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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 RECENT 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 the most recent research critically reviewed are presented in table 1 below.

Table 1: Critical Review of Recent Related Works on Co-ordination of Optimization Technique

| **Research (Author and Year)** | **Title** | **Methodology** | **Research gap/Limitation** |
|---|---|---|---|
| (Barukcic et al., 2021) [3] | Co-Simulation Framework for Optimal Allocation and Power Management of $DG_S$ in Power Distribution Networks Based on Computational Intelligence Techniques | Optimization tools applying Mixed Integer Distributed Ant Colony Optimization (MIDACO) and Artificial Neutral Network (ANN) were used to solve optimization problem while OpenDSS was used for load calculation. The computational tools were implemented in Python programming environment. | ANN has several advantages which includes outperformance in discrete space search. However, it easily gets trapped in global optimum dimensional search space. Thus, has low convergence rate. An improved optimization technique is required to handle the issue of local minima and global optimum problems. |

| | | | |
|---|---|---|---|
| (Injeti and Thunuguntla, 2020) [8] | Optimal Integration of $DG_S$ into Radial Distribution Network in the Presence of Plug-in Electric Vehicles to Minimize Daily Active Power Losses and to Improve the Voltage Profile of the System using Bio-inspired Optimization Algorithms. | An efficient multi-objective function is proposed using Particle Swamp Optimization (PSO) and Butterfly Optimization (BO) as optimization techniques to minimize the objectives of the system.<br>Load flow analysis was done using repetitive backward-forward sweep while the simulation was implemented using MATLAB software. | Two algorithms are combined in sequential form which favours optimal location but takes more time. Further modification is needed to improve time. Therefore, a robust improved optimization method that will combine the capabilities of both PSO and BO is required. |
| (Azizivahed | Multi-Objective | The proposed energy | Optimal DG size and placement |

| | | | |
|---|---|---|---|
| et al., 2019) [11] | Energy Management Approach Considering Energy Storages in Distribution Networks with Respect to Voltage Security. | management problem with two objective functions to minimize the operation cost and voltage deviation was solved using modified shuffled frog leaping algorithm (SFLA). The microgrid consists of PV units, diesel generator units and ESS | on the network was not done. Hence, the need for an integrated optimization technique for optimal sizing and location of DG units. |
| (Saleh et al., 2019) [12] | Impact of Optimum Allocation of Distributed Generations on Distribution Network Based on Multi-Objective Different Optimization | Single and multi-objective functions were solved using PSO and MSA (Moth–Swarm Algorithm) and tested on IEEE 33-bus radial system | Two optimization techniques were used independently and the results compared. PSO is effective for power loss reduction and MSA is effective for voltage deviation. Hence the need improved algorithm that can handle more objective |

| | | | |
|---|---|---|---|
| | Techniques. | | function at the same time |
| (Yang et al., 2019) [13] | Coordination Control Strategy for Power Management of Active Distribution Network | Coordination of both active and reactive power (PQ) injection through the scheduling of adjustable PQ node | The network system model was not optimized to determine the optimal values. Therefore, there is need for optimization for optimal solutions of the objective functions |
| (Mohamed et al., 2017) [14] | Power Management Strategy to Enhance the Operation of Active Distribution Networks. | Optimal power flow and particle swarm optimization | Optimal power flow shows ineffectiveness when hybrid renewable energy sources and large network are involved. PSO is subject to trapping at the local minimum in high-dimensional space and has low convergence rate in the iterative process. |

**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.

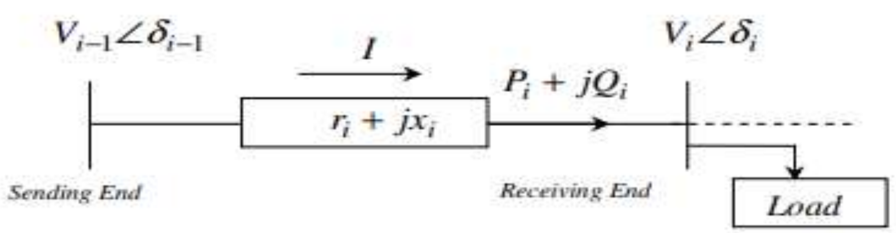


**Figure 1**: One line diagram of a two-bus system

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) $=r_i \frac{Pi^2+Qi^2}{Vi^2}$ ………………………………………. (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.

$P_L = \sum_{i=1}^{n} 1 \sum_{j=1}^{n} [Aij(PiPj + QiQj) + Bij(QiPj - PiQj)]$……………………… (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'
$V_i$ & $\delta_i$ = 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**

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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.

$$\textbf{Base current} = \frac{\textbf{base power}}{\textbf{base voltage}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(xv)}$$

$$\textbf{Base impedance} = \frac{\textbf{base voltage}}{\textbf{base current}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(xvi)}$$

**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:

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

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

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:

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

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

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:

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

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

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**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):

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

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

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.

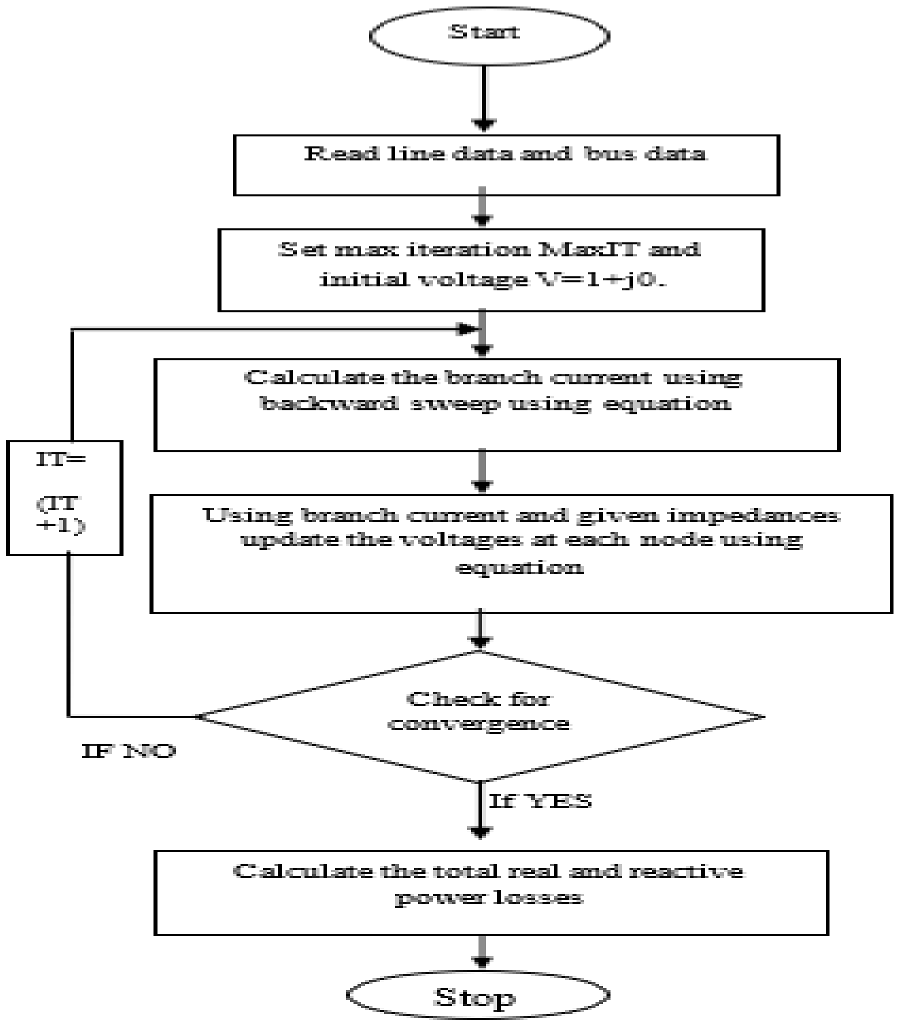


**Figure 2**: BFS Load Flow Implementation Algorithm Flow Chart

**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]:

$v_i^{k+1} = wv_i^k + c_1 r_1 (Pbest_i - s_i^k) + c_2 r_2 (Gbest - s_i^k)$ ......................................(xxiii)

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

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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.

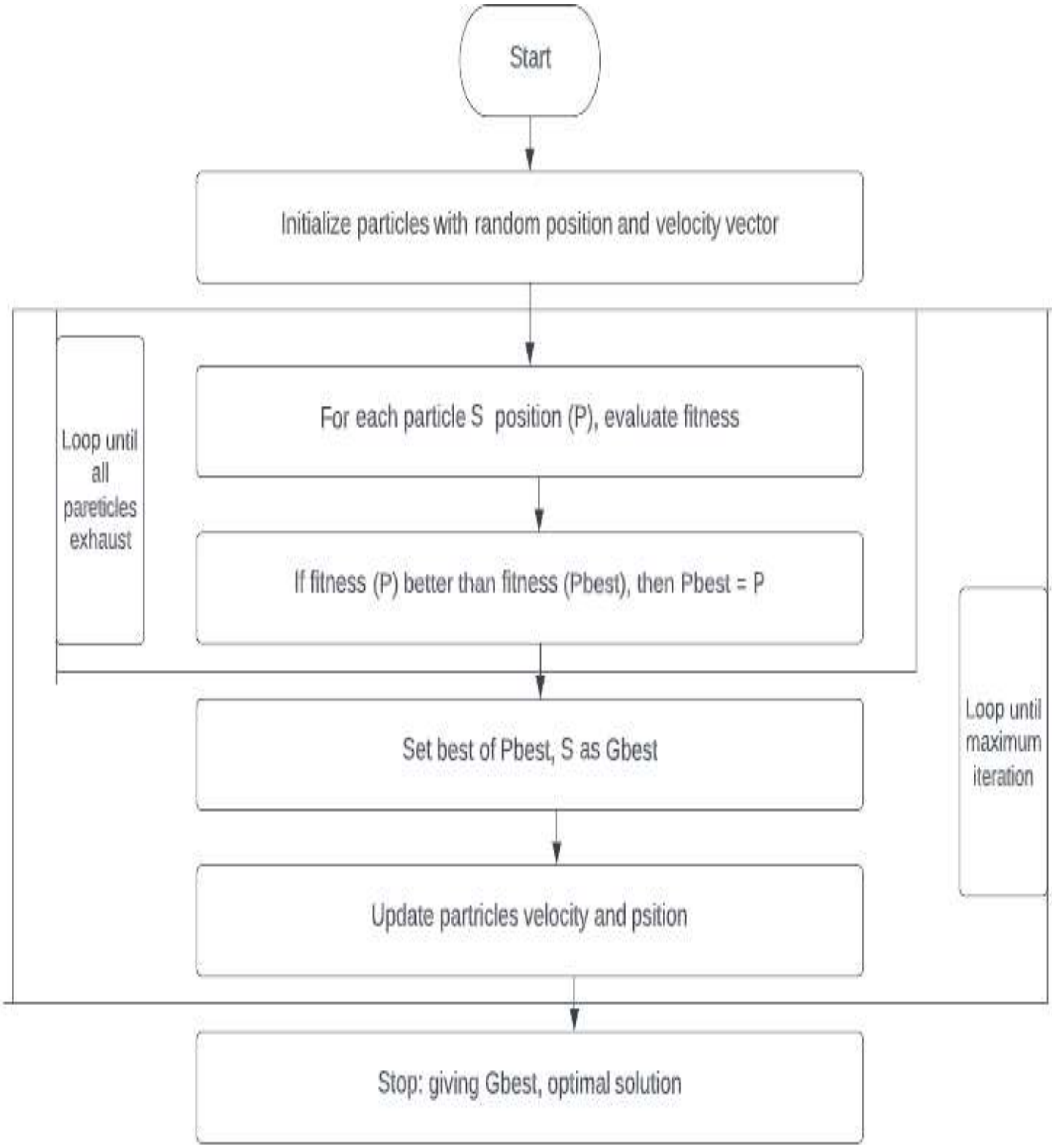


**Figure 3:** Algorithm Flowchart for the Particle Swamp Optimization (PSO) Implementation

**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.

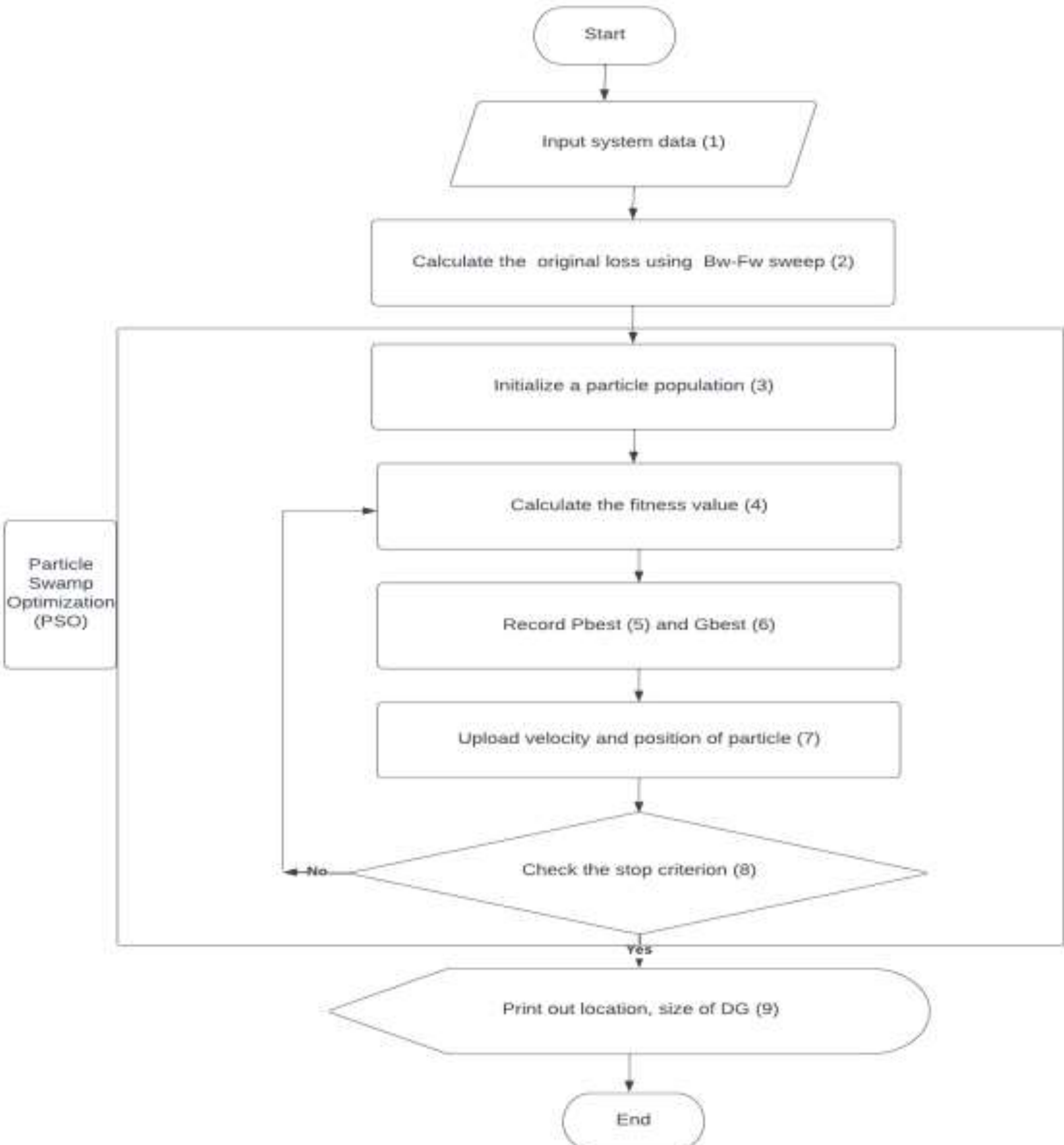


**Figure 4**: Overall flowchart for the multi-objective PSO-Based Optimal Placement and Sizing of DG optimization System

## 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 2& 3 present the line data and load data of the system, obtained from the Power Systems Test Case Archive, a secondary data source [20]

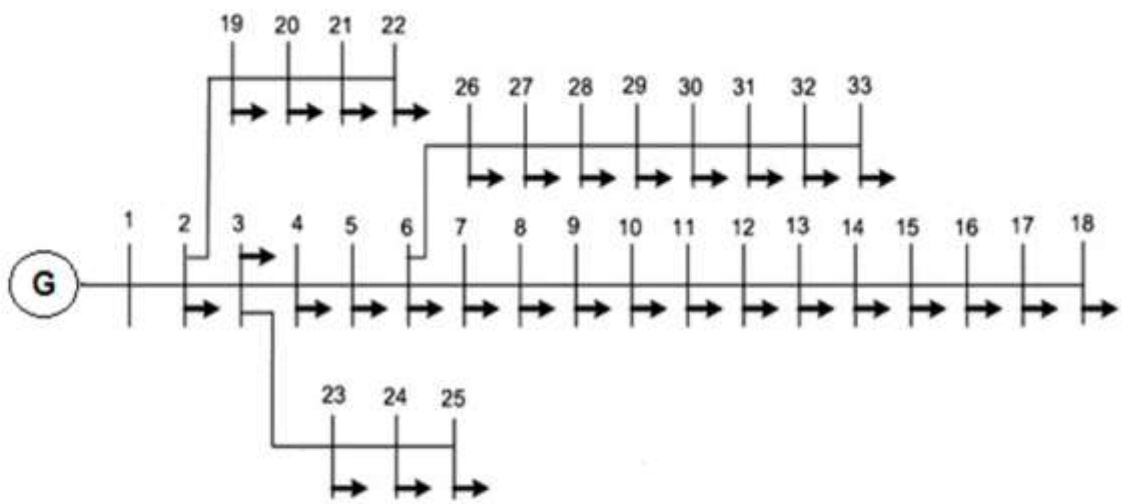


**Figure 5:** Single line diagram of the IEEE 33-bus radial electrical power distribution system [29].

**Table 2:** 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 3:** 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 3 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 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 4**: 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 5a**: Bus voltage profiles after the optimal installation of one DG unit in a standard IEEE 33-bus system

---------------

|Bus| |V|

No.   |Pu|

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---------------

| | |
|---|---|
| 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 5b:** Line power losses and power flow after the optimal installation of one DG unit in a standard IEEE 33-bus system

| \|Line\| No. | \|Ploss\| \|kW\| | \|Pflow\| \|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 5c:** 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

--------------------------------------------->>

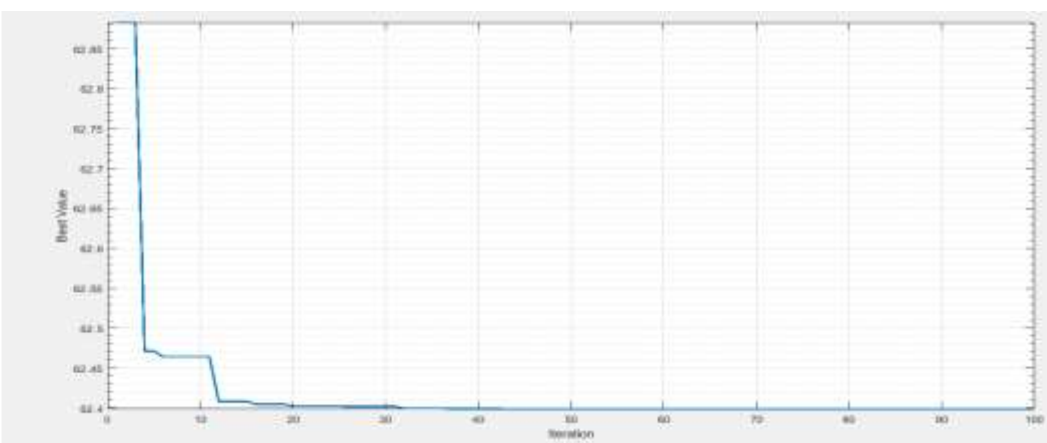

**Figure 6**: Best iteration values for the optimal placement of one DG unit

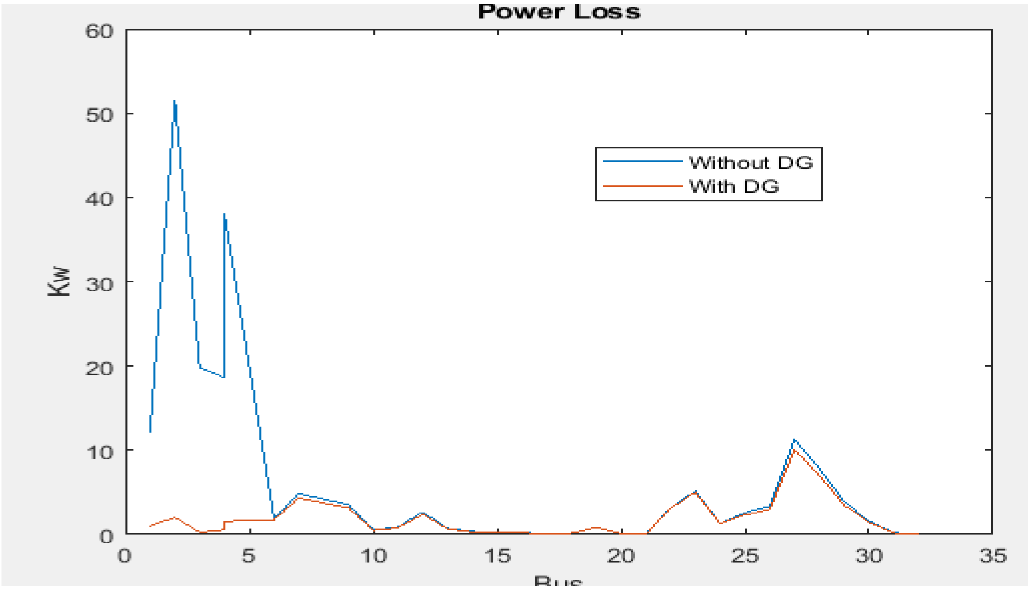


**Figure 7**: Power loss before and after the optimal placement of one DG unit in a standard IEEE 33-bus system

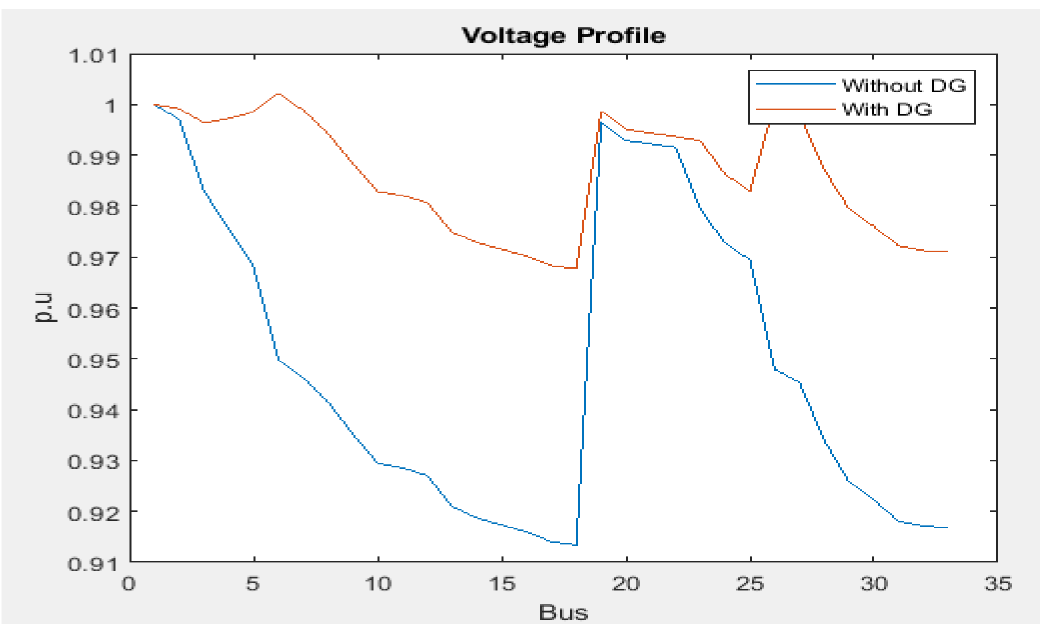


**Figure 8**: Bus voltage profiles before and after the optimal placement of one DG unit in a standard IEEE 33-bus system

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

| \|Bus\| No. | \|V\| \|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 6b:** 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| |

---------------------------

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| | | |
|---|---|---|
| 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 6c:** 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 | |

---------------------------------------------->>

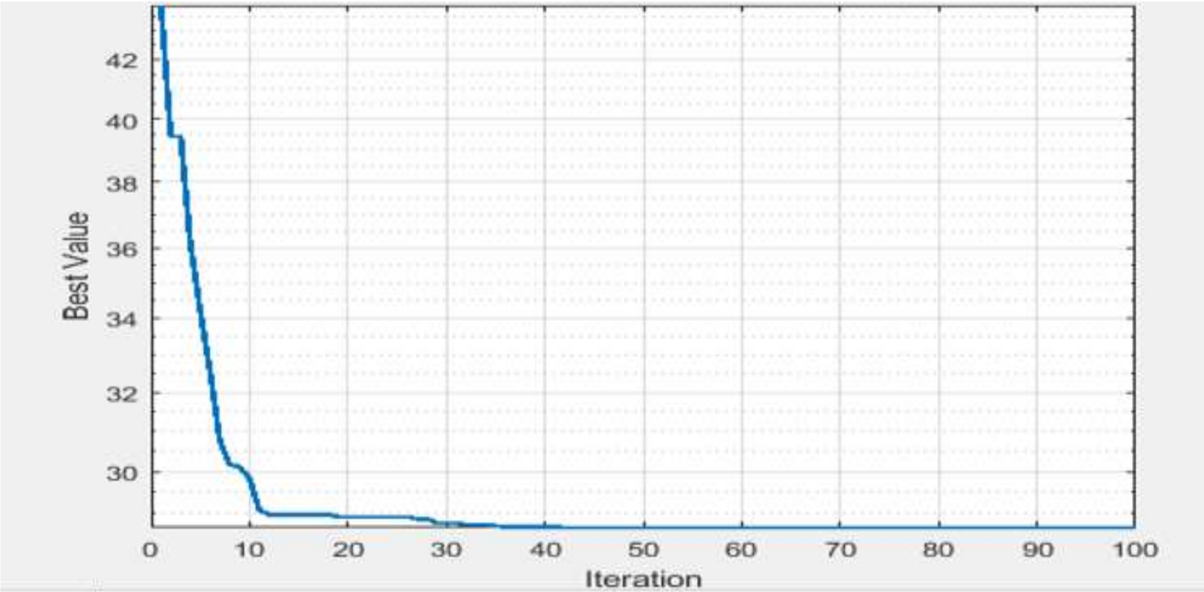


**Figure 9**: Best iteration values for the optimal placement of two DG units

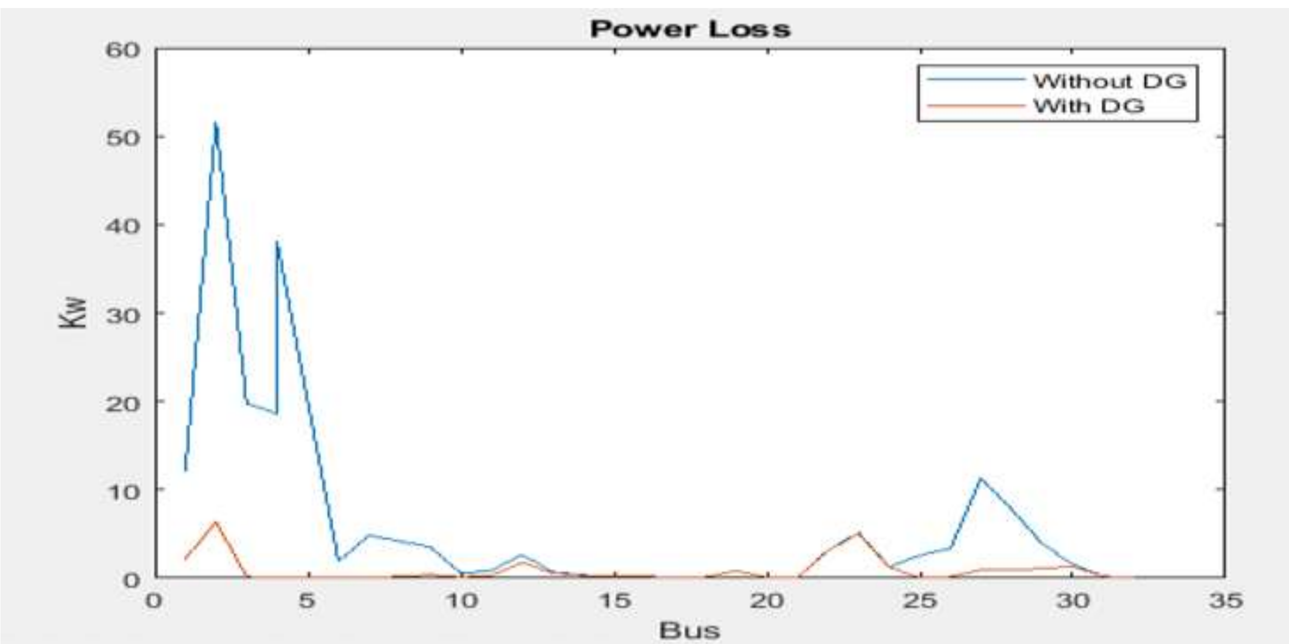


**Figure 10**: Power loss before and after the optimal placement of two DG units in a standard IEEE 33-bus system

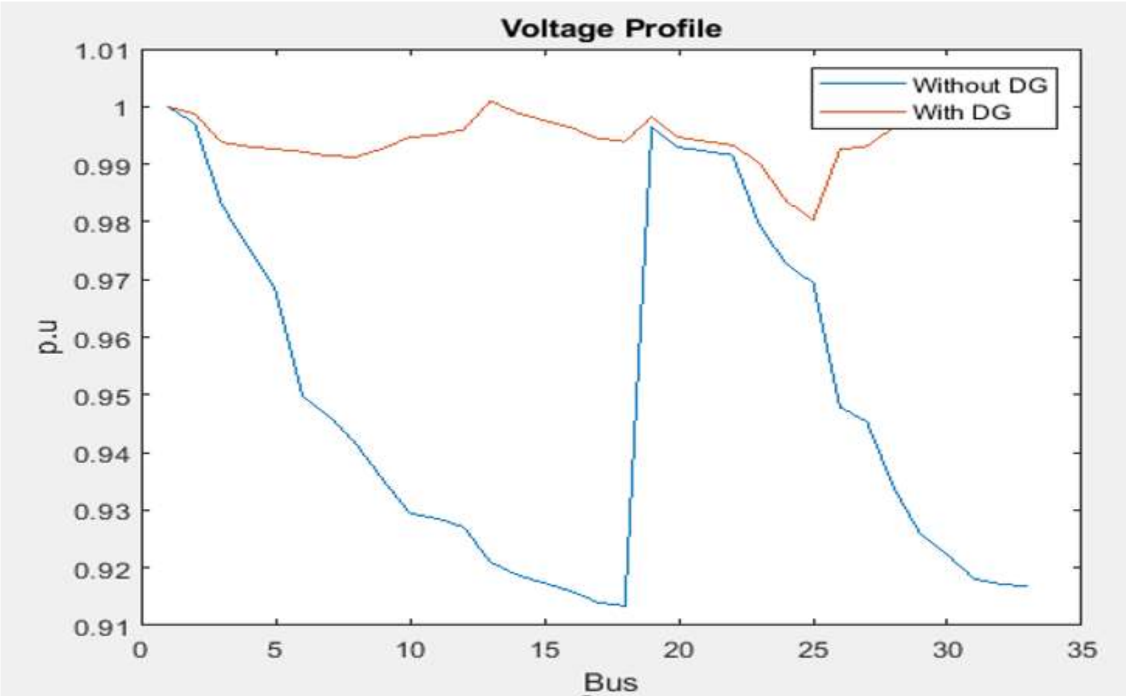


**Figure 11**: Bus voltage profiles before and after the optimal placement of two DG unit in a standard IEEE 33-bus system

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

| Line No. | Ploss kW | Pflow 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 7c:** 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

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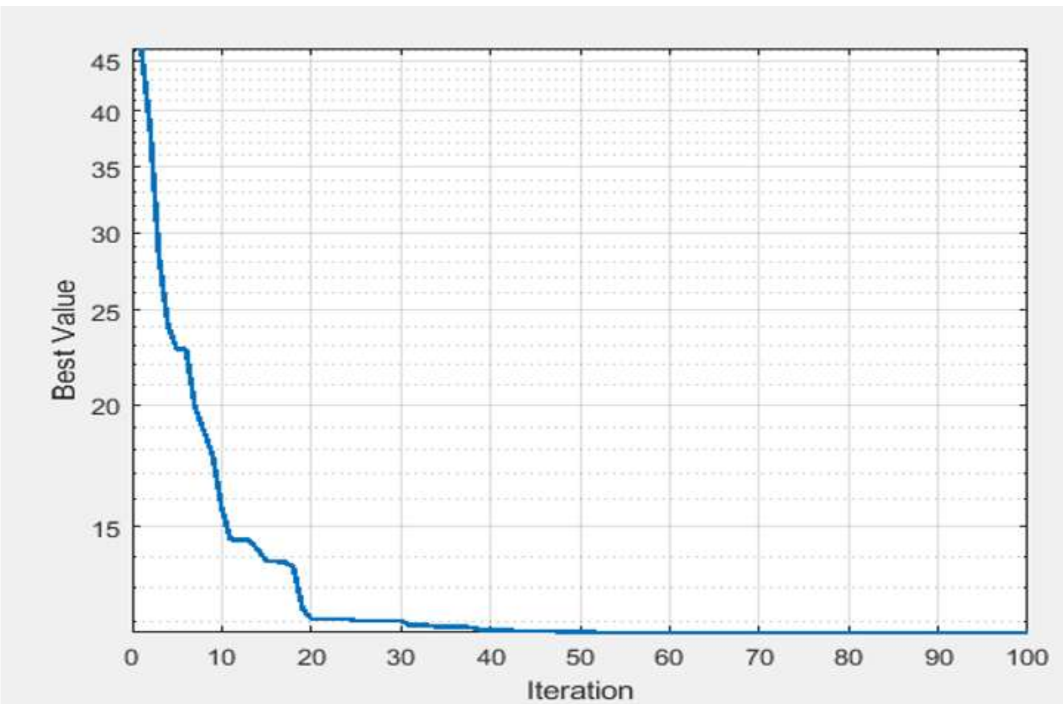


**Figure 12**: Best iteration values for the optimal placement of three DG units

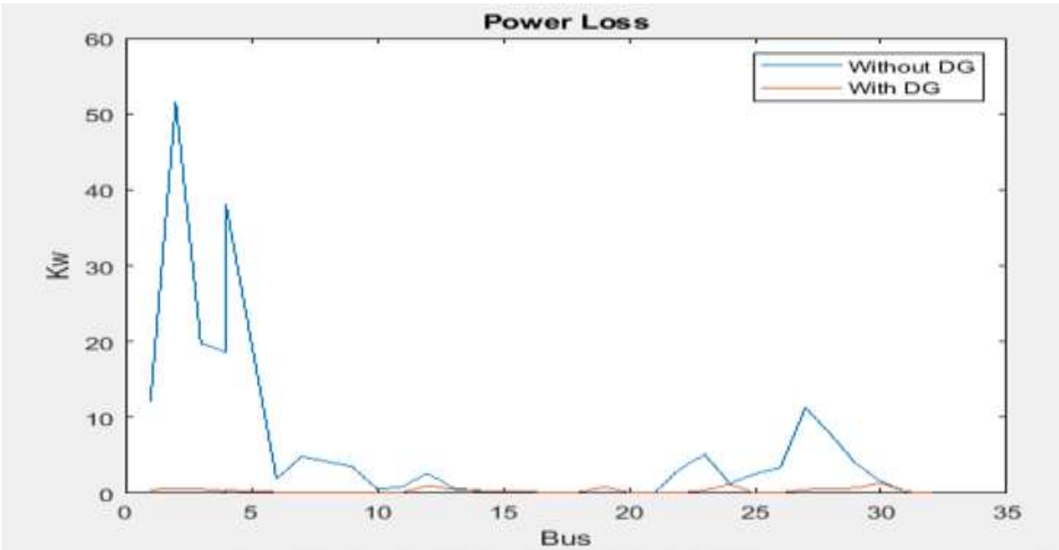


**Figure 13**: Power loss before and after the optimal placement of three DG units in a standard IEEE 33-bus system

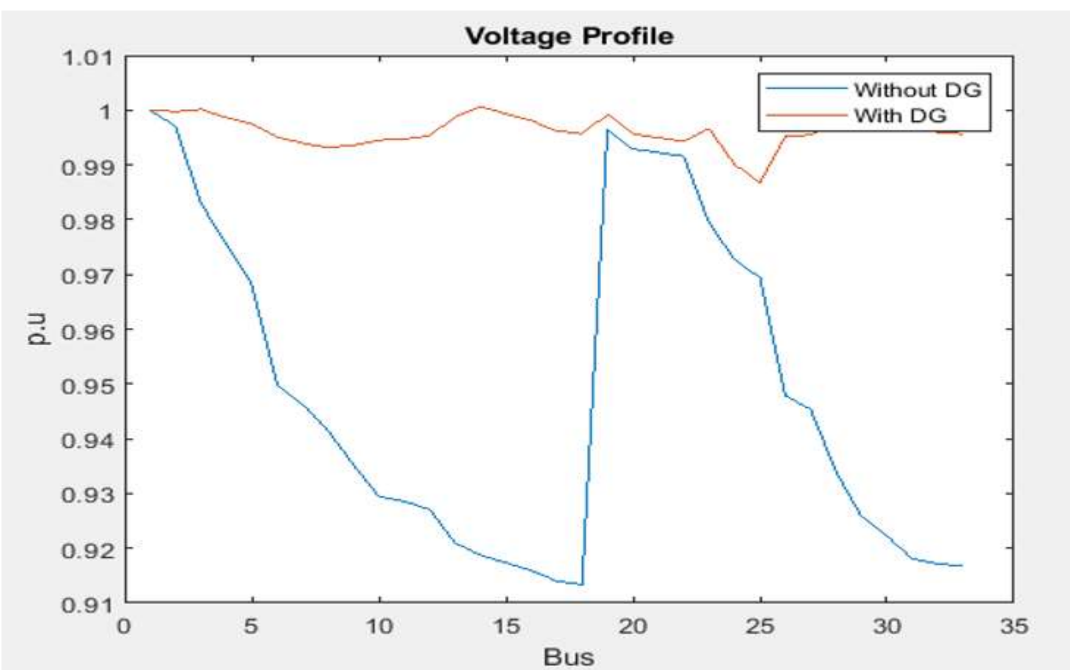


**Figure 14**: Bus voltage profiles before and after the optimal placement of three DG units in a standard IEEE 33-bus system

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 8a**: Bus voltage profiles after the optimal installation of four DG units in a standard IEEE 33-bus system

---------------

| \|Bus\| No. | \|V\| \|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 leve**l = 0.998364

**Minimum bus voltage level** = 0.994

**Table 8b:** 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 8c:** 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 | | | |

--------------------------------------------- >>

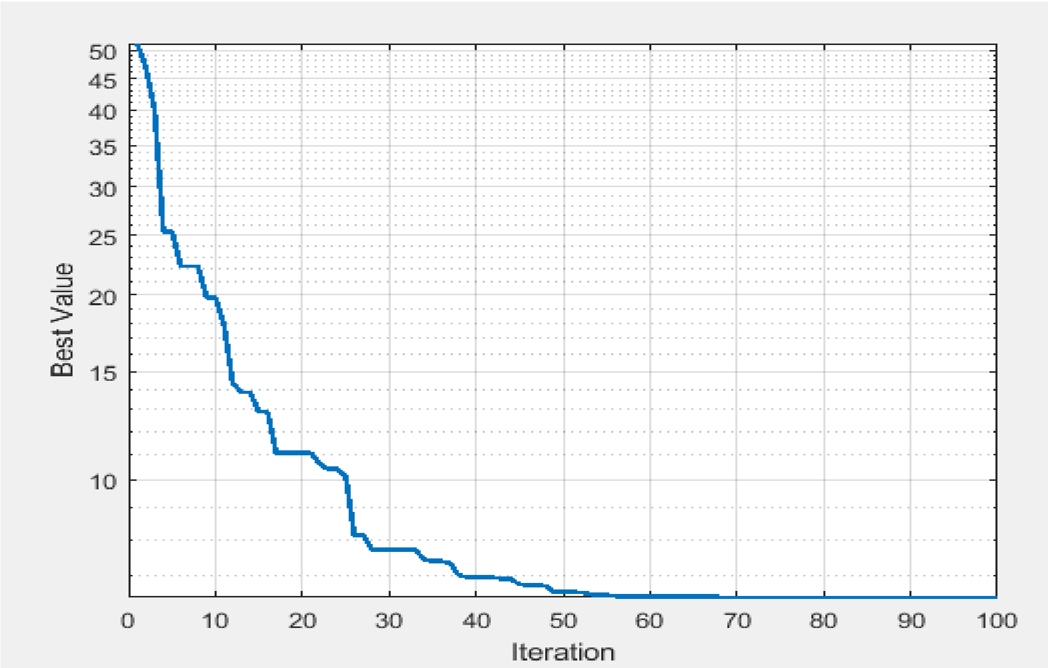


**Figure 15**: Best iteration values for the optimal placement of four DG units

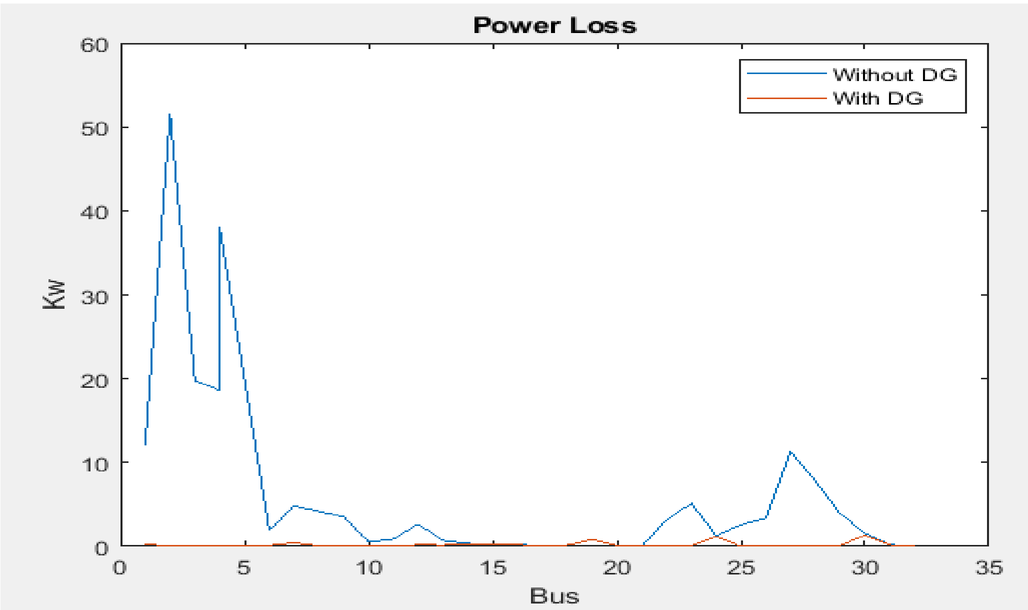


**Figure 16**: Power loss before and after the optimal placement of four DG units in a standard IEEE 33-bus system

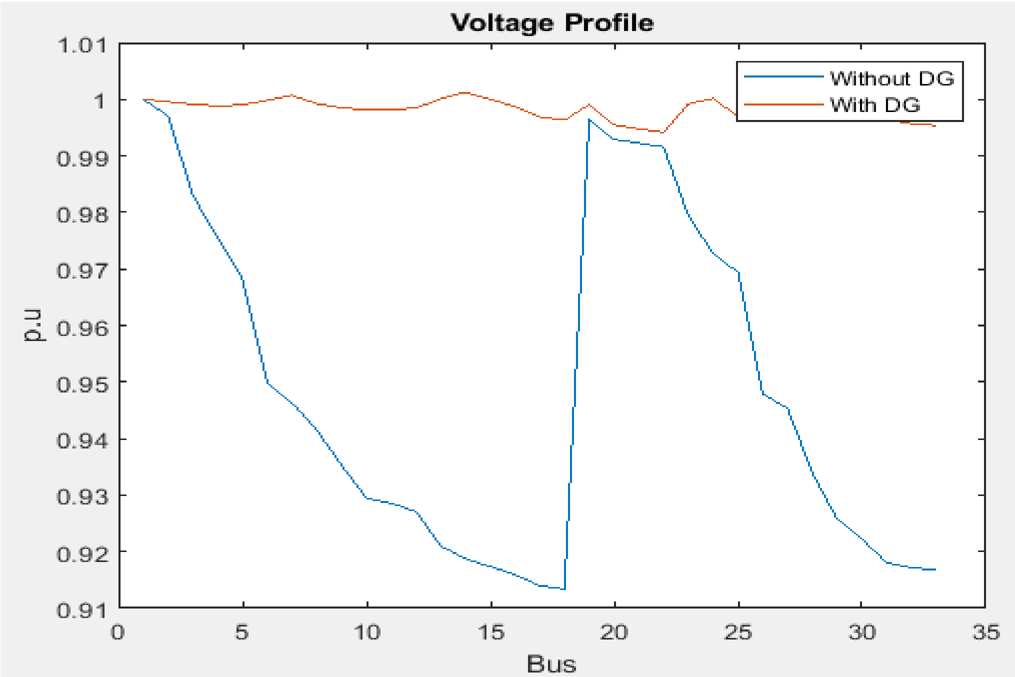


**Figure 17**: Bus voltage profiles before and after the optimal placement of four DG units in a standard IEEE 33-bus system

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 9. 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** = $\frac{\textbf{sum of voltages in all the 33 buses}}{\textbf{33}}$ ……………………… (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** =
$\left(\frac{\textbf{Average improvement in voltage level after DG placement}}{\textbf{Average bus voltage without DG}}\right) * \mathbf{100}$ ……………………..(xxvii)

**Table 9**: 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

| Bus No | No DG V (Pu) | 1 DG V (Pu) | 2 DGs V (Pu) | 3 DGs V(Pu) | 4 DGs 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 |

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| | | | | | |
|---|---|---|---|---|---|
| 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 |

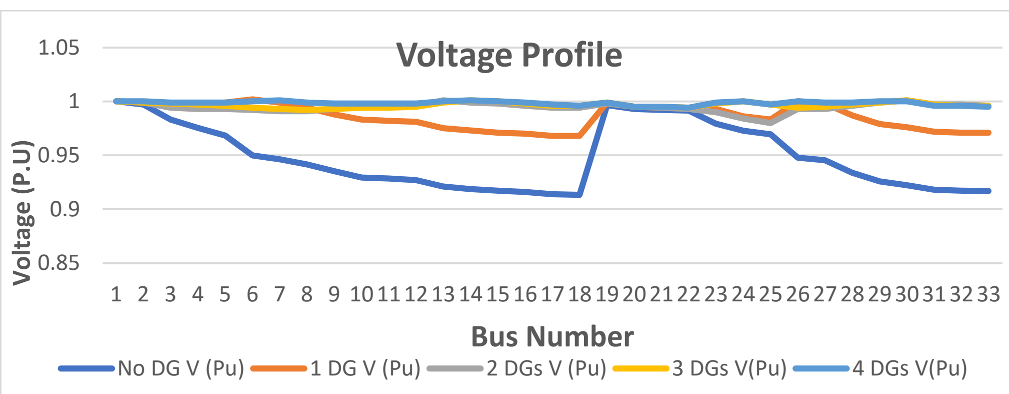


**Figure 18**: Bus Voltage profiles before and after the four cases of the optimal installation of DG units in a standard IEEE 33-bus test system.

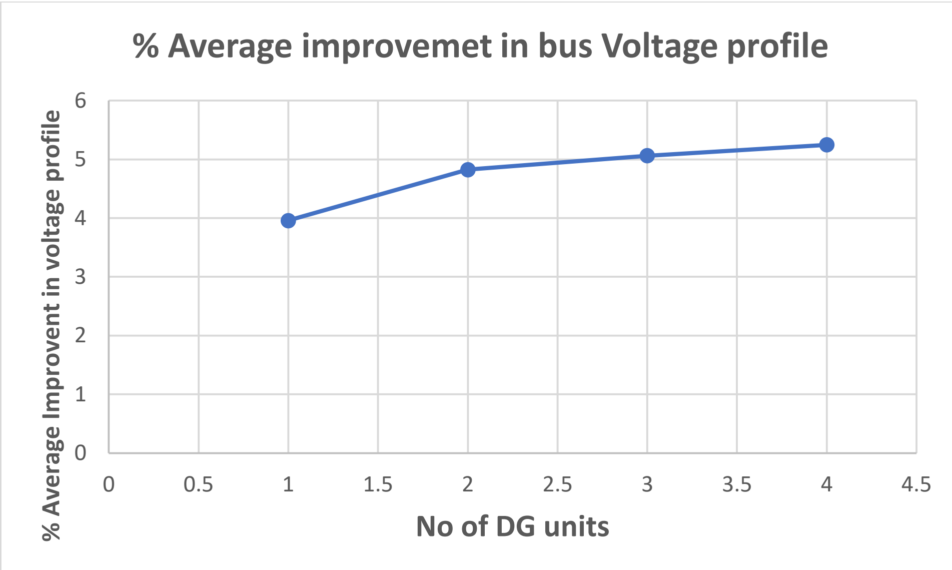


**Figure 19**: Plot of % average improvement in bus voltage profiles versus no of DG units in all the four cases of DG units' optimal placements

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 10 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)

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

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

**Table 10**: 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 |

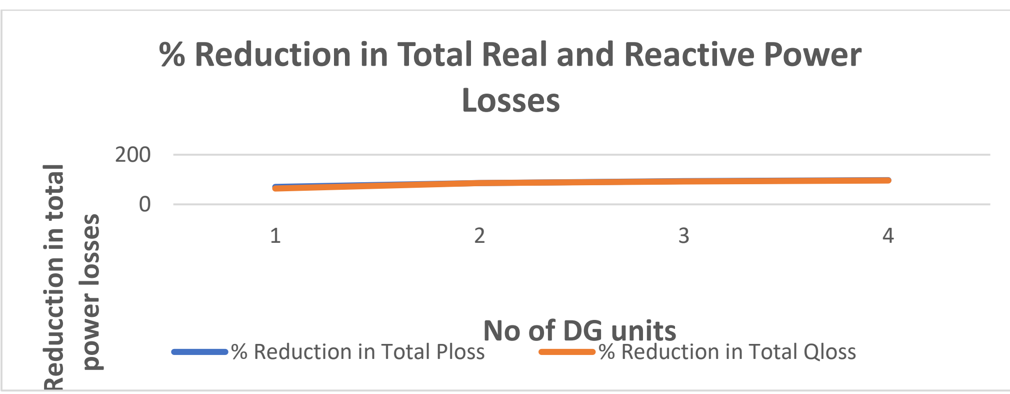


**Figure 20**: Plot of % reduction in total real and reactive power losses in all the four cases of DG units' optimal placements

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 11 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 11**: 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 12 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 12**: 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.

## IMPLICATION TO RESEARCH AND PRACTICE AND CONTRIBUTION TO KNOWLEDGE

The optimal integration of Distributed Generation(DG) units, which are mainly renewable energy resources, can have a variety of positive effects on the electrical power distributionsystem- including a decrease in overall power losses and an improvement in power standard and quality characteristics including voltage profile, standard voltage wave, and frequency (Azizivahed et al., 2019). The advantages however depend on how well-installed the units of DG are in the distribution system. By installing the appropriate DG units, for example, overall power loss might be drastically cut and reduced to 13% and below (Sahib et al., 2017). Moreover, placing units of DG in the wrong place and oversizing them might result in unanticipated problems with the power system, including, voltage sags, power loss, fault current, voltage flicker, and harmonic distortion. Most recent previous works have proposed optimization techniques with inefficient coordinating methods in optimizing and quantifying the capacity and siting of renewable energy sources for optimal power performance. Hence, the need to develop an improved adaptive optimization technique capable of demonstrating the best DG position at the lowest possible cost and identifying the best DG units with the goal of decreasing overall power losses to nearly zero while

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keeping the voltage at each bus within a predetermined range.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.

## 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.

## 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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