

# HEADROOM-BASED OPTIMIZATION FOR PLACEMENT OF DISTRIBUTED GENERATION IN A DISTRIBUTION SUBSTATION

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## Abstract:

*This paper presents a headroom-based optimization for the placement of distributed generation (DG) in a distribution substation. The penetration limits of DGs into the existing distribution substations are often expressed as a function of the feeder's hosting capacity (headroom). Therefore, it is important to estimate the reliability of the network's operation as well as that of the limits imposed by the power quality standards by evaluating of the hosting capacity (headroom) of the existing distribution feeder substation. This study aims at developing a novel algorithm for positioning a bus with permissible headroom capacity for DG positioning without causing voltage violations but maximizing the active power supply. Since DG increases short-circuit faults, the algorithm is useful for utility companies to select feeder substations that have permissible headroom capacity for DG installation and thus, contributing to reducing high DG penetration in the network. The modeling and optimization were carried out the Power System Software for Engineers (PSS/E) environment using the IEEE 14-bus test system. The results obtained from the case study show that only two (2) feeder substations out of fourteen (14) have the permissible headroom capacity for DG connections.*

## 1 Introduction

The latest direction of a massive penetration of distributed generation (DG) into the existing power distribution feeder substation will be maximized at the best planning operation of the power network. The best DG planning of the power system network relies on the technical constraints on the absorption capacity of the paraphernalia (headroom).

Under this circumstance, the magnitudes of the fault current contributions of the generators capable of replenishment are controlled by the capacity of the existing switchgear in the system, the reversal of the power flows, and voltage rise will be regulated in the network [1-3]. Therefore, the quantity of DG power injection into the load demand in the low voltage utility, and the power flow in the substation transformer will be in the usual working range.

## 2 Related Works

Different probabilities for peak DG arrangement with power networks have been used by many researchers. Mahmoud *et al.* [2] presented a novel method for the optimal placement of DG for power loss reduction in distribution systems (DS).

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The proposed method was tested on 33 and 69 test bus systems and was outperform existing methods. To determine the optimal position and size of multi-type DG, Mahmoud and Lehtonen [3] proposed a method to achieve this in a DS. The authors tested their method on a 69 test bus system. Hung and Mithulananthan [4] presented an analytical method to verify the best size and location of four different forms of DG, namely: DG capable of supplying both real and reactive power, DG capable of supplying only active power, DG capable of supplying real power and absorbing reactive power, and DG capable of supplying only reactive power.

The DGs' operating power factor was shown to be similar to the combined load power factor of the corresponding unit. An approach based on the Hereford ranch algorithm (HRA) to optimally allocate DGs in a meshed network was presented by Kim *et al.* [5]. The proposed algorithm was utilized to optimally positioned DGs to accomplish peak benefits by mitigating active power losses in the network. A Genetic Algorithm (GA) based on optimal size along with the placement of DG in distribution networks was proposed in [6]. In a system based on bus admittance, generation data, and load distribution of the system, the GA scheme was used to decide the optimal size and bus position for placing DG for power loss and energy loss reduction.

The effectiveness of this approach was evaluated by simulation results on 16, 37 and 75 bus test systems, and under-voltage and line loading constraints with uniform loading conditions were achieved with minimal system failure. Kim *et al.* [5] proposed an approach based on the Hereford ranch algorithm (HRA) to optimally assign DGs in a meshed network. In order to achieve peak advantages for minimizing active power losses in the network, the proposed algorithm was used to optimally position DGs. Optimal size and location of DG in distribution networks based on the GA have been proposed in [6].

The GA scheme was used in the system based on bus entry, generation data, and load distribution of the system to decide the optimal size and bus position for DGs for power loss and energy loss reduction. The effectiveness of the approach is validated by simulation results on 16, 37, and 75-bus test systems. The results show that under-voltage and line loading constraints with uniform loading conditions are obtained with minimal system failure. A method which used optimizing differential evolution has been used in [7]. Finding the optimum position and size of DG units was the goal of the study. For DG sizing and positioning, Partha *et al.* [8] made use of Artificial Neural Network (ANN) to optimally locate DGs in the distribution network. They established a voltage stability index (VSI) from the already known power flow equation to decide the permanence of buses. Then a priority list is setup using VSI to assign DG units. To ensure the allowable static voltage for each bus, the ANN technique was used to figure out the correct size of the DG units.

A combination of GA and particle swarm optimization (PSO) method for optimal DG positioning and sizing in distribution systems has been presented in [9]. The proposed hybrid algorithm was used to critically test the DG site and size for actual power reduction in the distribution network. The site of DG is explored by GA in this approach and its scale is optimized by PSO. First, the initial population is rendered in zigzag form for DG size and placement, followed by a load flow test using its cost function. In the next step, for each candidate size that is re-optimized by PSO, a new DG site optimized by GA and a new iteration is run. This minimizes the GA search area and also provides the power network with better optimization.

The results show that, in terms of solution dominance and the number of iterations, the combined GA/PSO approach is better than the GA and PSO in terms of performance with a lesser number of iterations.

Lakshmi *et al.* [10] carried out a fuzzy logic optimization for the optimum location of DG units in a radial distribution network for the reduction of power losses. In their work, the optimal size of the DG unit was analytically computed with the help of appropriate nodes for DG placement. While the distribution system nodes' voltage and power loss decrement indices were modeled by fuzzy membership functions with the location of DGs based on a fuzzy interference system comprising of a collection of rules. With the highest proper index, DG units are properly placed.

In [11], the authors used the Real Coded Genetic Algorithm (RCGA) to implement a new technique to position the distributed generator in the radial distribution system to minimize real power losses and to increase the voltage profile (VP). For the optimum DG placement, a two-stage procedure is used. The optimum size and position of DG units that should be positioned in the device where peak loss saving occurs are calculated by this algorithm.

In [12], the authors presented a genetic-based DG sizing and distribution system positioning technique to minimize the overall real power losses in the system. As an output from the GA software toolbox, both the optimal size and location of DG were obtained. To compute line losses as well as B-loss coefficients of the

network, Newton-Raphson (NR) load flow was used. In the genetic algorithm optimization toolbox (GAOT), the loss was then used as an estimation function to look for the optimum size and location of the DG.

Nair *et al.* [13] compared the reactive power cost before and after optimally dispatching the reactive power and thus maintaining the voltage stability of the power system with the application of the time-varying acceleration coefficient (TVAC) and the PSO for reactive power cost optimization.

The best power dispatch is solved by using a TVAC and PSO. The best size and positioning of DG for minimizing power losses in the primary distribution network have been presented in [14]. The paper applied the loss sensitivity factor method that generated a priority list that constitutes the top-ranking list in the order priority. For each bus in the list, the DG is placed and the size of DG is adjusted from minimum (0 MW) to a higher value until the minimum system loss is seen with the DG size. The paper developed an algorithm that put into deliberation not only the optimal size and location of DG but also cost in addition to the available power rating limits of the DG. A program named "BLOSS" is developed for the calculation of the B-coefficient which requires a power flow solution. The validity of this proposal was tested on the 6-bus system, 18-bus system, and 30-bus system.

Singh *et al.* [15] applied the exact loss formula in the analytical calculation for the optimal placement of DG in the radial distribution network for the minimization of losses to minimize system power loss. To calculate the optimal size of the DG for different buses and estimate total losses to find the best location with the DG at another location, is computationally intensive and this involves using the exact expression based on the loss formula. An algorithm based on bus-injection to branch-current (BIBC) and branch-current to bus voltage (BCBV) matrices were used to solve the load flow problem for the radial distribution network.

The authors in [16] worked on the analysis of the voltage sensitivity index as a method for optimal allocation of DG in the distribution system for the reduction of active power loss, improvement of the VP, and capacity building of substations. Using a forward-back sweep method, power flow analysis was performed. The optimal positioning of the DG is first detected in this voltage sensitivity index scheme by placing it at the node with the smallest voltage sensitivity index (VSI). When the PF constant was kept constant, its magnitude ranged from a minimum value to a value equal to the loading capacity of the feeders, with a constant step until the minimum system failure was detected. The DG size that leads to minimal losses was then taken as the optimum.

Using an analytical method, optimal sizing and positioning of DG in a radial distribution feeder were performed in [17] to resolve the problem of DG sizing and position through analytical calculations. The proposed strategy allows the power flow to be run twice. The first one is the original base case and the second is to obtain an optimal solution with the DG at the final point. Real power losses and reactive power losses were reduced using this method as well as the corresponding voltage values were enhanced.

Kuri *et al.* [18] employed a GA optimization method for DG placement and sizing in a distribution network. Power losses, costs, and network interruptions were reduced using this approach. Voltage, thermal, short circuit, and generator active and reactive power capabilities were the constraints considered. Generators were mounted on individual buses in a single unit, thus ignoring the interdependence of the buses and the sterilization of the network that could result in incorrect DG placement in the system.

Rashmi *et al.* [19] applied a GA approach to optimum generator position and sizing in a distribution network system aimed at reducing real losses in the system. In their analysis, the loss sensitivity factor was used to pick approximate DG planning nodes for different buses. This was done by using a radial network load flow program that represents how the feeder power losses shift as more real power is injected at a specific node to obtain the correct candidate nodes to locate the DGs. To position DG on a radial feeder with a uniformly distributed load, they applied a 2/3 law. However, the size of DGs was not optimized in their approach, and line loading constraints were not considered during optimization. A method for placing DG units in a distribution network was proposed by Hedayati *et al.* [20].

The method of the authors was based on the study of the continuity of power flow and the determination of the voltage collapse of the most responsive buses. The effect of load models on DG planning was studied in the distribution system and the findings show that DG planning can be significantly influenced by the load model. In most of the studies, the assumption was made based on the model of constant power (active and reactive) load. The proposed method was tested on a standard 34-bus system and the results proved to be efficient for improving VP and reducing power losses, enabling power transfer capability, maximum loading, and for voltage stability. The assumption made, however, may lead to contradictory and misleading results

regarding the deferral values and the reduction of losses. DG preparation based on such a hypothesis would therefore not be successful after implementation [21].

The study dealt with the different optimization techniques for optimal DG planning but the permissive headroom of buses for hosting DG was not considered. However, this paper carried out a study on the technical requirements based on headroom analysis by developing a novel algorithm for maximum active power supply of distributed generators into power sub-stations without causing voltage violations. The optimization was carried out using Power System Software for Engineers. The capability of the developed novel algorithm was tested using the IEEE 14-bus test system. Section 2 presented the related work, while section 3 provides the proposed methodology. Section 4 presents the results and discussion. The concluding remarks are found in section 5.

### 3 Methodology

#### 3.1 Study Test System

The IEEE-14 bus system presented in Figure 1 is made up of 14 buses, 5 generations, 3 transformers, 20 branches, and 2 shunt capacitors. The system consists of 11 loads with a total real load of 244.1 MW and a reactive load of 72.4 MVar. The system network was modeled and tested with the developed algorithm in the PSS/E environment.

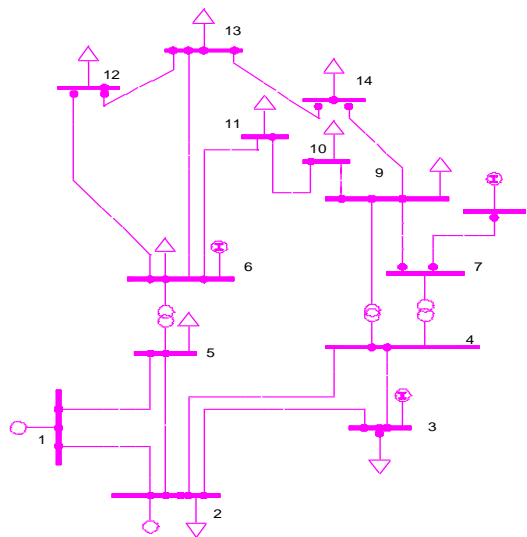


Figure 1. IEEE 14 – bus test system.

#### 3.2 Proposed Algorithm

In Figure 2, we present the developed novel algorithm that is capable of hosting DG with permissible headroom capacity. The algorithm consists of different stages, ranging from input to output at the end of the process. The input load data, buses, and generators [22] were entered as inputs to the PSS/E software to run the Newton Raphson base-case load flow solution. This was followed by the selection of a feeder bus with permissible headroom and was determined by the short circuit level of the individual bus, similar to [23].

The fault level is defined as the product of the magnitude of a buses' pre-fault voltage and the post-fault current that would flow if that bus happened to be defective. In the case of a short circuit occurring on a bus in an interconnected system, the pre-fault voltage of the bus is close to the nominal value and the bus voltage will be reduced to almost zero as soon as the fault occurs [24].

For safety reasons, the number of faults must always be below the equipment rating of the system. Normally, the severity of the fault level is determined by the rating of the current switchgear in the vicinity of the link point. The upper limit is commonly referred to in the direction of the network as the design fault level [25].

This forms a limiting factor in the connection of new DGs which is determined by the headroom capacity. The term "headroom" is used to describe the difference between the equipment ratings in a given part of the network and the calculated fault level in that same part of the network. Restating this differently, it is the

amount of additional fault current that could be added by additional sources before the network rating is exceeded.

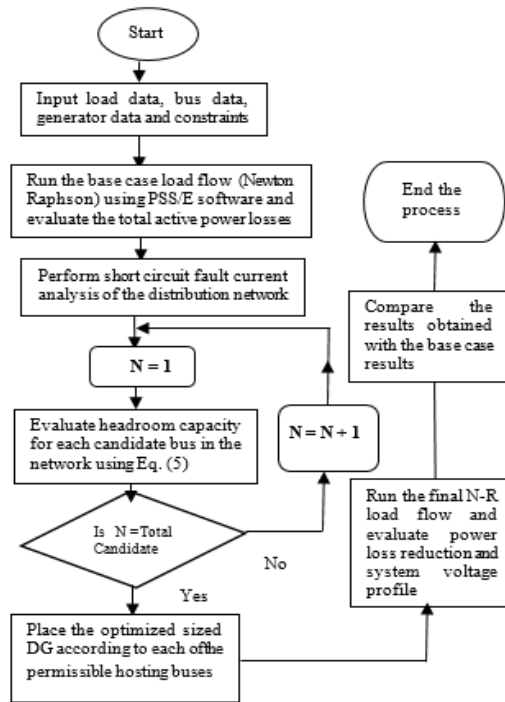


Figure 2. A novel algorithm for the location of buses with permissible headroom for DG placement.

It is common practice amongst distribution network operators to keep a safety margin of 5% below the switchgear rating [25]. This is to ensure the safe operation of the system. Fault current depends on the network configuration [26] and loads demand of each main substation [27].

The fault current level is given by Eq. (1-4).

$$I_{base} (Amp) = \frac{MV A_{base}}{\sqrt{3k V_{base}}}; Z_{base} = \frac{(kV_{base})^2}{MVA_{base}} \tag{1}$$

$$Fault\ current\ (I_f)p.\ u. = \frac{(kV_{base})^2}{|Z_{TH}(p.u)|} \tag{2}$$

$$Fault\ current\ (I_f)p.\ u. * I_{base} (Amp) = fault\ current\ (I_f)(Amp) \tag{3}$$

$$Fault\ current\ (I_f)(kA) = \frac{Fault\ current(I_f)(Amp)}{1000} \tag{4}$$

Headroom capacity,  $\gamma_b$ , for the bus equipment is evaluated using Eq. (5) as the objective problem formulation of this study.

$$Headroom\ capacity(\gamma_b) = (K_b + 0.05 K_b) - Fault\ current\ (I_f)(kA) \tag{5}$$

where:  $K_b$  is the switchgear rated capacity (kA).

The next stage of the process is to realize the best sizing of the DG. The probable minimum network loss situation would mark the optimal location for the solar DG as discussed in [28]. The minimum rate of power loss shift due to the implementation of the new DG will be at its minimum if:

$$\frac{\delta P_L}{\delta P_i} = 2 \sum_{j=1}^N (\alpha_i P_j - \beta_i Q_j) = 0 \quad (6)$$

This implies that:

$$\alpha_{ij} P_j - \beta_{ij} Q_i + \sum_{j=1, j \neq i}^N (\alpha_i P_j - \beta_i Q_j) = 0 \quad (7)$$

and

$$P_i = \frac{1}{\alpha_{ij}} [\beta_{ij} Q_i + \sum_{j=1, j \neq i}^N (\alpha_i P_j - \beta_i Q_j)] \quad (8)$$

where:  $\alpha_{ij}$  = real loss coefficient at the i-jth bus  $\beta_{ij}$  = reactive loss coefficient at the i-jth bus

$V_i \angle \delta_i$  = the complex voltage at the i-th bus,

$P_i$  and  $P_j$  = active power injection at i-th and i-jth bus respectively.

where;  $P_i$  is the actual power injection at the i-th node which is the difference between the real power generated and the real power demanded. Eq. (9) satisfies the real power demand at the i-th node:

$$P_i = (P_{DG} - P_{load}) \quad (9)$$

The minimum optimum DG size is given as:

$$P_{Solar} = P_D + \frac{1}{\alpha_{ij}} [\beta_{ij} Q_i - \sum_{j=1, j \neq i}^N (\alpha_i P_j - \beta_i Q_j)] \quad (10)$$

The injection of power from solar generators must satisfy the following constraints:

*Equality Constraints:* Power flow constraints for balancing constraints related to the non-linear equation as expressed in Eq. (11).

$$P_{bus} = (P_{Solar} - P_{Load}) \quad (11)$$

*Inequality constraints:* Voltage constraints (PU) at each bus must not be above rated voltage ( $\pm 5\%$  of rated voltage).

$$V_{min} \leq V_i \leq V_{max} \quad (12)$$

*The right-of-way buses:* Buses that is not suitable for DG allocation should be excluded due to due to negative permissible headroom capacity.

## 4 Results and Discussion

### 4.1 Base Case Newton-Raphson Load Flow Solution

In the base case flow solution, input data of the load, buses, and generators were entered as input to the PSS/E software to run the Newton Raphson base-case load flow solution. A total active PL of 13.85 MW was obtained after the load flow solution. The losses experienced by each bus are shown in Figure 3. Analysis showed that higher losses are obtained from those feeder buses with higher load density.

Also, the voltage profile (VP) for the base-case load flow is presented in Figure 4. Figure 4 showed that some of the buses were operating with a low voltage range below 0.99 p.u. These buses included 9, 10, 11, 12, 13, and 14.

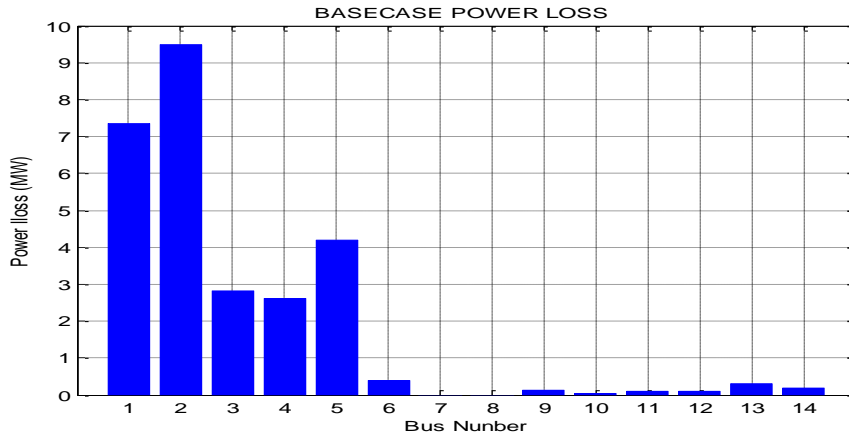


Figure 3. IEEE 14 – bus test system base power loss output.

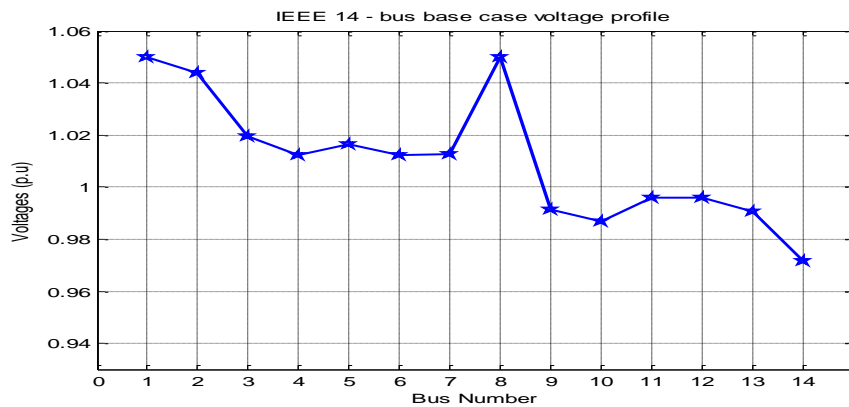


Figure 4. IEEE 14 – bus test system base voltage profile.

#### 4.2 Feeder Buses with Permissible Headroom Capacity

In this analysis, the initial bus voltages from load flow studies were used as the pre-fault voltages before computation. Figure 5 showed the result of the short-circuit fault current levels for candidate buses with the headroom capacity at a 5% safety margin. The fault current analysis is a constraint-based criterion that forms an exclusion principle for the selection of candidate buses capable of hosting distributed generation in a power system network. This, in effect, reduced the search space for the optimal position for DG placement in the distribution network. The results indicated that two (2) out of fourteen (14) candidate buses have a positive permissible headroom capacity for DG connection. Hence, the search for an optimal position for a single DG connection in the network should be navigated between these two options (buses 12 and 14).

The location of a bus with permissible headroom capacity for DG positioning in effect produced no voltage violations but maximize the active power supply. Because DG increases short-circuit faults, this analysis is useful for utility companies to select feeder substations that have permissible headroom capacity for DG installation and thus, contributing to reducing high DG penetration in the distribution network.

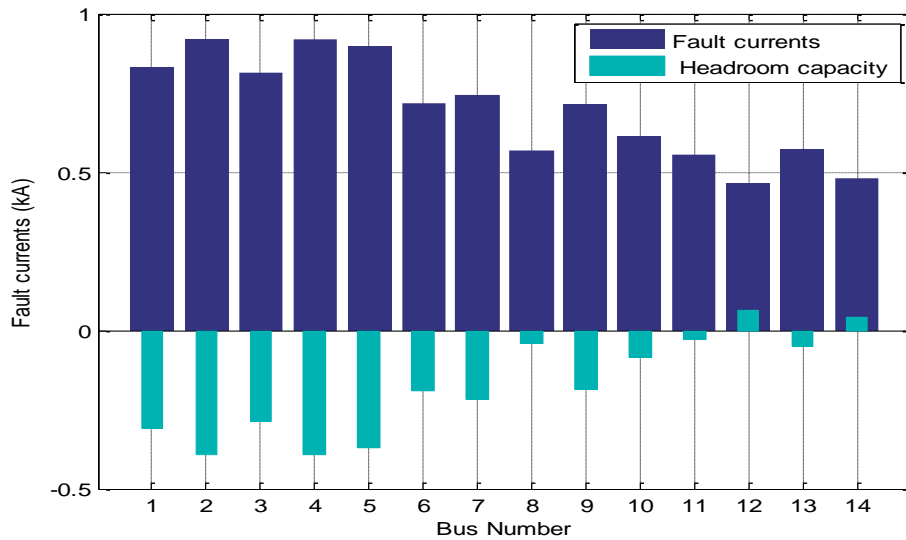


Figure 5. Bus fault current level with the headroom capacity.

#### 4.3 Placement of Optimally Sized DG on Permissible Headroom Buses

The candidate feeder buses that have permissive headroom capacity for hosting DGs were placed with optimized sizes according to Eq. (10). Thereafter, a final Newton-Raphson load flow analysis was carried out. This is aimed at determining the network's VP and power losses. The findings show that an appropriate DG location plays an important role in reducing power losses, improving the efficiency of the grid, providing a better voltage, and improved power quality. This is shown in the analysis of the comparative result is displayed in Figure 6, 7, and 8 respectively. Compared to the base case when DG was not installed in the network, Figure 7 and 8 demonstrate the improved reduction of the system active power losses in the network. The total system losses are displayed in Fig. 8 with PL reduction from 13.85 MW (base case) to 12.14 MW (with DG). The DG reduced the system losses to 10.32%. It is also observed that DG placement produced higher improvement on the load buses of the test system network.

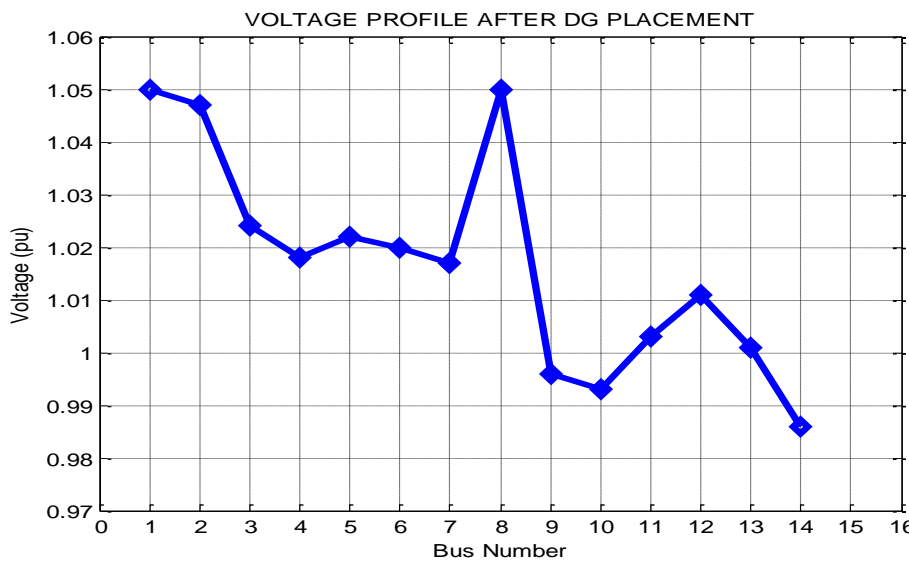


Figure 6. Voltage profile with DG placement.



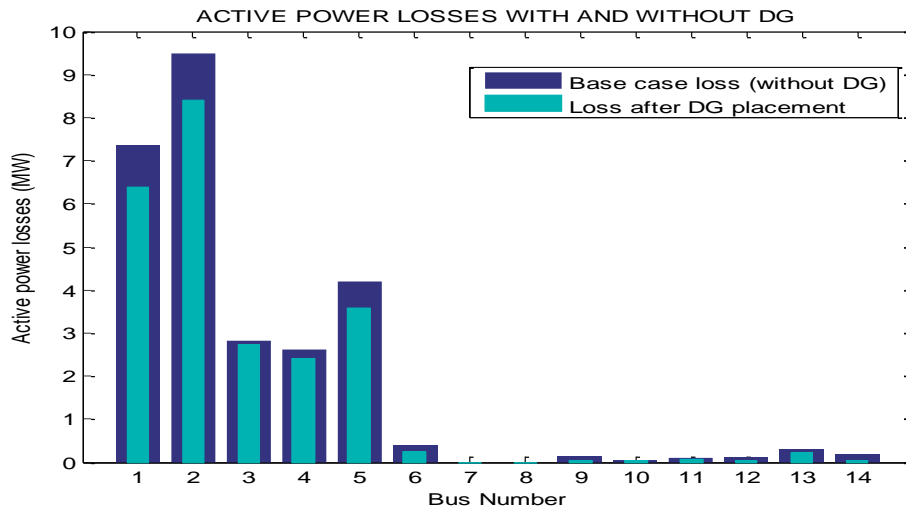


Figure 7. Bus power losses with and without DG.

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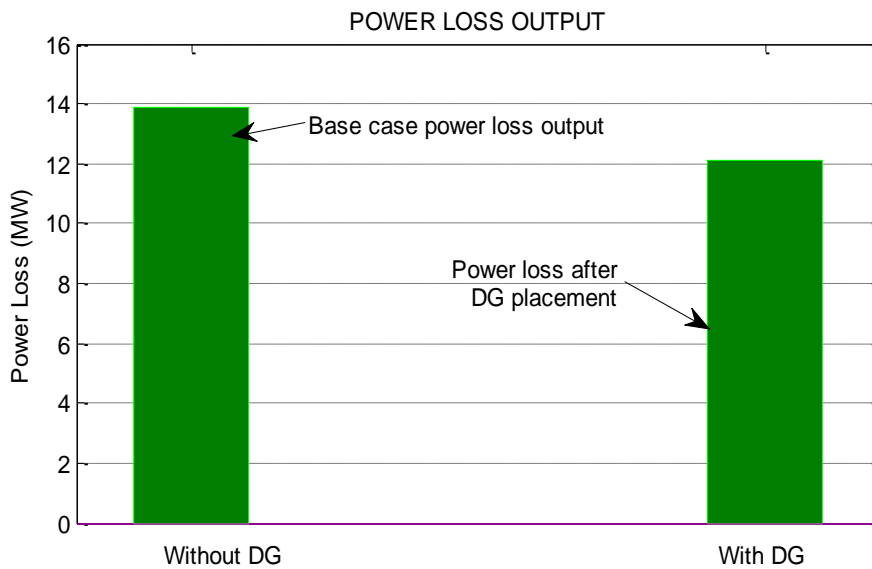


Figure 8. Total system power loss with and without DG.

Figure 9 shows the comparison between the base case VPs with the result after the integration of DG into the network. The result indicated that; bus voltages were operating at low the voltages through; 9, 10, 11, 12, 13, and 14 were all improved. This resulted in better voltage support, improvement in power quality and overall improvement of reliability and efficiency in the network.

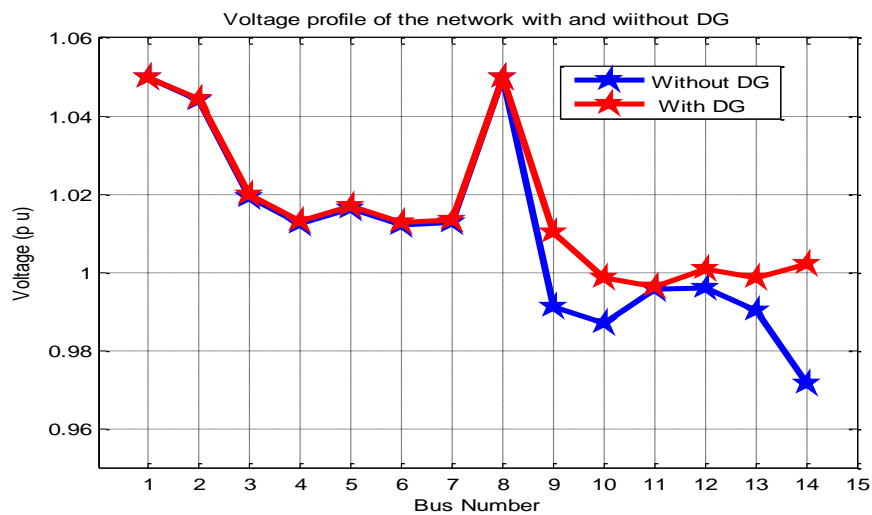


Figure 9. Total system voltage profile with and without DG placement.

## 5 Conclusion

The increasing daily load demand, improper planning of power systems, especially in distribution systems result in negative impacts such as high system power losses and unstable voltage conditions. The introduction of a renewable source of energy, especially DGs in a power system network is one of the solutions considered by the power utility experts to solve the problem of unreliable power supply. Therefore, this study developed a novel algorithm for the location of permissible headroom in a power substation for maximum active power supply by distributed generators into each system bus without causing voltage violations. One of the contributions of this study is that the buses with headroom capacity schemes have a 75% safety advantage over the conventional methods under short-circuit faults. Secondly, since DG increases short-circuit faults, this study contributes to reducing high DG penetration in the distribution network which would have produced voltage violation and other negative impacts to the system.

Thirdly, it maximizes active power supply unlike the conventional methods. The developed novel algorithm is useful for utility companies (Transmission Company of Nigeria) to evaluate and select feeder substations that have permissible headroom capacity for DG installation. The modeling and optimization were carried out in Power System Software for Engineers (PSS/E) environment using the IEEE 14-bus test system to assess the efficacy of the developed algorithm. The results obtained from the case study show that only a few feeder substations have the permissible headroom capacity for DG connections. Also, the DG reduced the system losses to 10.32% which ranges from 13.85MW (base case) to 12.14 MW (with DG).

In a further work, this newly developed algorithm can be extended to solve the problem of selecting buses with permissible headroom capacity for mix DG technologies' placement into a micro-grid network. For instance, wind and solar sourced renewable energy can be optimized using DG mix technologies.

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