

Table 6c: Optimal DG size and location and total power losses before and after the optimal installation of three DG units in a standard IEEE 33-bus system

```
---------------------------------------------
         Optimal Size & Location
---------------------------------------------
Power-Loss Before DG (kW):            201.89
Power-Loss Before DG (kvar):         134.64
Power-Loss After DG (kW):              12
Power-Loss After DG (kvar):           10
Optimal Location DG (Num Bus):          24        14        30
Optimal Size Power-DG (kW):             1080    752      1053
Optimal Size Power-DG (kvar):          521     351       1021
Total Active Power Demand (kW):        3715
Total Reactive Power Demand (kvar):  2300
```

```
------------------------------>>
```

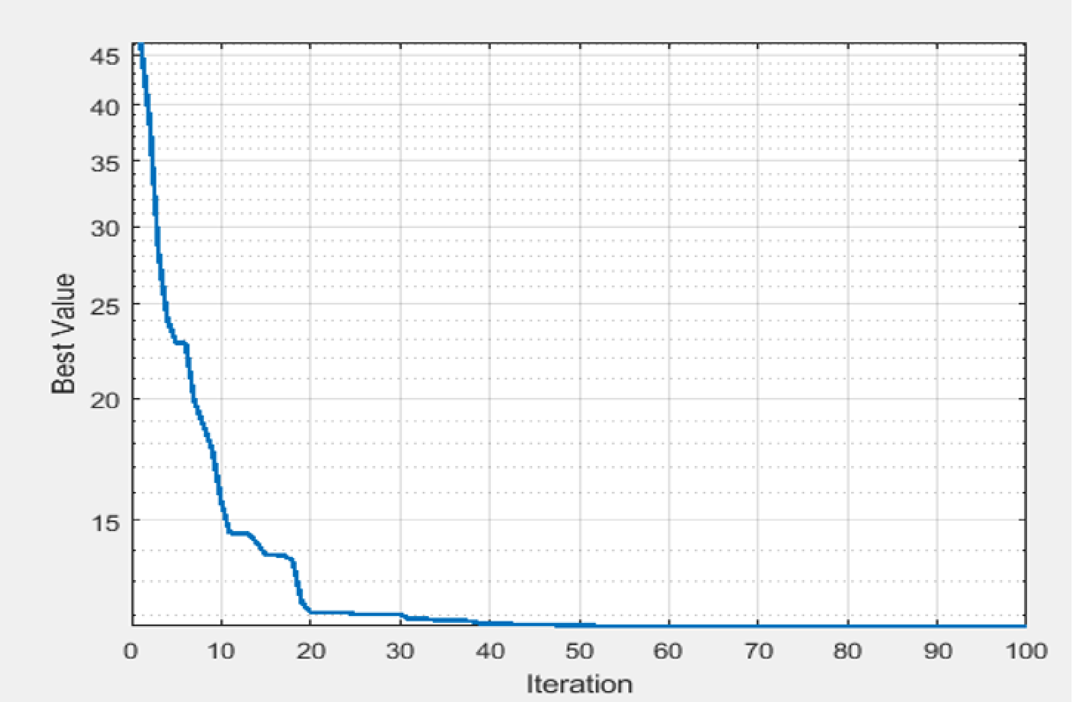

Figure 12: Best iteration values for the optimal placement of three DG units

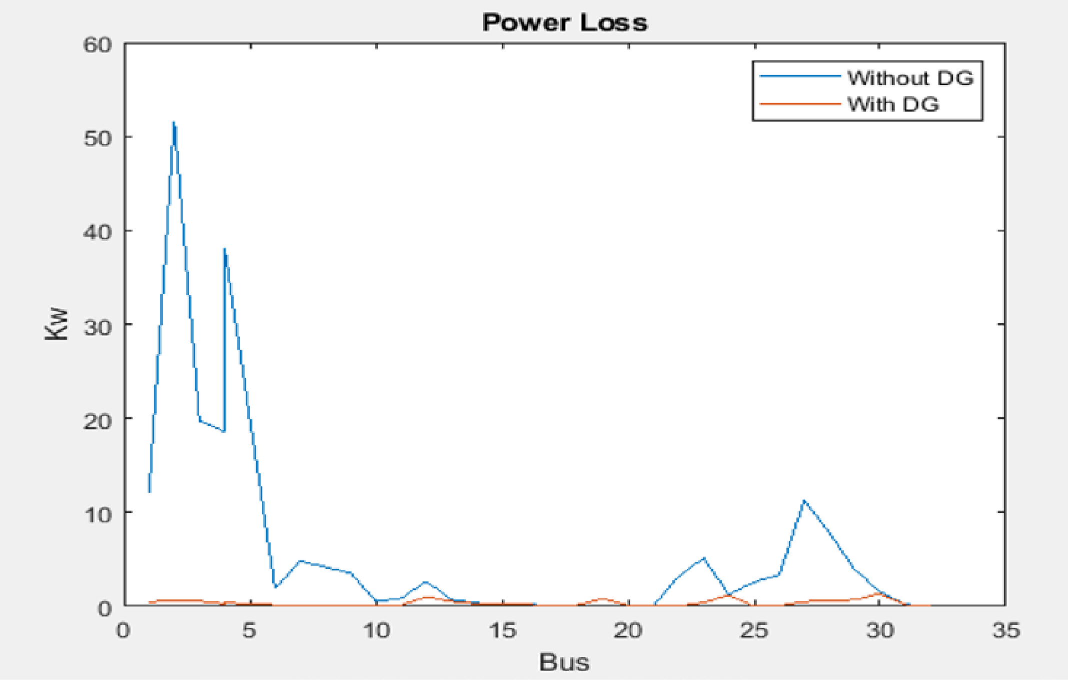

Figure 13: Power loss before and after the optimal placement of three DG units in a standard IEEE 33-bus system

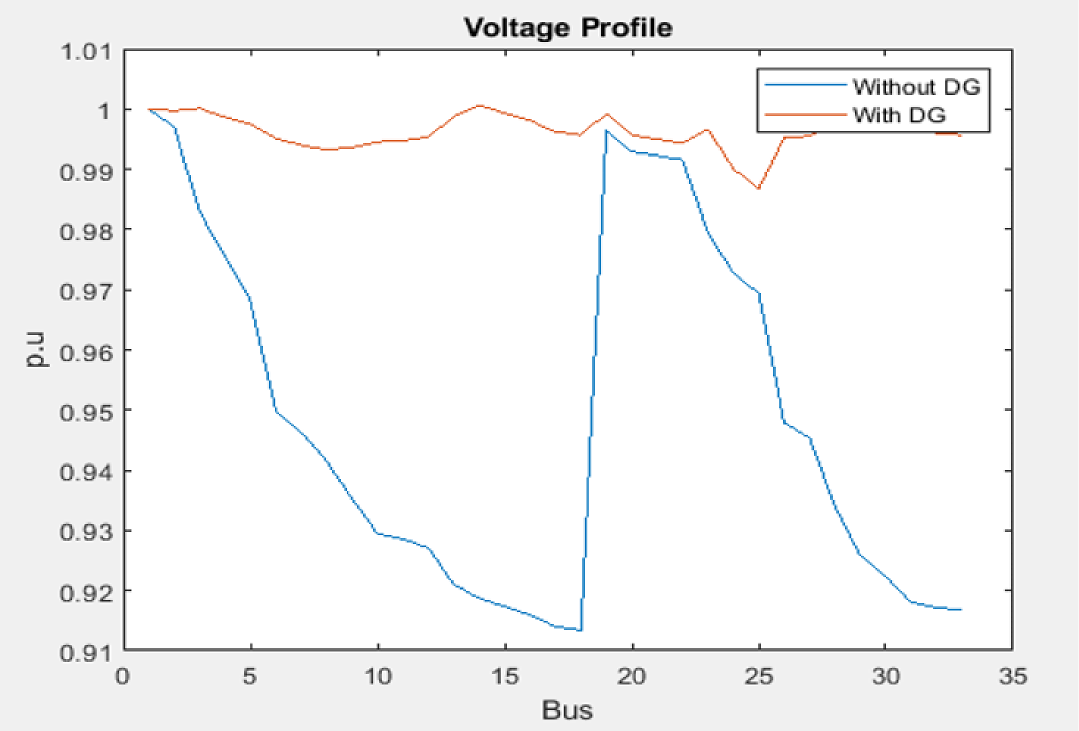

Figure 14: Bus voltage profiles before and after the optimal placement of three DG units in a standard IEEE 33-bus system

The optimal installation of three type 3-DG units produces better average bus voltage levels (0.996606 per unit) as opposed to (0.948594 per unit), and also raises the lowest voltage level in the system from 0.9168 per unit to 0.992 per unit, in comparison to the old system without DG units. Similar to this, the three DG units' optimal installation resulted in reductions in the overall real and reactive power losses of 189.89 kW, or 94.06%, and 124.64 kvar, or 92.57.15%. respectively.

Placement of Four DG units

```
Please Enter Number of DG [1 to 4]:  4
Please Enter Type of DG (1: Real Power only, 2: Reactive Power Only 3: Real & Reactive Power):  3
```

Table 7a: Bus voltage profiles after the optimal installation of four DG units in a standard IEEE 33-bus system

```
---------------
  |Bus| |V|
  No.   |Pu|
---------------
   1   1.000
   2   1.000
   3   0.999
   4   0.999
   5   0.999
   6   1.000
   7   1.001
   8   0.999
   9   0.998
  10   0.998
  11   0.998
  12   0.998
  13   1.000
  14   1.001
  15   1.000
  16   0.999
  17   0.997
  18   0.996
  19   0.999
  20   0.995
  21   0.995
  22   0.994
  23   0.999
```

```
 24   1.000
 25   0.997
 26   1.000
 27   0.999
 28   0.999
 29   1.000
 30   1.000
 31   0.996
 32   0.996
 33   0.995
```

Average bus voltage level = 0.998364
Minimum bus voltage level = 0.994

Table 7b: Line power losses and power flow after the optimal installation of four DG units in a standard IEEE 33-bus system

```
---------------------------
 |Line| |Ploss| |Pflow|
  No.    |kW|     |kW|
---------------------------
  1   0.251    592.516
  2   0.068    130.732
  3   0.017     73.975
  4   0.008    -45.966
  5   0.078   -106.012
  6   0.127   -297.265
  7   0.458    280.332
  8   0.061     86.510
  9   0.008     28.362
 10   0.001    -30.161
 11   0.016    -73.046
 12   0.210   -130.652
 13   0.164   -186.020
 14   0.300    258.689
 15   0.237    203.119
 16   0.211    146.165
 17   0.045     90.084
 18   0.160    361.754
 19   0.828    272.687
 20   0.100    186.036
 21   0.043     93.604
 22   0.004    -34.794
 23   0.110   -123.254
 24   1.217    419.073
```

```
25   0.026    133.541
26   0.011     72.083
27   0.001     12.269
28   0.013    -47.621
29   0.112   -166.613
30   1.352    419.422
31   0.181    278.274
32   0.011     63.045
```

Table 7c: Optimal DG size and location and total power losses before and after the optimal installation of four DG units in a standard IEEE 33-bus system

```
---------------------------------------------
        Optimal Size & Location
---------------------------------------------
Power-Loss Before DG (kW):            201.89
Power-Loss Before DG (kvar):          134.64
Power-Loss After DG (kW):              6
Power-Loss After DG (kvar):           6
Optimal Location DG (Num Bus):         14     30     24      7
Optimal Size Power-DG (kW):            587   790    965   789
Optimal Size Power-DG (kvar):         272   895   466   377
Total Active Power Demand (kW):        3715
Total Reactive Power Demand (kvar):   2300
---------------------------------------------  >>
```

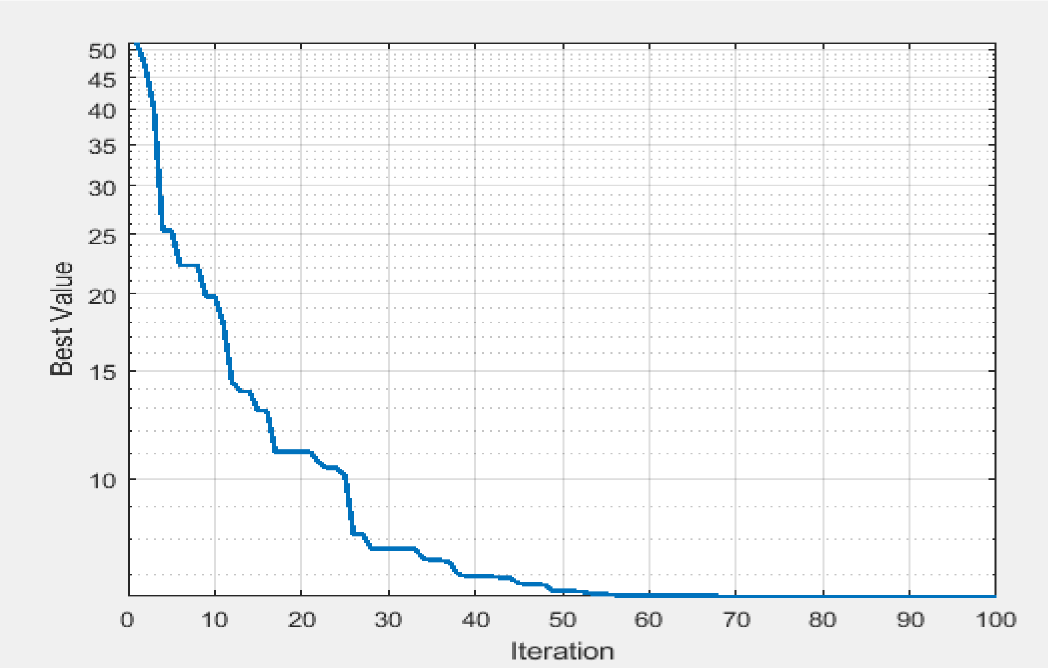

Figure 15: Best iteration values for the optimal placement of four DG units

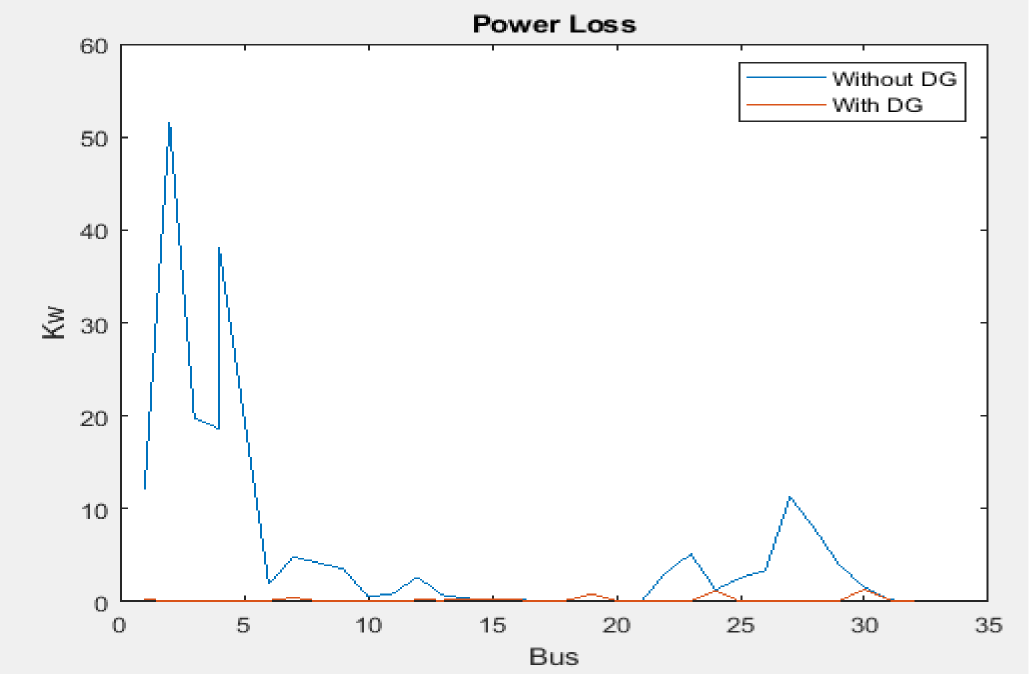

Figure 16: Power loss before and after the optimal placement of four DG units in a standard IEEE 33-bus system

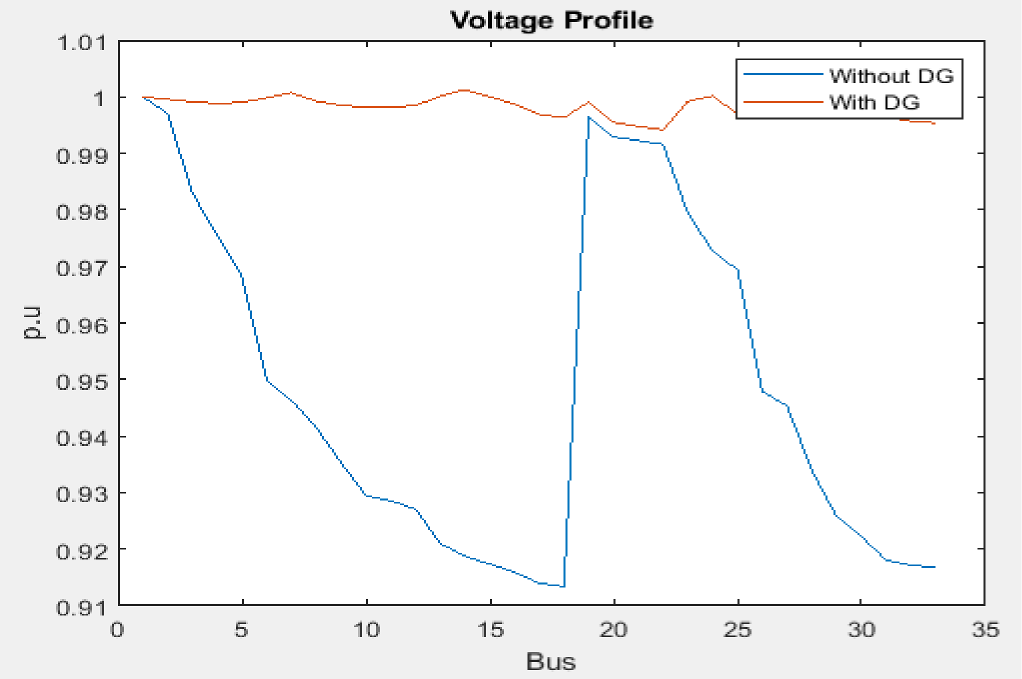

Figure 17: Bus voltage profiles before and after the optimal placement of four DG units in a standard IEEE 33-bus system

In comparison to the old system without DG units, the optimal installation of four type 3-DG units results in better average bus voltage levels (0.998364 per unit) as opposed to (0.948594 per unit), and also raises the lowest voltage level in the system from 0.9168 per unit to 0.994 per unit. Similar to this, the three DG units' ideal placement reduced actual and reactive power losses overall by 195.89 kW, or 97.03%, and 128.64 kvar, or 95.54%, respectively.

Overall Comparison of Voltage Profiles and Power Losses Before and After the Four Cases of DG Units Placement

Having obtained the simulation results for the four different cases of DG units' placement, the overall comparison of the bus voltage profiles and power losses before and after the DG placements was done and the results of the analysis including graphical plots using excel are presented in the following sections.

Overall Voltage Improvement comparison and Calculations

The overall comparison of the bus voltage profiles before and after the DG units' placements was done and the overall % average improvement in the bus voltage profiles in all the four cases of DG units' optimal placements were calculated in excel using the values obtained from the simulations and equations xxv-xxvii. The results of the analysis are presented in table 8. The bus voltage profiles for all the scenarios in a single plot and the % average improvement in bus voltage profiles versus no of DG units for the four cases of DG unit's optimal placements were also plotted in excel as shown in figure 18 and figure 19 respectively.

Average bus voltage levels = $\frac{\textit{sum of voltages in all the 33 buses}}{33}$ …………………….. (xxv)

Average improvement in bus voltage levels after DG placement = **(**Average bus voltage after DG placement **−** Average bus voltage without DG) ………………… (xxvi)

% Average improvement in bus voltage levels after DG placement =
$(\frac{\textit{Average improvement in voltage level after DG placement}}{\textit{Average bus voltage without DG}}) * \mathbf{100}$ ……………………..(xxvii)

Table 8: Overall bus voltage profiles comparison of without DG and after the four cases of DG unit's optimal placement and bus voltage profiles improvement calculations

	No DG	**1 DG**	**2 DGs**	**3 DGs**	**4 DGs**
Bus No	**V (Pu)**	**V (Pu)**	**V (Pu)**	**V(Pu)**	V(Pu)
1	1	1	1	1	1
2	0.997	0.999	0.999	0.999	1
3	0.983	0.996	0.994	0.998	0.999
4	0.9755	0.997	0.993	0.997	0.999
5	0.9682	0.999	0.993	0.996	0.999
6	0.9498	1.002	0.992	0.994	1

7	0.9463	0.999	0.991	0.993	1.001
8	0.9415	0.994	0.991	0.992	0.999
9	0.9352	0.988	0.993	0.993	0.998
10	0.9294	0.983	0.995	0.994	0.998
11	0.9286	0.982	0.995	0.994	0.998
12	0.9271	0.981	0.996	0.995	0.998
13	0.921	0.975	1.001	0.999	1
14	0.9187	0.973	0.999	1.001	1.001
15	0.9173	0.971	0.998	1	1
16	0.916	0.97	0.996	0.998	0.999
17	0.914	0.968	0.994	0.996	0.997
18	0.9134	0.968	0.994	0.996	0.996
19	0.9965	0.999	0.998	0.999	0.999
20	0.9929	0.995	0.995	0.995	0.995
21	0.9922	0.994	0.994	0.995	0.995
22	0.9916	0.994	0.993	0.994	0.994
23	0.9794	0.993	0.99	0.998	0.999
24	0.9727	0.986	0.984	1	1
25	0.9694	0.983	0.98	0.997	0.997
26	0.9479	1	0.993	0.994	1
27	0.9453	0.998	0.993	0.995	0.999
28	0.9339	0.987	0.996	0.997	0.999
29	0.9257	0.979	0.999	0.999	1
30	0.9222	0.976	1.001	1.001	1
31	0.918	0.972	0.997	0.997	0.996
32	0.9171	0.971	0.997	0.996	0.996
33	0.9168	0.971	0.996	0.996	0.995
Average level	0.948594	0.986152	0.994375	0.996606	0.998364
Average Improvement		0.037558	0.045781	0.048012	0.04977
% Average Improvement		3.959289	4.826202	5.061399	5.246681

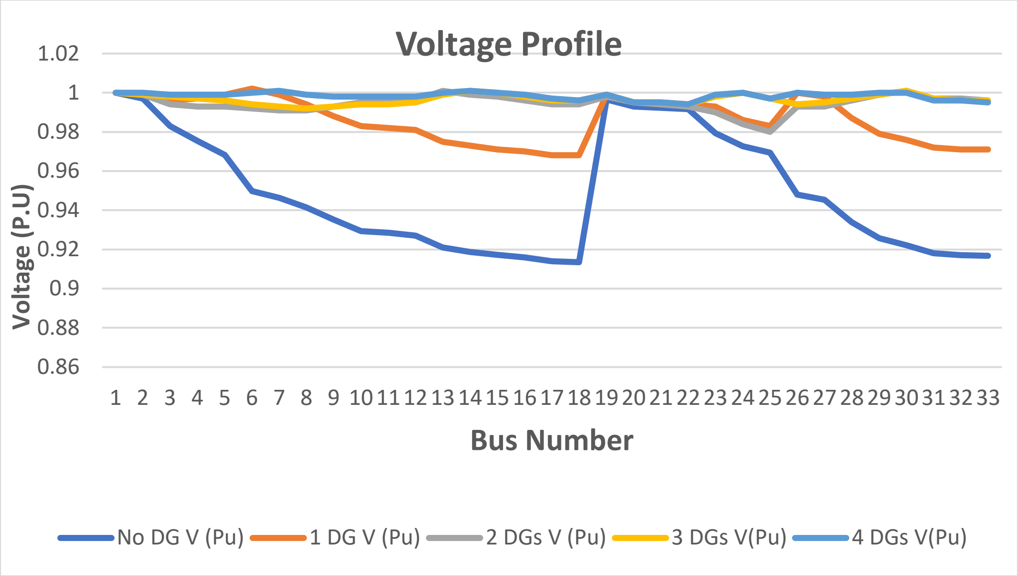

Figure 18: Bus Voltage profiles before and after the four cases of the optimal installation of DG units in a standard IEEE 33-bus test system.

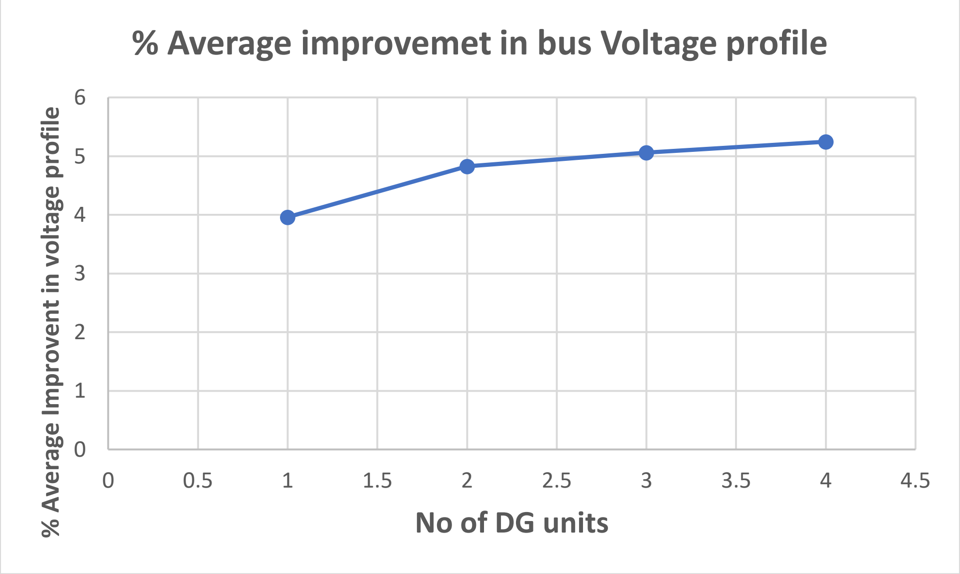

Figure 19: Plot of % average improvement in bus voltage profiles versus no of DG units in all the four cases of DG units' optimal placements

Figure 18 above clearly shows the significant improvements in the bus voltage profiles starting from the optimal placement of one type 3-DG to four type 3-DG units in the network. Also, from table 8, it is observed that the improvement in the voltage profiles increases progressively as the number of DG units increases and the highest % average improvement (being 5.246681%) in bus voltage profiles was attained when four type 3-DG units were optimally placed in the network. Figure 19 further clearly confirmed how these improvements in bus voltage profiles vary proportionally with the number of DG units optimally placed in the system.

Overall Power Losses Reduction Comparison and Calculations

The overall comparison of the power losses before and after the DG units' placements was done and the % reduction in total real and reactive power losses in all the four cases of DG units' optimal placements were calculated using the values obtained from the simulations and equations xxviii-xxxi. The results of the analysis are presented in table 9 and the % reduction in the total real and reactive power losses for the four scenarios of optimal placements of DG units are also plotted in a single plot in excel as shown in figure 20.

Reduction in total Real Power Losses (Ploss) after DG placement = **(**Total Ploss after DG placement **—** Total Ploss without DG) …………………………………… (xxviii)

Reduction in total Reactive Power Losses (Qloss) after DG placement = (Total Qloss after DG placement **—** Total Qloss without DG) …………………………… (xxix)

% Reduction in Total Ploss after DG placement = $\frac{\textbf{Reduction in Total Ploss after DG placement}}{\textbf{\textit{Total Ploss without DG}}}) * \mathbf{100}$………………………………………(xxx)

% Reduction in Total Qloss after DG placement = $\frac{\textbf{Reduction in Total Qloss after DG placement}}{\textbf{\textit{Total Qloss without DG}}}) * \mathbf{100}$………………………………………(xxxi)

Table 9: Comparison of total power losses without DG and after the four cases of optimal placement of DG units and % reduction in total power losses calculations

Scenario	Total Ploss (kW)	Total Qloss (kvar)	Reduction in Total Ploss (kW)	Reduction in Total Qloss (kvar)	% Reduction in Total Ploss	% Reduction in Total Qloss
Without DG	201.89	134.64	-	-	-	-
1 DG	61	48	140.89	86.64	69.79	64.35
2 DGs	28	20	173.89	114.64	86.13	85.15
3 DGs	12	10	189.89	124.64	94.06	92.57
4 DGs	6	6	195.89	128.64	97.03	95.54

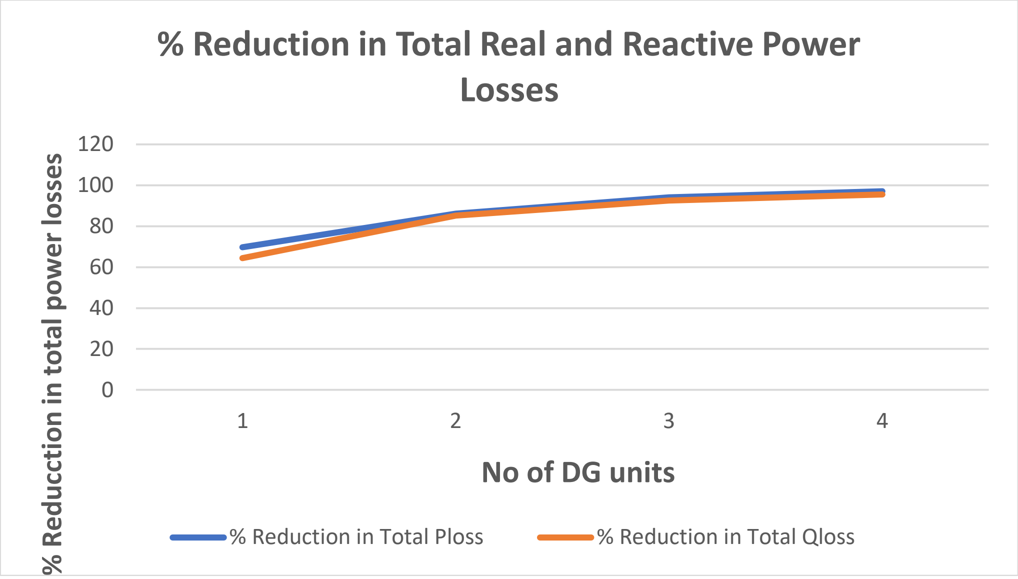

Figure 20: Plot of % reduction in total real and reactive power losses in all the four cases of DG units' optimal placements

The analysis presented in table 9 clearly demonstrated the effectiveness of the optimal placement of the DG units in the network in reducing the total active and reactive power losses whereby significant reduction was achieved in each of the case of DG unit's placement. It is also observed that the reduction in total active and reactive power losses increases progressively as more DG units are being optimally placed in the system attaining the highest % reduction of 97.03% and 95.54% in total active and reactive power losses when four type 3-DG units were optimally placed in the network. Figure 20 further clearly demonstrated this correlation between the reduction in total power losses and the number of DG units and also, the reduction in the total active power losses is slightly more than the reduction in the total reactive power losses in each scenario of DG unit's optimal placement.

Overall Comparison of Optimal DG Locations and DG sizes with the Corresponding Bus Voltage Profiles

Table 10 below presents a summary of the optimal DG sizes (in terms of real and reactive power), the optimal DG locations (bus numbers) and the corresponding bus voltage levels for all the four cases of DG units' optimal placements based on the simulation results earlier presented.

Table 10: Optimal DG locations and DG sizes comparison with the corresponding bus voltage profiles

Parameter	1 DG	2 DGs		3 DGs			4 DGs			
Optimal DG location bus no	6	30	13	24	14	30	14	30	2	7
Bus Voltage (Pu)	1.002	1.001	1.001	1.000	1.001	1.001	1.001	1.000	1.000	1.001
Optimal DG size (kW)	2583	1146	845	1080	752	1053	587	790	965	789
Optimal DG size (kvar)	1770	1065	396	521	351	1021	272	895	466	377

It is observed that the optimal locations of the DG units correspond to the buses with the highest values of voltage levels in all the four cases of the optimal placements of the DG units. In other words, the optimal location and size of the DG units simultaneously determines the improvement in the voltage profile as it also does determine the decrease in the total power losses.

Comparison of Produced Results with Those of Earlier Studies

The results of other approaches that were also applied to and tested on the IEEE 33-bus radial distribution system with one type 3-DG unit optimal placement and were given in [11, 30, 31] are presented in table 4.11 along with the outcomes of the obtained results. The comparison has shown that the developed technique in this study has proven to be comparable with; and even achieved a higher reduction in the total power losses than those of previous studies for an approximately the same size of DG (2.5 MW) optimally placed in bus 6 of the standard IEEE 33-bus radial electrical power distribution network.

Table 11: Comparison of existing methods and proposed method with type 3-DG optimal placement for 33-bus radial distribution system

Author and year	**Methodology/Optimization Technique Employed**	**Optimal DG location bus**	**DG type**	**DG size (MW)**	**% Reduction in Total Real power losses**	**% Reduction in Total Reactive Power losses**
Current work	Multi-Objective PSO	6	Type 3	2.583	69.79%	64.35%
(Injeti and Kumar, 2011) [11]	Fuzzy Logic	6	Type 3	2.590	52.6%	36.9%
(Peyman et al., 2016) [30]	Mixed PSO	6	2.550	Type 3	67.83%	61.66%
(Vijay and Singh, 2016) [31]	General Algebraic Modelling Systems (GAMS)/Non-Linear Programming (NLP)	6	2.533	Type 3	67.86%	-

DISCUSSION

The obtained results demonstrate that the voltage profiles of the buses and the total power losses are significantly impacted by both the optimal locations and sizes of the DG units. In all the four cases of the type 3-DG units' optimal placements, the bus voltage levels have been significantly improved and the total power losses have been remarkably reduced; with this improvement in voltage profiles and reduction in the total power losses proportional to the number of and hence, the capacity of the DG units optimally installed in the network. Furthermore, it has been noted throughout the simulations that the connection position of DG units is crucial for the entire network because it can lead to drastically different performance for different types of DG units.

As far as the overall network power losses go, the findings indicate that the linked DG's size, independent of the DG type, plays a significant role because it has been found that the larger the DG, the greater the impact on the overall network power losses of the system. Furthermore, the location in which a DG unit (of any kind) is located is crucial because it has a completely different impact on the network's overall power losses (both actual and reactive). Although, a set DG unit size cannot ensure the system will operate optimally (from the perspective of minimizing power losses) given the variability in system demands during the day, month, or year; for Distribution Network Operators (DNOs), this set ideal position is crucial for their planning since it enables them to integrate dispatchable DG units with a variety of power production sources and ensure the system will operate at its best.

Results from earlier techniques for the same distribution system have been contrasted with those from the developed algorithm in this study, which was generated for the IEEE 33-bus radial distribution system. The comparison has demonstrated that the suggested method is effective and can offer solid options for the best DG unit size and placement in electrical power distribution networks.

It should be noted that the annual load variability and the cost implications of installing DG units are other factors that have not been considered in the current work. Distribution network loads vary significantly over the course of days, weeks, and months, which causes power losses and voltage profiles to vary significantly as well. Additionally, the price of various types of DGs varies, with the initial installation cost per kW of DGs typically being greater than that of large centralized plants. On the other side, the majority of DGs are pollution-free and have low operating costs, but even so, while assessing their benefits, important distinctions between the various DG types should be taken into account. Many European and national support mechanisms have been created in an effort to encourage the installation of DG units in electrical distribution networks. The most well-known of them is the feed-in tariff, in which the owners of DGs are rewarded at a rate that enables them to quickly recoup the cost of their investment. The aforementioned parameters should be researched and taken into consideration in upcoming research aimed at improving the suggested algorithm. They should also be used to analyze an existing electrical power distribution network.

CONCLUSION

In this research work, an optimization system, based on multi-objective Particle Swamp Optimization (PSO) technique for identifying the optimal sizes and positions of Distributed Generation (DG) unit's placement in radial electrical power distribution networks has been developed. The developed algorithm was evaluated on the industry-standard IEEE 33-bus radial electrical power distribution system, and the test results were compared to those of previous research, demonstrating that the algorithm is well-functioning and has a tolerable level of accuracy. The validation test of the developed algorithm conducted on a standard IEEE 33-bus radial electrical power distribution benchmark network shows that the total real power loss satisfying the line limits and constraints and the total reactive power loss of the system, were significantly decreased; and the voltage profile of the system was drastically enhanced by incorporating DG units at predetermined places. As clearly shown from the simulation results, the decrease in the total real and reactive power losses and the improvement in bus voltage profiles is a function of the optimal location and size of the DG unit's placement and these also increases as the number of DG units increases for the type 3-DGs. The highest % reduction in total real and reactive power losses (which are 97.03% and 95.54% respectively) were obtained when four type 3-DG units were placed in the network and this scenario also gives the maximum % average improvement (which is 5.246681%) in bus voltage profiles obtained. The adopted optimization technique is quick and precise and this approach can be used to solve mixed integer nonlinear optimization issues in electrical power systems. This method's parameters can be easily adjusted, and it has a very good convergence characteristic.

SIGNIFICANCE AND CONTRIBUTIONS TO KNOWLEDGE

This research work has developed a very flexible and robust adaptive multi-objective Particle Swarm Optimization (PSO)-based optimization system for the optimal sizing and placement of renewable energy sources in the conventional electrical power distribution networks for significant power losses reduction and voltage profile improvement. The developed optimization system can accommodate the optimal placement of three different types of Distributed Generation (DG) units (Types 1-DG such as solar PV, fuel cells, microturbines, Type 2-DG such as gas turbines and Type 3-DG such as small hydro, geothermal and combined cycles) contained in literature and also up to four DG units. The application of the developed algorithm in a real electrical power distribution network can assist engineers, electric utilities, and distribution network operators in the more efficient integration of new Distributed Generation (DG) units in the current electrical power distribution networks.

RECOMMENDATIONS FOR FUTURE RESEARCH

The proposed algorithm should be improved in further work while taking the following factors into account:

1. Yearly load fluctuations
2. Economic concerns with the installation of Distributed Generation (DG) and the accompanying installation costs
3. Environmental effects brought on by the use of DG technologies
4. The application of the algorithm in a real electrical power distribution network.

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