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Headroom Based Analysis for Placement of Distributed Generation (DG) in Power Substation

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ABSTRACT: *The penetration limits of distributed generation (DG) into the existing distribution substations are often expressed as a function of the feeder hosting capacity (headroom). In feeders serving consumer demand, the nominal power should not exceed 25% of the nominal power of the transformer. It is then important to estimate the maximum reliable operation of the network as well as the limits imposed by the power quality standards through the evaluation of the hosting capacity (headroom) of the existing distribution feeder substation.The study aims at developing 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. The developed novel algorithm can be used by utility companies to 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 novel algorithm. The results obtained from the case study shows that only four (4) feeder substations out of twenty – one (21) have the permissible headroom capacity for DG connections.*

KEYWORDS -*Headroom, substation, feeder, permissible, distributed generation*.

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I. INTRODUCTION

The recent trend of high penetration of DG into the existing distribution feeder substation will be maximized at the optimal planning operation of the network. The optimal DG planning of the network is dependent on the technical constraints of the equipment hosting capacity (headroom). Under this condition, the values of fault current contributions from the renewable generators beyond the capacity of the existing switchgear in the system, reversal of power flows and voltage rise will be controlled in the network [1]. Hence, the amount of DG power injection into the load demand in the LV grid, and the power flow in the substation transformer will be within the normal operating range.

Different possibilities for optimal DG planning with power system networks have been employed by several researchers. Acharya et al. [2] calculated the optimal size and location of the DG to minimize active power loss based on the exact loss formula. Wang and Nehrir [3] presented an analytical method based on phasor current to identify the optimal location of DG in both mesh and radial systems for power loss minimization. Since the proposed approach is a non-iterative, there are no convergence problems associated with it. Duong Quoc Hung and Nadarajah Mithulananthan [4] proposed an analytical method for determining optimal size and location of four different DG types viz: DG capable of delivering both real and reactive power, DG capable of delivering only active power, DG capable of delivering real power and absorbing reactive power and DG capable of delivering reactive power only. It was shown that the operating power factor of the DGs is found to be nearer to the power factor of the combined load in the respective system.

Kim et al. [5] presented an approach based on the Hereford ranch algorithm (HRA) to optimally allocate DGs in a meshed network. The proposed algorithm was used to optimally allocated DGs to achieve maximum benefits by minimizing active power losses in the network. A Genetic Algorithm based optimal size and placement of DG in distribution networks have been proposed [6]. The GA methods were used to find optimal size and bus location for placing DG using power loss and energy loss minimization in a network system based on bus admittance, generation information, and load distribution of the system. The effectiveness of the proposed method is tested through simulation results on 16, 37, and 75-bus test systems, and minimum system loss is obtained under-voltage and line loading constraint with uniform loading conditions.

A differential evolution optimization approach has been proposed [7] to find the optimal location and size of DG units. The DG resources are embedded in the network to mainly reduce power losses and improve the voltage profile of the system. Partha et al [8] used Artificial Neural Network (ANN) for DG size and placement. It is a simple and fast approach for allocation and size evaluation of DG in the distribution network. They developed a voltage stability index (VSI) from the conventional power flow equation to determine the stability of buses. Then a priority list is set up using VSI to allocate DG units. The artificial neural network technique was used to determine the proper size of the DG units to ensure the permissible static voltage for each bus.

A combination of genetic algorithm and particle swarm optimization for optimal DG location and sizing in distribution systems have been proposed [9]. The combined algorithm proposed was used to evaluate the DG site and size in the distribution network objectively for real power minimization. In this method, the site of DG is searched by a genetic algorithm and its size is optimized by particle swarm optimization (PSO). First, the initial population for DG size and site are produced randomly followed by load flow run using the given cost function. In the next step, a new site of DG optimized by GA and predetermined iteration is run for each candidate size which is re-optimized by PSO. This reduces the search area for GA and gives better optimization. The results showed that the proposed combined GA/ PSO method is better than the GA and PSO in terms of solution quality and the number of iterations.

Lakshmi et al [10] applied fuzzy logic optimization for optimal placement of DG units in a radial power distribution network for power loss reduction. In their research, the optimal size of the DG unit is calculated analytically using suitable nodes determined for DG placement. Whereas voltage and power loss reduction indices of distribution system nodes are modeled by fuzzy membership functions, fuzzy interference system containing a set of rules is used to determine the DG placement. DG units are placed with the highest suitable index. In [11] the authors presented a new methodology using the Real Coded Genetic Algorithm (RCGA) for placement of distributed generator in the radial distribution system to reduce real power losses and improve voltage profile. A two-stage methodology is used for the optimal DG placement. This algorithm determines the optimal size and location of DG units that should be placed in the system where maximum loss saving occurs. Also, in [12] the authors presented a genetic-based DG sizing and placement technique in the distribution system for minimizing the total real power losses in the system. Both optimal size and placement of DG are obtained as output from the genetic algorithm software toolbox. Newton-Raphson (NR) load flow was used to calculate line losses as well as B-loss coefficients of the network. The loss is then used as an evaluation function in the genetic algorithm optimization toolbox (GAOT) to search the optimal size and location of the DG.

Rajitha Nair et al [13] on the application of tine varying acceleration coefficient (TVAC) and particle swarm optimization (PSO) for reactive power cost optimization compared the reactive power cost both before and after optimally dispatching the reactive power and thereby ensuring the voltage stability of the power system. The optimal power dispatch is solved by using a time-varying acceleration coefficient and particle swarm optimization. The optimal size and location 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 which 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 varied from minimum (0 MW) to a higher value until the minimum system loss is found with the DG size. The paper developed an algorithm that put into consideration 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 computation 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. Ram Singh et al [15] on optimal placement of DG in the radial distribution network for minimization of losses applied exact loss formula in the analytical expression to calculate optimum size and site for DG placement under the objective of system power loss reduction. It is computationally demanding and this involves using the exact loss formula-based expression to calculate the optimal size of the DG at various buses and approximate total losses with the DG at a different location to identify the best location. An algorithm based on bus-injection to branch- current (BIBC) and branch – current to bus voltage (BCBV) matrices is used to solve the load flow problem for the radial distribution network.

Another researcher [16] presented voltage sensitivity index analysis as a method for optimal allocation of DG in the distribution system for real power loss reduction, voltage profile improvement, and substation capacity building. Power flow analysis is evaluated using a forward-back sweep method. In this method of voltage sensitivity index, the optimal location of DG is first found by placing it at the node with the least voltage sensitivity index (VSI). Keeping the power factor constant, its size is varied from minimum value to a value equal to feeder loading capacity with a constant step until the minimum system loss is found. Then the DG size which results in minimum losses is taken as optimum. Optimal sizing and placement of DG in radial distribution feeder using an analytical approach as a research [17] tackle the problem of sizing and location of DG through analytical calculation. The proposed approach needs power flow to be run two times. The first is the initial base case and the second is at the final stage with the DG to obtain an optimal solution. Under this approach, real power losses and reactive power losses were minimized as well as the corresponding voltage values improved. Kuri et al [18] applied a genetic algorithm (GA) optimization method for placement and sizing of DG in the distribution network. In this method, power losses, costs, and network disruption were minimized. The constraints considered were voltage, thermal, short circuit, and generator active and reactive power capabilities. Generation is placed in a single unit at individual buses while ignoring the interdependence of the buses and the network sterilization that can result in improper DG placement in the system.

Rashmi et al [19] applied a genetic algorithm approach toward optimal location and sizing of the generator in a distribution network system aimed at system real loss minimization. In the research, the loss sensitivity factor at different buses was used to select the approximate node for DG planning. This is done by using a load flow program suitable for the radial networks which reflect how the feeder power losses change if more real power is injected at a particular node to obtain the right candidate nodes to locate DG. They applied a 2/3 rule to place DG on a radial feeder with a uniformly distributed load. However, in the above approach, the size of DG was not optimized and line loading constraint is not considered during the optimization. Hasan Hedayati et al [20], proposed a method for the placement of distributed generation units in a distribution network. The authors' methods were based on the analysis of power flow continuation and determination of most sensitive buses to voltage collapse. The effect of load models on DG planning in the distribution system was investigated and the result showed that the load model can significantly affect the DG planning. The assumption was made in most of the studies based on the constant power (active and reactive) load model. The proposed method was tested on a typical 34-bus system and the result proved efficiency in the improvement of voltage profile and reduction in power losses, permits power transfer capacity, maximum loading, and voltage stability margin. However, the assumption made may lead to inconsistent and misleading results about the deferral values and loss reduction. Thus, DG planning based on such an assumption would not be effective after implementation.

Abu-Mouti et al [21] introduced DG in the distribution network under the objective of reducing power loss and cost, environmental friendliness, voltage improvement, postponing system upgrading, and enhancing system reliability. The technique proposed here finds the optimal location and size of the DG to minimize the total system power loss for radial distribution systems by solving two independent sub-problems of size and location. A hybrid method was proposed in [22] to determine the optimal number of deployed DG in the distribution networks. They applied the GA-OPF technique to solve the static optimization problem (single-period analysis) utilizing the economic dispatch formulation. The method was designed to enable distribution network operators to strategically connect a predefined number of DGs among a large number of potential combinations. Kotamarty et al [23] proposed contingency analysis in the system due to DG location and sizing. The objective function was to find the optimal location and size of DG to minimize voltage deviation from a predetermined profile. The authors [24] proposed analytical expression for finding the optimal size and power factor of four types of DGs units. The DG units are sized to achieve the highest loss reduction in the distribution network. The proposed method is limited to DG types capable of delivering real power only. The method has been tested in three distribution systems with varying size and complexity and validated using an exhaustive method. Elnashar et al [25] analyzed the impact of DG on the distribution network as positive- (voltage profile improvement) and negative - (increased system losses, increased short-circuit level). The authors used this analysis to formulate a multi-objective function. Nevertheless, this problem formulation is flawed because DG would lead to an increase in loss only when it is sited in improper locations, and so its impact cannot be considered negative in all cases.

The state of - art - of the study dealt with the different optimization techniques for optimal DG planning, however, this paper carried out a study on the technical requirements based on headroom analysis through developing a novel algorithm for maximum active power supply by distributed generators into power sub-stations without causing voltage violations. The optimization is carried out using Power System Software for Engineering. The capability of the developed novel algorithm is tested using the IEEE 14 – bus test system. Section 2 deals with the methodology. Section 3 deals with the results and discussion. The concluding remarks are found in section 4

II. METHODOLOGY

The IEEE-14 bus system shown in Fig. 1 is build up with 14 bus, 5 generations, three transformers, 20 branches, 2 shunt capacitors [26]. The system consists of 11 loads in which a total real load of 244.1 MW and a reactive load of 72.4 MVA. The system network is modeled and tested with the developed algorithm in a PSS/E environment

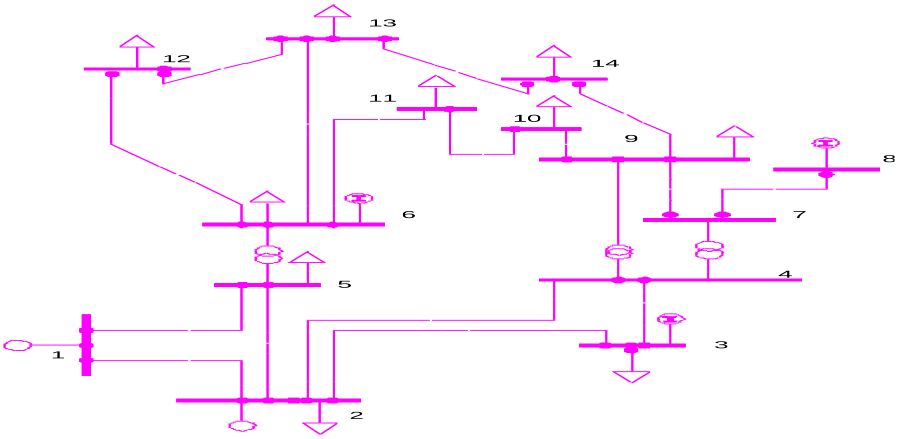

Fig 1. IEEE 14 – bus Test System

2.1 Selection of Feeder Buses with Permissible Headroom Capacity

The selection of buses for DG placement is determined by the short circuit level of the individual bus [27]. The fault level is defined as the product of the magnitude of the pre-fault voltage at a bus and the post-fault current, which would flow if the fault occurs on that bus. In the event of a short-circuit occurring at a bus in an interconnected system, the pre-fault voltage of the bus is near to the nominal value and as soon as the fault takes place, the voltage of the bus reduces to almost zero [28].

For safety reasons, fault levels must always be below the rating of equipment in the system network. The magnitude of the fault level is normally determined by the rating of the existing switchgear in the vicinity of the point of connection. This upper limit is usually referred to as the design fault level in the part of the network [29]. 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. It is common practice amongst distribution network operators to keep a safety margin of 5% below the switchgear rating [29]. This is to ensure the safe operation of the system. Fault current depends on the network configuration and load demand from each main substation [30]. As shown in Fig. 2, the headroom capacity of switchgear for a bus operating at a maximum fault current cannot afford to be related to DG. Hence this is an exclusion principle for selecting the candidate number of buses for DG placement. Normally, the distribution network operator would not permit the connection of new DG which would push the maximum fault levels beyond the network design fault levels. This is because the presence of DG in a network affects the short circuit levels of the network. It creates an increase in the fault currents when compared to normal conditions at which no DG is installed in the network [31]

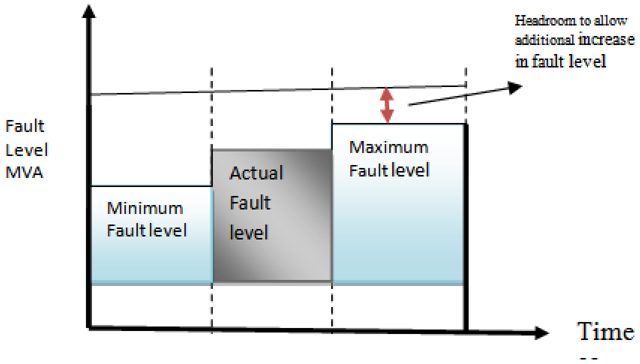

Fig. 2. Fault level showing headroom of switchgear [30]

The fault current level is given as [32]:

$$I_{base}(Amp) = \frac{MVA_{base}}{\sqrt{3}\,kV_{base}}; \quad Z_{base} = \frac{(kV_{base})^2}{MVA_{base}} \quad (1)$$

$$Fault\ current\ (I_f)\ p.u = \frac{1}{|Z_{TH}\,(p.u)|} \quad (2)$$

$$Fault\ current\ (I_f)\ p.u * I_{base}(Amp) \quad = \quad \text{fault current } (\text{I}_\text{f})\,(\text{Amp}) \quad (3)$$

$$Fault\ current\ (I_f)\ (kA) = \frac{Fault\ current\ (I_f)\ (Amp)}{1000} \quad (2.25)$$

Headroom capacity (γ_b) for the bus equipment is (4) evaluated in equation (2.26)

$$Headroom\ capacity\ (\gamma_b) == (K_b + 0.05K_b) - Fault\ current\ (I_f)\,(kA) \quad (5)$$

Where: K_b = switchgear rated capacity (kA)

2.2 Optimal DG sizing and Placement

The possible condition for minimum loss in the network will mark the optimal position for the solar DG as given by [33]. The rate of change of power loss to injected power due to the introduction of the new DG will be at its minimum when: $\frac{\delta P_L}{\delta P_i} = 2\sum_{j=1}^{N}(\alpha_i P_j - \beta_i Q_j) = 0$ (6)

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

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

Where; Pi is the real power injection at the ithnodewhich is the difference between real power generation and equation (9) that satisfies real power demand at that node:

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

The minimum optimal size of the DG will be given:

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

The power injection from DGmust satisfy the following constraints:

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

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

Inequality constraints:Voltage constraints (PU) at each bus ($\pm$ 5% of rated voltage) must be:

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

The right-of-way buses: The buses which are not appropriate for DG allocation due to some restricting considerations such as non-availability of solar energy in that locality should be excluded.

2.3**A Novel Algorithm for the Methodology**

A developed novel algorithm capable of hosting DG is shown in fig. 4.

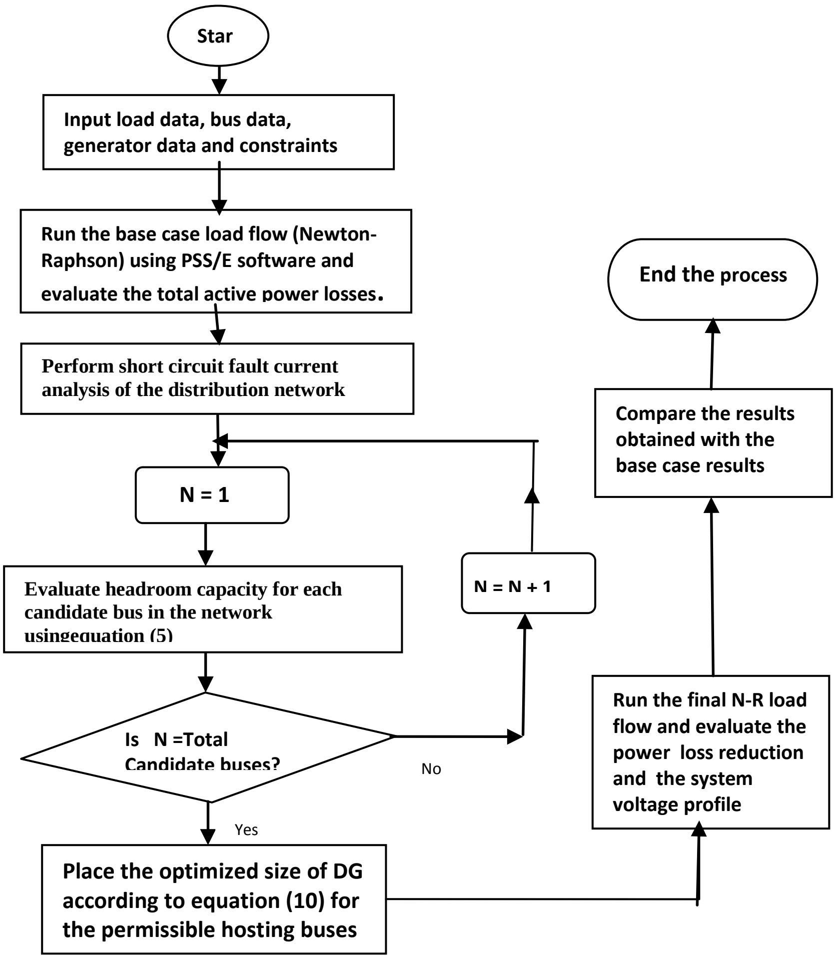

Fig. 3. A novel algorithm for location of buses with permissible headroom for DG Placemen

III. RESULTS AND DISCUSSION

The developed novel algorithm is tested with the IEEE 14-bus existing network test system through the PSS/E environment. The obtained results from the test case study validate the efficacy of the results obtained from the case study.

3.1 Base-case load flow solution

In the base-case load flow solution, input data of load, bus, and generator [26] were entered as input to PSS/E software to run the Newton Raphson base-case load flow solution. A system totalpower loss of 13.85 MW was obtained after the load flow solution. The losses on each of the buses is shown in fig. 4. Analysis shows that higher losses are obtained from those feeder buses with higher load density.

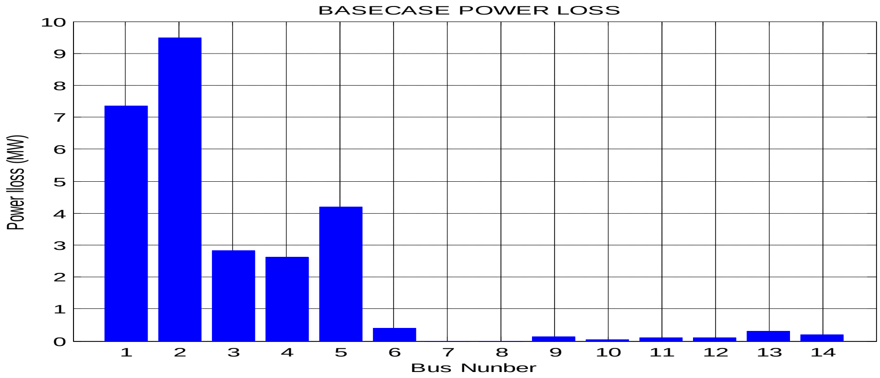

Fig. 4. IEEE 14 – bus test system base power loss output

Also, the voltage profile for the base-case load flow displayed in Fig.5 shows that some of the buses are operating with low voltages range below 0.99 p u. These buses include 9, 10, 11, 12, 13, and 14.

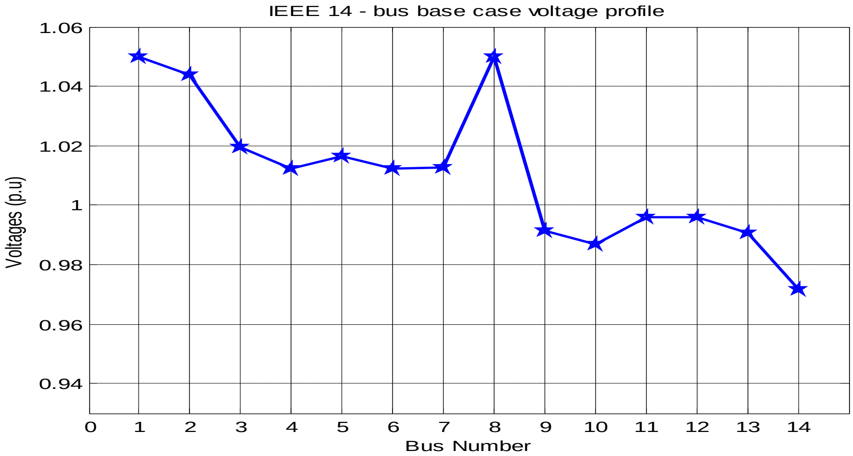

Figure .4: IEEE 14 – bus test system base voltage profile

3.2 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. The results shown in Fig. 6 indicated that two (2) out of fourteen (14) candidate buses have a positive permissible headroom capacity for DG connection. It also showed the result of the short - circuit faults current level for candidate buses with the headroom capacity at a 5% safety margin. The fault current analysis is a constraint-basedcriterion 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.

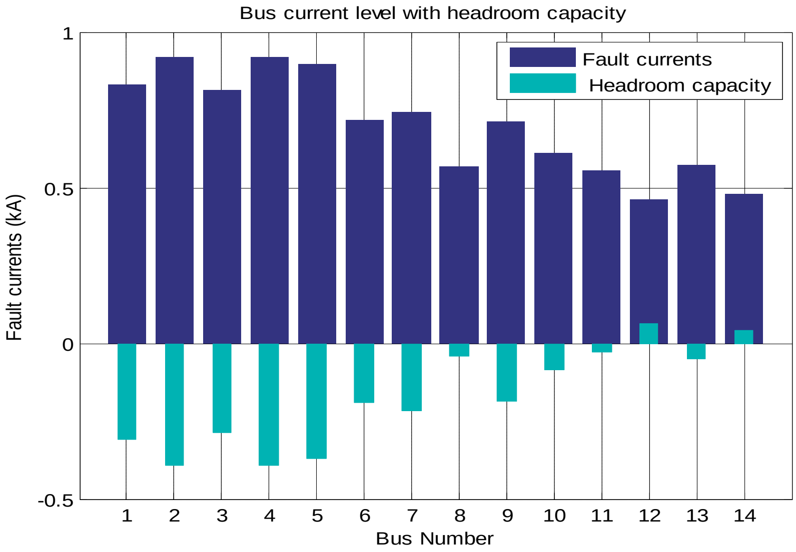

Fig. 6. Bus fault current level with the headroom capacity

3.3 IEEE 14 - Bus Test System with DG Placement

For every candidate bus, the optimal size is evaluated according to equation (10) and installed. This is followed by running a full Newton Raphson load flow. Generally, DG has an important role in reducing power losses, improving grid reliability, providing better voltage support, and improving power quality. The results analysis on the impacts of the optimal size and placement of the DG in the network are shown in Figures 7, 8, and 9 respectively. Fig. 7 displays the improved reduction of system active power losses in the network compared to the base case when DG has not been installed into the network. It is observed that DG placement produced higher improvement on the load buses.

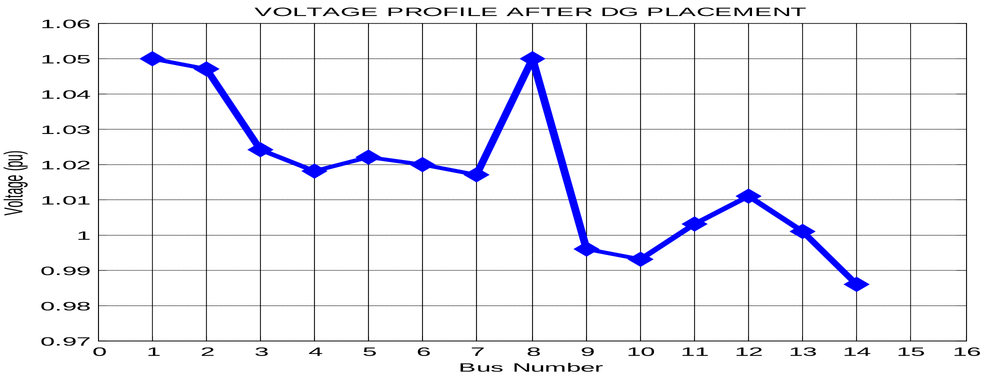

Fig. 7 Voltage profile with DG placement

Fig. 8 shows a comparative result of DG impacts on each of the buses before and after its placement. There isageneral improvement of the system network in the reduction of losses with an optimized size of 6.7MW and 7.9 MW placed at buses 12 and 14 respectively. The total system losses are displayed in fig. 9 with power loss reduction from 13.85MW (base case) to 12.14 MW (with DG). The DG reduced the system losses to 10.32%

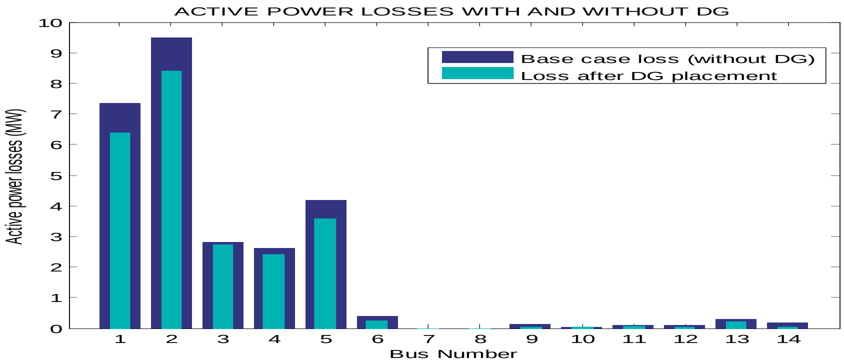

Figure 8: Bus power losses with and without DG

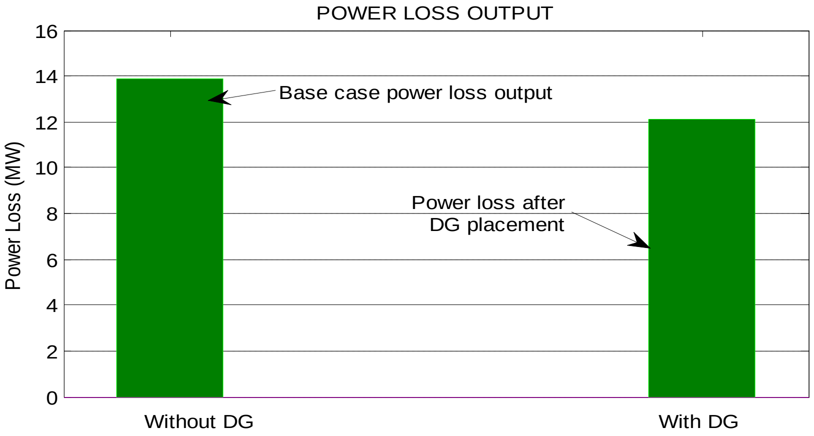

Figure 9: Total system power loss with and without DG

Fig. 10 represents the comparison between the base case voltage profiles with the result after the integration of DG into the network. The result shows that; bus voltages are operating at low the voltages via; 9, 10, 11, 12, 13,and 14 were all improved. This in effect, provides better voltage support, improving the power quality and overall improvement of reliability and efficiency of the network.

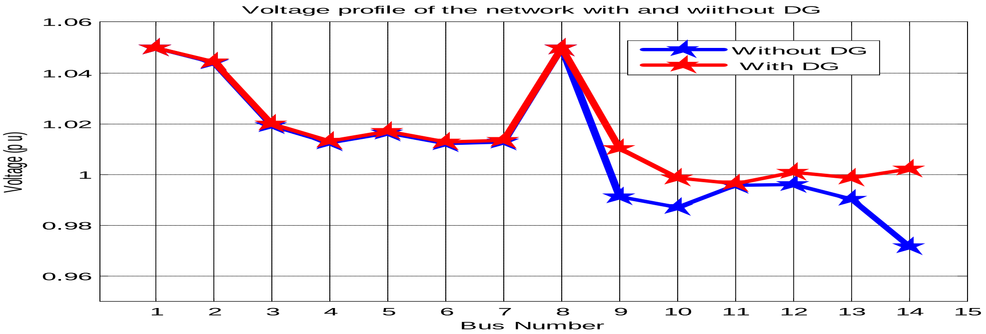

Fig. 10. Total System Voltage Profile with and without DG placement

IV. CONCLUSION

The increasing daily load demand, improper planning of power systems, especially in the distribution system results in negative impacts such as high-power losses and unstable voltage conditions.Theintroduction of a renewable source of energy especially DGs in a power system network has been one of the solutions considered by the power utility to solve the problem of unreliable power supply. However, this study aims at developing 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. The developed novel algorithm can be used by 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. The results obtained from the case study shows that only four (2) feeder substations out of twenty – one (14) have the permissible headroom capacity for DG connections. There was significant network improvement after DG placement to 10.32% power loss reduction with a better voltage profile.

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