

# Optimal location of a single distributed generation unit in power systems

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## Abstract

Generally, electrical power distribution networks are considered to be a significant part of the energy supply chain. The main concept behind distributed generation (DG) units is based on the use of small electrical power plants that are directly connected to the electric system near to customers. The reduction of power losses this engenders can decrease the electric power that flows into distribution system feeders, leading to positive impacts on voltage stability, voltage profile, and the capacity of the electrical network. Additionally, from the perspective of utility, DG units allocated near to loads can dramatically decrease power losses in electrical distribution networks. However, DG units must be allocated optimally and correctly to avoid adverse results on electric networks in terms of voltage profiles and power losses throughout the whole network. Thus, this paper presents a simple way to determine optimal location for DG units in both mesh and radial systems by using conventional iterative methods, with the aim of reducing the overall electrical power losses and enhancing the voltage of the network. Both the Newton-Raphson method and a backward and forward method were implemented in a MATLAB environment to solve the optimization problem in an IEEE 14 bus meshed system and an IEEE 33 bus radial system.

Keywords: Distributed generation, power losses, optimal location, IEEE 14, IEEE 33.

## 1. Introduction

Renewable energy sources such as solar, wind, and geothermal in conjunction with improved storage technologies have emerged globally as sustainable and alternative approaches for generating electrical power. Recently, standard electrical grids have thus experienced high penetration levels of renewable resources with the aim of producing clean and safe energy as well as to make the current grid more reliable, resilient, and efficient. The integration of renewable energy resources and storage technologies into electric power grids may, however, be achieved more efficiently in many cases in the form of small units of distributed generation (DG).

Thus, DG units have attracted a significant amount of attention as effective and feasible solutions to the issues caused by centralised electrical power stations, driven by an environment of electrical deregulation and liberalisation. Consequently, DG technologies may play an important role in providing for the requirements of future electric power generation by offering flexible, reliable, and cost-effective approaches for consumers' needs. However, the integration of such technologies into power grids is considered to be a significant challenge because any inappropriate location and sizing of these units might lead to power loss maximization, voltage profile deterioration and a reduction in reliability.

Smart integration for DG units is thus sorely needed in terms of optimal placement and sizing of these units taking into consideration the different environmental, economic, and technical constraints. This



paper thus presents an approach based on an iterative method for finding the perfect placement for a pre-specified size of distributed generation (DG) module such that total power losses are significantly minimised; this uses the Newton Raphson Method for meshed systems as well as the backward and forward sweep method for radial systems.

Several different methods have been used for the purpose of optimal planning of DG units. An advanced and improved technique based on analytical techniques was presented in [1] for the purpose of determining optimum power factor and rated size of DG units to reduce energy losses in the distribution network. Although this method considered both dispatchable and non-dispatchable DG units by calculating the optimal factor of each DG unit, however, the optimal allocation of each unit was not considered.

Additionally, a probabilistic method based on Mixed Integral non-linear programming was proposed in [2] for the optimal location of various types of DG units in distribution grids such that energy losses are minimized and the constraints of voltage stability are satisfied. This method utilised the principle of deterministic optimal power flow with the aim of modelling solar irradiance and wind speed. However, this method did not consider the optimal size of distributed generation units, although it proved to have high performance in comparison with conventional methods of DG planning. Another method based on Optimal Power Flow (OPF) was presented in [3] for the purpose of optimum placement and sizing of DG units such that overall profit and social welfare were maximised; here, the DG units were placed based on the principle of locational marginal price (LMP). However, this study considered the load as a constant model, while in fact the load changes continuously.

According to IEEE standard 1547, DG units based on renewable technologies are only allowed to provide real power [4]. Consequently, this study supposes that an injected DG unit has a specific size as well as operating with a unity power factor; this mean that DG only supplies active power. The study is implemented using the MATLAB simulation program; both methods are coded in the MATLAB application and are tested in the 14-bus meshed system and the 33-bus radial system.

## 2. Distributed generation overview

Generally, a DG unit can be simply described as an electric energy source that is directly linked to the electric network or to customers [5]. However, there are several more precise definitions for distributed generation in terms of location, sizing, and capacity. For example, with regard to the rated size of distributed generation units, the Electric Power Research Institute defined distributed generation in terms of generation from a few kilowatts to 50 Megawatts [2]. The definitions of distributed generation may thus vary in terms of size depending on the area and the applications that it is used for. Additionally, various ratings of distributed generation exist, as presented in Table 1 [6].

**Table 1: The possible ratings of distributed generation units**

DG Technology	Rated Size of DG Technology
Combined cycle gas	35 MW – 400 MW
Micro-Turbines	35 kW – 1 MW
Internal combustion engines	5 kW – 10 MW
Combustion turbine	1 MW – 250 MW
Wind turbine	200 W – 3 MW
Small hydro	1 – 100 MW
Photovoltaic arrays	20 W – 100 kW
Micro hydro	25 kW – 1 MW
Solar thermal, Lutz system	10 MW – 80 MW
Solar thermal, central receiver	1 MW – 10 MW

Geothermal	5 MW – 100 MW
Biomass	100 kW – 20 MW
Fuel cells, proton exchange	1 kW – 250 kW
Fuel cells, phocid	200 kW – 2 MW
Fuel cells, solid oxide	250 kW–5 MW
Fuel cells, molten carbonate	250 kW – 2 MW
Stirling engine	2 KW – 10 kW
Ocean energy	100 kW – 1 MW
Battery storage	500 kW – 5 MW

Distributed generation units have a significant number of benefits, including technical, economic and the environmental advantages. Distributed generation units also play an important role in supplying auxiliary benefits such as voltage regulation, frequency control, spinning reserves, and the support of reactive power [7] [8]. In addition, DG units may play a vital role in decreasing transmission power losses and enhancing grid stability as well as in improving the power quality of the electrical network so that both consumers and producers can be satisfied with the performance of the grid. DG units also contribute to reducing gas emissions, which consequently reduces the impact of electricity supply on global warming and climate change, as well as providing clean and safe energy to consumers [9] [10]. However, the integration of these technologies into the grid is considered to be a challenge because the inappropriate location and sizing of such units might lead to increased power losses and voltage deterioration as well as reliability reduction; optimal planning of DG units is thus sorely needed.

### 3. Case study one: a 14-bus meshed system

The first case study involved finding the optimal location for a single DG unit with a rated size of 25 MW in a 14-bus meshed network using the Newton Raphson iterative method to calculate the optimum location of the unit. The 14-bus electric system with five generators is shown in Figure 1, and the data for this system was taken from [11] and [12]. The Newton Raphson method was then applied to the test system to find the voltage of all buses as well as the whole system power loss and the losses for each bus, both under normal conditions and with the 25 MW DG unit located at each load bus.

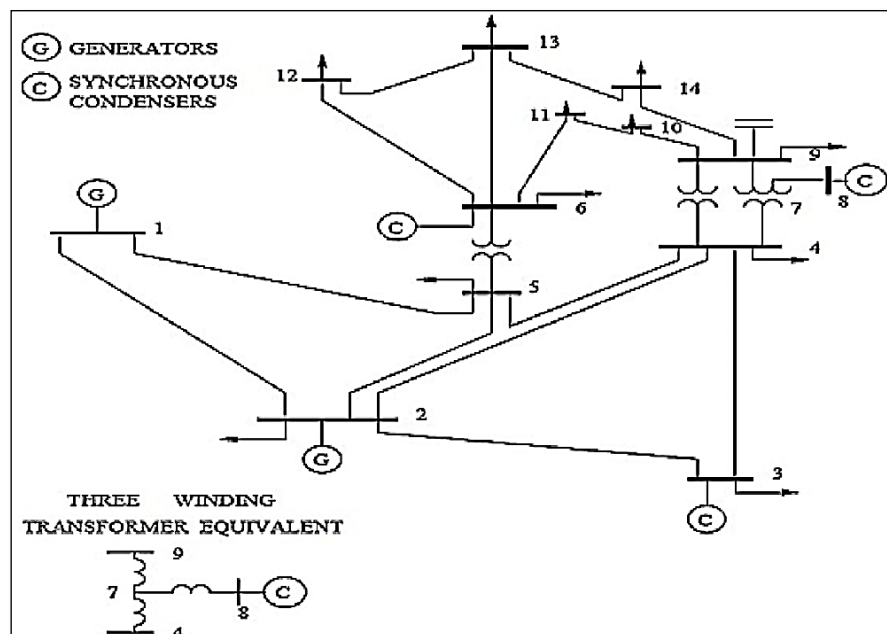


Figure 1: Single line diagram of IEEE 14 bus meshed system [11].

### 3.1 Problem Formulation

The Newton-Raphson method can be defined as an iterative approach that is used for the purposes of solving a group on non-linear equations. The original formulation for solving load flow issues with a Newton-Raphson approach was first introduced in the late 1960s [13]. This iterative method aims to convert a group of nonlinear equations into a group of linear algebraic equations using the principle of the Taylor series. The speed of this method is relatively high, and a specific problem for a particular power system can be solved and the results obtained within 4 to 5 iterations [13]. The relatively high speed of the Newton Raphson method can be attributed to the convergence features of this method, as well as to the specific programming approaches that used [14].

The Newton Raphson method is frequently used to evaluate and test the behaviours of meshed systems, as meshed systems are associated with high values of X/R. Thus, the Newton Raphson method can be used to find the voltage of all buses as well as the overall power loss. The DG's optimal location is determined based on the power losses at each load bus where the DG is connected. The power losses at each load bus are calculated with MATLAB, using the Newton-Raphson method; this approach begins from the initial values of voltage angle and magnitude at buses with generators and the voltage angles at buses with loads. The main objective of this method is to obtain the total power loss through a series of linear equations as follows:

$$\begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} = [J]^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}, \quad \Delta P_i = -P_i + P_i^{sch}, \quad \Delta Q_i = -Q_i + Q_i^{sch}$$

$$\Delta P_i = -P_i + \sum_{j=1}^N |V_i||V_j| (G_{ij} \cos \theta_{ij} + B_{ik} \sin \theta_{ij})$$

$$\Delta Q_i = -Q_i + \sum_{j=1}^N |V_i||V_j| (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij})$$

$$J = \begin{bmatrix} \frac{\delta \Delta P}{\delta \theta} & \frac{\delta \Delta P}{\delta |V|} \\ \frac{\delta \Delta Q}{\delta \theta} & \frac{\delta \Delta Q}{\delta |V|} \end{bmatrix}$$

where:

$|V|$ : Voltage magnitude

$\theta, \theta_{ij}$ : The phase voltage and the voltage between buses I and j respectively

$P_i$ : the power injected into bus i

$G_{ij}, B_{ij}$ : The real and imaginary parts of the element in the bus admittance matrix corresponding to the i row and j column

$\Delta P, \Delta Q$ : The mismatch equations

J: the matrix of partial derivatives (the Jacobian matrix)

Additionally, the new values of angles and magnitudes of voltages are

$$\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta\delta_i^{(k)}, \quad |V_i^{(k+1)}| = |V_i^{(k)}| + \Delta|V_i^{(k)}|$$

The process of iteration in terms of solving the Newton Raphson matrix continues until the maximum errors in both reactive and active power are smaller than a predefined tolerance or constant (e.g.  $10^{-3}$ ); this is called  $\varepsilon$  where

$$|\Delta P_i^{(k)}| \leq \varepsilon, \quad |\Delta Q_i^{(k)}| \leq \varepsilon$$

After applying the Newton Raphson method, the objective is to obtain the total power loss and the voltage of all buses; this method was thus coded with MATLAB (R2015b) and applied repeatedly.

### 3.2 Simulation results for the 14-bus system with 25 MW DG unit

The proposed optimisation method based on the Newton Raphson method was employed to find the perfect placement for a 25 MW DG unit by placing the DG unit at all load buses (4, 5, 7, 9, 10, 11, 12, 13, 14) and, in each case, recording the total real power losses. The proposed method was applied in the normal case without adding any DG units and the total power losses also recorded; and this was repeated after adding a single DG unit of 25 MW. The electric system losses were as follows:

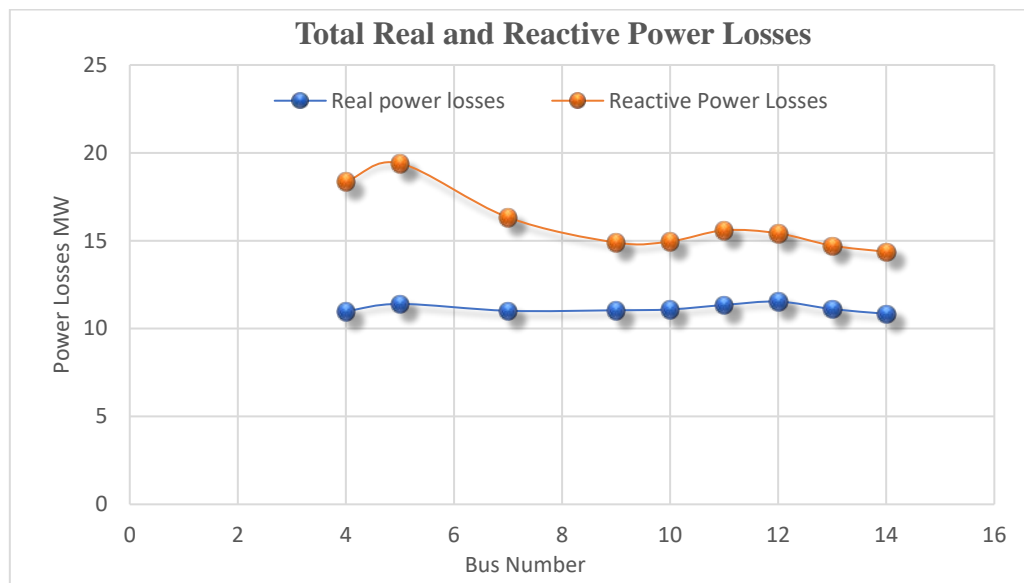
Total Real Losses without DG: 13.583 MW

Total Reactive Power without DG: 27.085 MVar

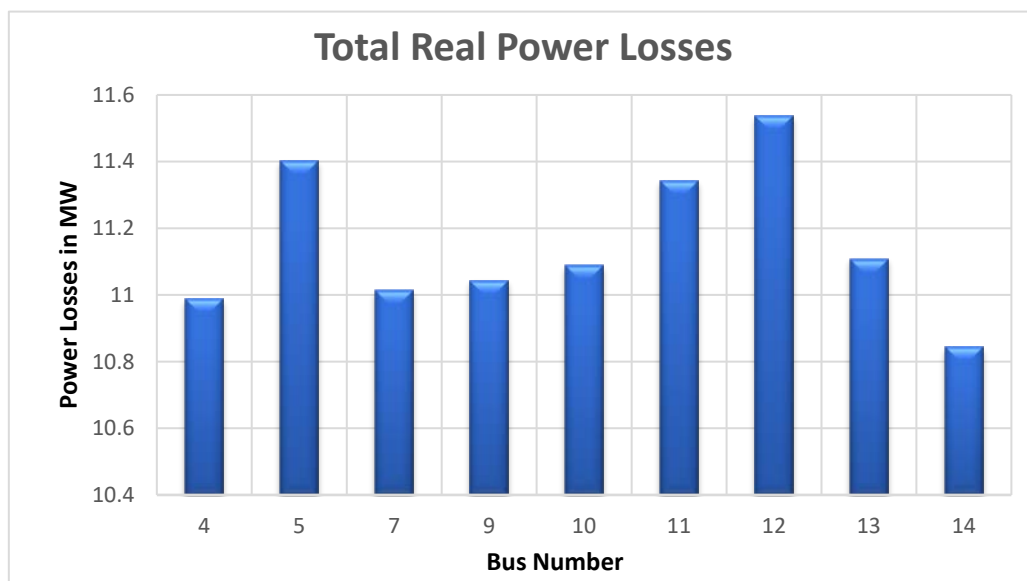
The bus with the least real power loss is considered to be a candidate bus for the optimal location of the DG unit. The obtained results for both real and reactive power losses after placing the DG at different buses are tabulated in Table 2 and shown graphically in Figure 2 and Figure 3 below:

**Table 2: Total real and reactive power losses for each load bus**

Bus Number	Real Power Losses (MW)	Reactive Power Losses (MVar)
1	---	---
2	---	---
3	---	---
4	10.988	18.372
5	11.403	19.403
6	---	---
7	11.014	16.329
8	---	---
9	11.043	14.896
10	11.090	14.963
11	11.343	15.594
12	11.538	15.421
13	11.109	14.719
14	10.843	14.370



**Figure 2: Total real and reactive power losses for each load bus**



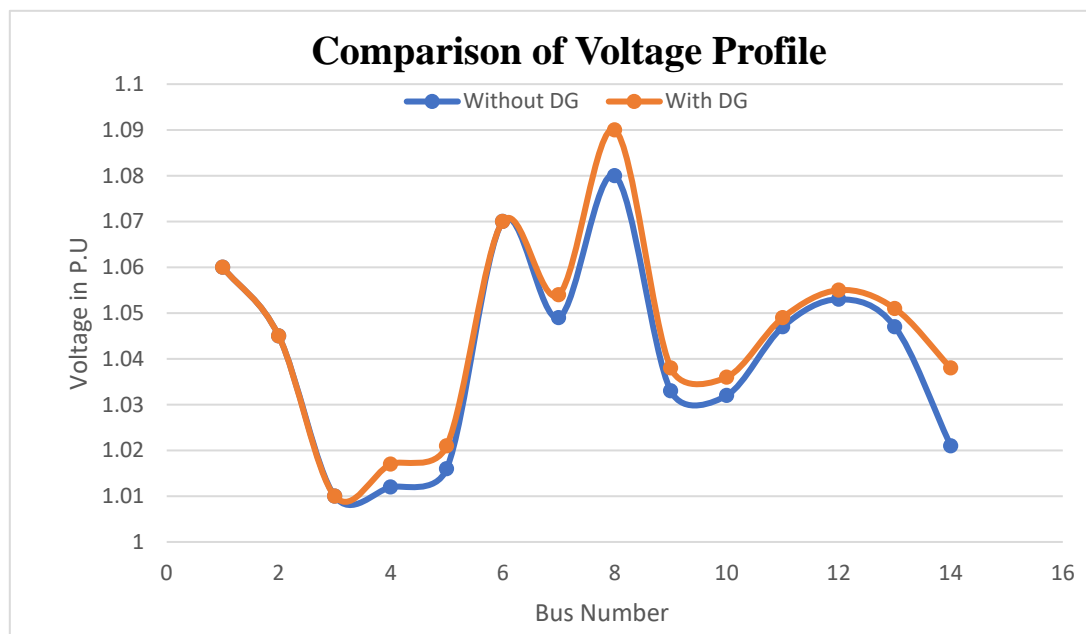
**Figure 3: Total real power losses for load buses**

It can be seen that the perfect location of a 25 MW DG is at bus 14, as this is associated with the least amount of real power loss, at around 10.843 MW, in comparison with other buses. In addition, the total real power losses are reduced from 13.583 MW in the case without DG to 10.843 MW with a 25 MW DG unit placed at bus 14, which represents around a 20% improvement. The total power loss can also be dramatically reduced by increasing the rated size of the DG. The optimal location of the DG unit can also enhance the voltage of the whole system, as the use of a DG unit increases the generation power of the system by 25 MW. Consequently, generation increases and hence the voltage profile improves for buses with loads, as well as power losses being dramatically reduced as seen in Figure 4 below. The voltage profile of load buses also improves slightly, and this can be improved more dramatically as the size of the injected DG unit is increased. In addition, the voltage profile improves as the injected DG unit reduces the total power loss and increases forward power flow.

The use of this method achieves better results in terms of power loss in comparison with another case study in the same system in [15] that used an NSGA\_II technique to reduce power losses by allocating DG units. The study in [15] used 4 DG units with an overall size of 46 MW to reduce power losses by around 35%, while the proposed method reduces power loss by 20 % with only a single DG unit . A similar case study was used in [16] that used Neplan Software to test the allocation of a single DG unit to a 14-bus system. However, only a small size of DG unit was considered, which reduced the power losses by only 3%, and the improvement in the voltage profile of the system was not considered. A brief comparison of the results obtained by this method is presented in Table 3 below [15-17]. The reliability and the efficiency of the system are also enhanced, as these two factors are affected by the voltage profile which is enhanced by the inclusion of a DG.

**Table 3: Comparison of results of the proposed method with other methods in 14 bus system**

Study Type	Bus Number (DG location)	DG Size in MW	Real Power Losses (MW)	Percentage of Improvement
Proposed Study	14	25 MW	10.843 MW	20 %
Study 1 [17]	8	16 MW	11.7 MW	13.7 %
Study 2 [16]	14	2.3 MW	13.16 MW	3 %
Study 3 [15]	4, 9, 10, 14	46 MW	8.73 MW	35 %

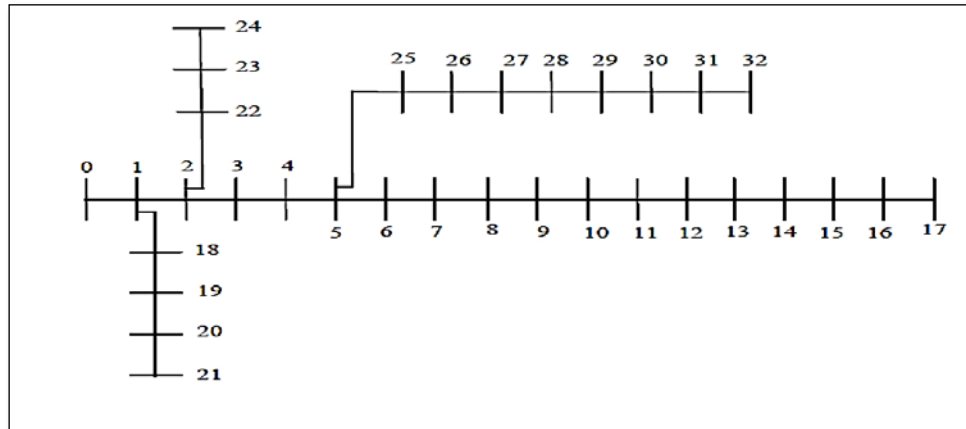


**Figure 4: Comparison of voltage profile with and without DG unit**

#### 4. Case study two: 33-bus radial system

The second case study involved finding the optimal location of a single DG unit with a rated size of 0.25 MW in a 33-bus radial network by using a Backward and Forward Sweep approach to obtain the optimal placement. The 33-bus electrical test network with one generator is shown in Figure 5, and the data for this system was taken from [18]. However, the Newton Raphson method cannot be applied to radial systems, as these systems are associated with low values of X/R in comparison to meshed systems. Thus, the Backward and Forward Sweep method was used to obtain relevant load flow values such as voltage profile and overall electrical power losses.





**Figure 5: Single line Diagram of IEEE 33 bus radial system [18].**

#### 4.1 Problem Formulation

Generally, the configurations of distributions networks are radial, while transmission systems are meshed systems; thus, the distribution systems are associated with low values of X/R, and the load flow of electrical distribution networks cannot be obtained using the Newton Raphson method, as this approach is only appropriate for systems with high values of X/R. The backward and forward sweep method is, however, suitable for obtaining the total power loss and voltage of radial systems efficiently. This approach for the calculation of load flow is also an iterative method, and at each iteration throughout the process, two calculation steps are utilised. The power flow of a network with one source is thus iteratively obtained from two groups of equations [19]. The first group used for calculation of the load flow starts from the final branch and continues in a backward direction through the main node. The second group of equations is used to obtain the angle and the magnitude of the voltage of each node, beginning from the main node and continuing in the forward direction through the final node. The main equations of the backward and forward sweep method in terms of real and reactive power can be written as

$$P'_i = P_m^L + P_m^F \quad Q'_i = Q_m^L + Q_m^F - V_m^2 y_m$$

where  $P'_i$  and  $Q'_i$  are the real and imaginary power flows through the downstream branches

The real and imaginary power losses in the branch can be formulated as follows:

$$P_i^{loss} = R_i \frac{P_i'^2 + Q_i'^2}{V_m^2} \quad Q_i^{loss} = X_i \frac{P_i'^2 + Q_i'^2}{V_m^2}$$

The active and imaginary power flows through the main branch near bus K can be written as

$$P_i = P'_i + P_i^{loss} \quad Q_i = Q'_i + Q_i^{loss} - V_k^2 y_k$$

The complex bus voltages at buses k and m can be expressed as

$$V_m = V_k - I_i(R_i + jX_i) \quad V_m = (V_k - \frac{P_i R_i + Q_i X_i}{V_k}) + j \left( \frac{Q_i R_i - P_i X_i}{V_k} \right)$$

where:  $Q''_i = Q_i + V_k^2 y_k$



The above equations were coded in a MATLAB simulation program (R2015b) in order to obtain the load flow results for radial systems in terms of voltage profile as well as the total power loss. The active and reactive power through all branches were calculated in a backward direction using the following equations:

$$P'_i = P_m^L + P_m^F \quad Q'_i = Q_m^L + Q_m^F - V_m^2 y_m$$

The voltage magnitude and the phase angle of all buses were then determined in the forward direction by applying the following equations:

$$V_m = \sqrt{[V_k^2 - 2(P_i R_i + Q_i'' X_i) + (P_i^2 + Q_i''^2)(R_i^2 + X_i^2)/V_k^2]}$$

$$\delta_m = \tan^{-1} \left[ \frac{j(V_m)}{\mathcal{R}(V_m)} \right]$$

These two steps, backward and forward, are repeated until the algorithm converges to an acceptable value or to a pre-specified tolerance value.

The real power in the electrical network can be expressed as

$$P_{Loss} = \sum_i^n |I_{branch(i)}|^2 R_i$$

Hence, the objective is to reduce the total real power loss as follows:

$$\text{Minimize Total Real Power Losses} = \text{Minimize} \left\{ \sum_i^n |I_{branch(i)}|^2 R_i \right\}$$

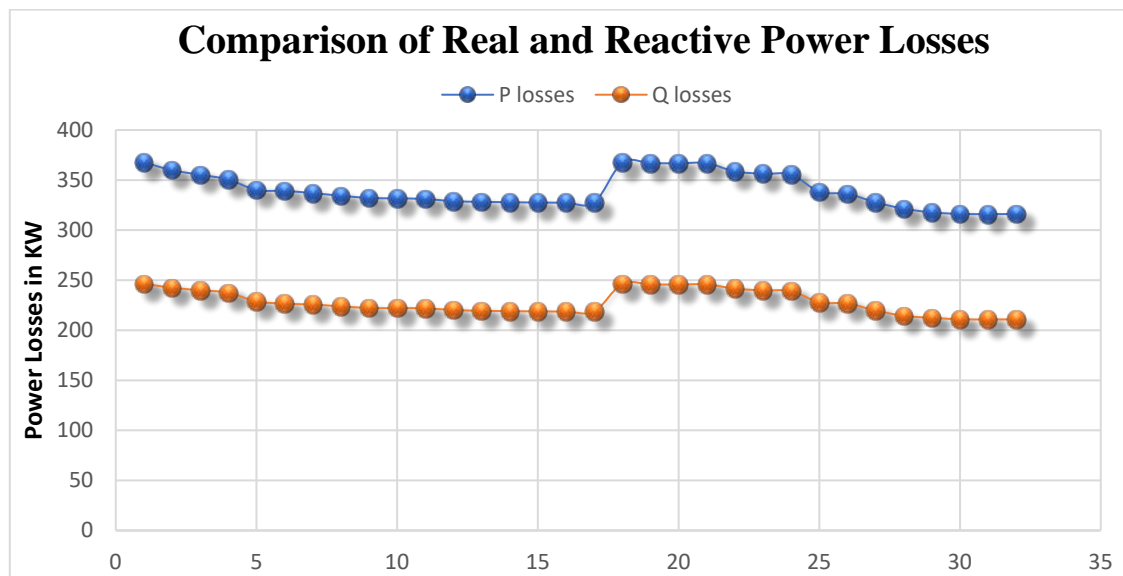
#### 4.2 Simulation results for 33-bus system with a 0.25 MW DG unit

The proposed optimisation method based on backward and forward sweep was used to find the optimal location of a 0.25 MW DG by placing the DG at all load buses and recording the total real power losses in each case. The bus with least real power loss is the candidate bus for the optimal location for the DG. The proposed method was also applied the normal case without adding a DG unit, and the total power losses recorded; after this, a single DG unit of 0.25 MW was added. The overall electrical power losses for the tested system were

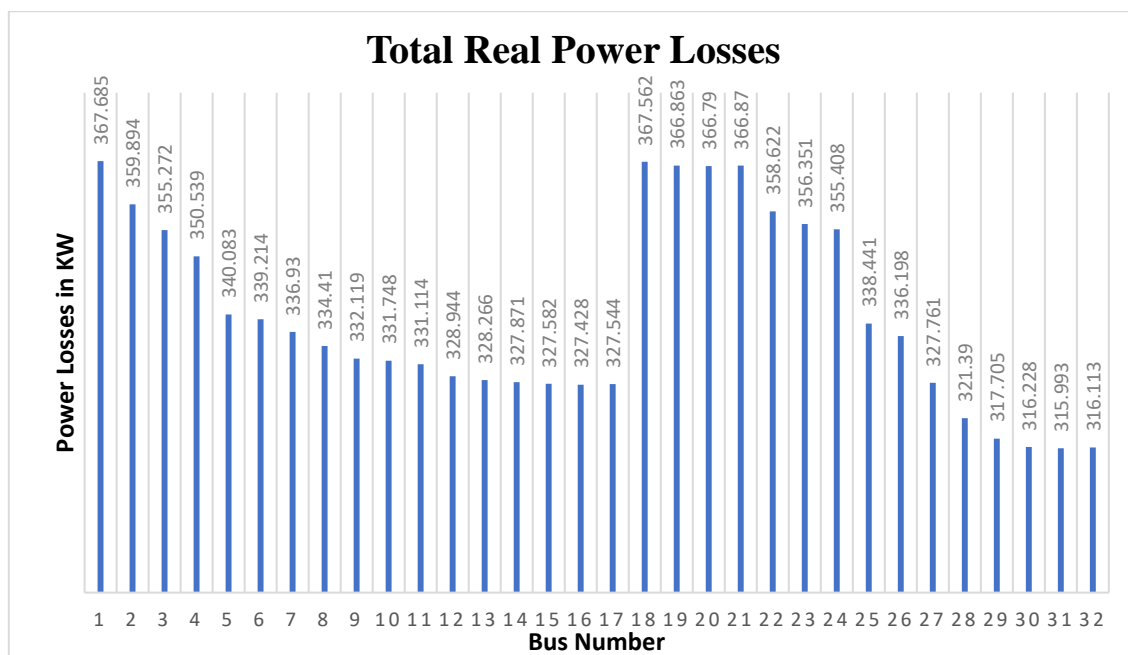
Overall Real Power Losses: 369.249 KW

Overall Reactive Power Losses: 247.326 Kvar

The bus with the least real power losses after adding the DG unit at all buses was considered the candidate bus for the optimal location for the DG unit. The obtained results for both real and reactive power losses after placing DG at different buses are presented in Figure 6 and Figure 7 below:

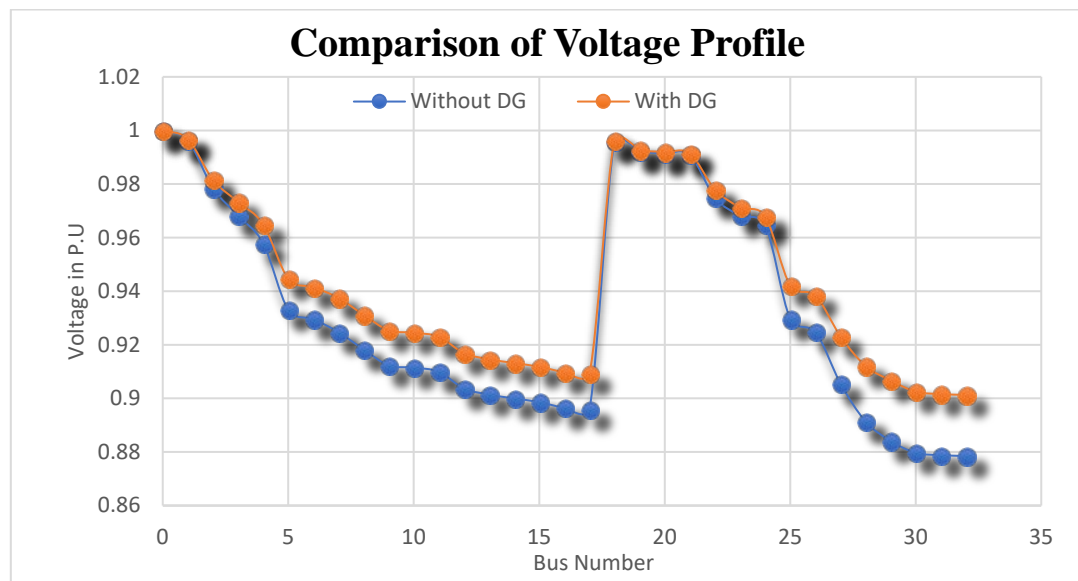


**Figure 6: Total real and reactive power losses in each case**



**Figure 7: Total real power losses for each load bus**

Here, the optimal location of a 0.25 MW DG is bus 31, which is associated with the least amount of real power loss, at around 315.993 kW. In addition, the total real power loss was reduced from 369.249 kW for the case of without DG, representing a 14.42%. The total power losses could be more dramatically reduced by increasing the size of the DG. The optimal location of DG unit will also enhance the voltage of the whole network, as the use of a DG unit increases the generation of the system by 0.25 MW. Consequently, generation increases and hence the voltage profile is improved for all buses with loads, as shown in Figure 8 below. In fact, all the buses except the first one, which is the generator bus, demonstrate a dramatic improvement in voltage profile. The reliability and the efficiency of the system are also enhanced, as these two factors are affected by the voltage profile, which is itself improved.



**Figure 8: Comparison of voltage profile with and without DG unit**

## 5. Conclusion

DG units can contribute to reducing total electrical power losses, enhancing the security of electric networks, improving voltage profiles, and satisfying both consumers and suppliers when appropriately employed. However, the planning of DG technologies must be accurate in terms of placing and sizing these units in order to maximise the economic, technical, and environmental benefits. Thus, this paper presented two different methods, based on iterative approaches, for determining the placement of a predefined DG unit in both transmission and distribution electric grids. The two different methods used to obtain the load flow results, which are the Newton Raphson method and the Back and Forward Sweep method, are suitable for meshed and radial systems, respectively. The results illustrate that the location of a DG unit has a dramatic effect on the voltage and overall power losses of the tested systems. From the trial results, the optimal location for DG unit in the 14-bus meshed system is bus 14, as it is associated with least power loss, while the optimal location for a DG unit in a 33-bus radial system is bus 31 for similar reasons. However, the iterative methods are not applicable for multiple placements of DG units as this method is time consuming and might not converge where the solution is more complicated. However, even with the addition of a single unit, the behaviours of both systems are significantly improved; total losses are decreased, and voltage profiles are improved. The analysis for future studies should, however, include other objectives such as the cost of generation and a reliability index.

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