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# Loss Minimization in Radial Distribution Systems Using Ladder Load Flow Method with Incorporation of Distributed Generation

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***Abstract***
*Load flow analysis is the backbone of power system analysis and design. They are necessary for system planning and operation of Distributed Generation (DG) in distribution systems. DG penetration in distribution network requires an enhance power load flow method to ensure the best possible placement. This paper presents loss minimization in distribution system using ladder load flow method with incorporation of DG. In this study, existing ladder load flow method was modified by incorporation of DG to form a new equation for power flow analysis. Two set of equations were solved simultaneously using Ladder load flow iteration methods without and with incorporation of DG. Simulation was done using MATLAB 7.9.0529 (R2012b) and validated on standard IEEE 13-bus and 25-bus distribution test feeders for computation of power losses. For 13-bus system, the total power losses without incorporation of DG were 1.663 p.u and 0.5205 p.u. having installed DG (power losses reduced by 1.1425 p.u, that is, a 68.7% reduction). For 25-bus system, the total power losses without introduction of DG without were 4.4793 p.u and 2.0128 p.u. having installed DG (power losses reduced by 2.4665 p.u, that is, a 55.1% reduction). The results revealed that the power losses reduced after incorporation of DG into the distribution system which is in agreement with the experimental results, thus confirming the reliability of the model.*

***Keyword:*** *Load Flow, Distributed generation, Loss minimization, Ladder load flow, Simulink, Distribution system.*

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## I. INTRODUCTION

Distribution systems are inherently radial in structure with high resistance to reactance ratio compared to the transmission systems, with resultant high power losses and a dip in voltage magnitude along radial distribution lines. Such significant losses in spite of growing energy demand increase the burden and have negative impact on the efficiency of ageing distribution system [1]. Therefore, there is need for a well planned and effective installation of Distributed Generation (DG) in distribution network that can cope with the ever increasing demand for domestic, commercial and industrial loads. Thus, introduction of DG into distribution system reduced system losses and this relieve capacity constraints on the distribution system [3], [5].

Distributed Generation (DG) is an electrical generating source connected to the power network in a point very close to consumer's side which is small enough when compared with the centralized power plants with the aid of supply of adequate and stable electricity to consumers as well as to reduced power losses [2]. Distributed Generation is more economical than running a power line to remote locations because it provides back-up power during utility system outages for facilities requiring uninterrupted service, aids network stability in using fast response equipment for a secured transmission system, helps to improve energy reliability, system security, service interruption mode and efficiency for consumers [4], [6] [8].

The load flow study of radial distribution system is of prime importance for effective planning of load transfers. Load flow is used to ensure that electrical power transfer from generators to consumers through the grid system is stable, reliable and economic. Power companies are interested in finding the most efficient configuration for minimization of real power losses and load balancing among distribution feeders to save energy and enhance the overall performance of distribution system [1], [7].

### A. Load Flow Studies of Radial Distribution System

In order to facilitate and evaluate the performance, planning, design and operation of a distribution system, its load flow needs to be examined repeatedly. Load flow is synonymous to power flow, thus are used interchangeably. The essence of the load flow studies is to find out the real and reactive powers flowing in each line along with the magnitude and phase angle of the voltage at each bus of the system as well as the line losses for the specific loading conditions [9].

Load flow algorithm should be efficient since it has to be run number of times. Therefore, solution for the load flow of distribution system need to posses robust and time efficient characteristics [12]. The characteristic features such as radial or tree topology, high R/X ratio, un-transposed lines, and unbalanced loads associated with the distribution systems, make conventional power flow computations such as Netwon – Raphson and Gauss Siedel that are successful applied to transmission systems load flow somewhat difficult or inefficient with distribution network. The inherent nature of RDN with its wide ratio of resistance and reactance values and large number of buses and branches, cause the distribution system to be ill-natured for conventional load flow methods [2], [11], [13].

The power injected at bus $(i+1)$ when considering a ladder power flow equation is given as [10], [13]:

$$P_{i+1} = P_i - P_{Li+1} - R_{i+1}\frac{{P_i}^2+{Q_i}^2}{|V_i|^2} \quad (1)$$

$$Q_{i+1} = Q_i - Q_{Li+1} - X_{i+1}\frac{{P_i}^2+{Q_i}^2}{|V_i|^2} \quad (2)$$

While voltage at receiving end is

$$|V_{i+1}|^2 = |V_i|^2 + \left({R_{i+1}}^2 + {X_{i+1}}^2\right)\frac{{P_i}^2+{Q_i}^2}{|V_i|^2} - 2(R_{i+1}P_i + X_{i+1}Q_i) \quad (3)$$

where

$P_{i+1}$: Active Power at bus$(i+1)$, $Q_{i+1}$: Reactive Power at bus $(i+1)$, $P_i$ : Active Power at bus $i$, $Q_i$: Reactive Power at bus $i$, $|V_i|$ : Voltage magnitude at bus $i$, $|V_{i+1}|$ : Voltage magnitude at bus$(i+1)$, $R_{i+1}$ : Resistance at bus $(i+1)$, $X_{i+1}$: Reactance at bus $(i+1)$, $P_{Li+1}$: Active Power loss at bus $(i+1)$, $Q_{Li+1}$: Reactive Power loss at bus $(i+1)$

### B. Load Flow Bus Classification

In a power system, each bus or node is associated with four quantities, real power, reactive powers, bus voltage magnitudes and phase angles. In a load flow solution two out of four quantities are specified and the remaining two are calculated through the solution of the equations. The buses are classified into the following three types depending upon the quantities specified [15], [17], [21].

1. Load bus: At this bus the real power and reactive power are specified. It is desired to find out the voltage magnitude $V$ and phase angle $\delta$ through the load flow solution. This is a bus in which no generator is connected to it; hence the control variables real power generated $P_G$ and the reactive power generated $Q_G$ are zero.
2. Generator bus or voltage-controlled bus: Here, the voltage magnitude corresponding to the generator voltage and real power corresponding to its ratings is specified. It is required to find out the reactive power generation and the phase angle of the bus.
3. Slack/Swing or reference bus: In this bus, the voltage magnitude and phase angle is specified. This will take care of the additional power generation required and distribution losses. This is required to find the real and reactive power generations (P, Q) at this bus.

### C. Element of Distribution System

Distribution system is derived from electrical system which is sub-stationally fed by the consumers' premises and the transmission system. The equipment associated with the distribution system usually begins downstream of the distribution feeder circuit breaker. These feeders consist of combinations of overhead and underground conductor, three phase and single phase switches with load break and non – load break ability, relayed protective devices, fuses, transformers, surge arresters, voltage regulator and capacitors [6], [19]. The line diagram of a typical low tension distribution system is depicted in Figure 1 which comprises Distributed Feeders, Distributor and Services Mains [17].

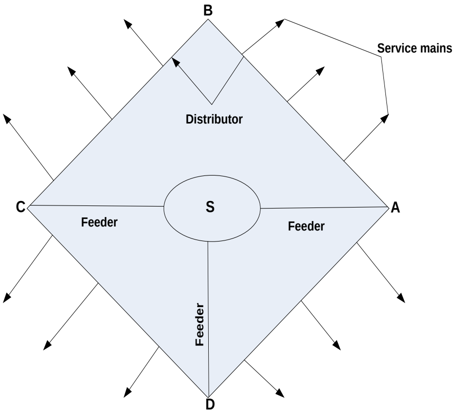

Figure 1: Element of Distribution System

### D. Losses in Distribution System

Electrical losses are wasteful energy in systems that take a considerable part of the electrical power transmitted and distributed. However, losses are well pronounced in an electrical distribution system compared to transmission system because of the lower voltage of operation in distribution system. No practical distributions system is lossless; losses are inevitable and can only be reduced to minimum. Thus loss minimization in distribution network is an exercise deserving consideration [16], [18], [20], [23].

Electrical losses are classified basically as technical or non- technical losses. The technical losses are due to energy in the conductors and equipment used for distribution of power. While the non-technical losses are caused by defective meters, errors in meter reading, pilferage and in estimating unmetered supply of energy. The losses in any system would, however, depend on the pattern of energy usage, intensity of load demand, load density capability and configuration of the distribution system that vary for various system elements [19], [23].
The complex power injected at bus $i$ when considering a power flow equation is given as [9]:

$$S_i = P_i + jQ_i \tag{4}$$

$$P_i = V_i \sum_{j=1}^{n} Y_{ij} V_i \cos(\delta_i - \delta_j - \gamma_{ij}) \tag{5}$$

$$Q_i = V_i \sum_{j=1}^{n} Y_{ij} V_i \sin(\delta_i - \delta_j - \gamma_{ij}) \tag{6}$$

where
$P_i$, : Active Power at bus $i$, $Q_i$: Reactive Power at bus $i$, $Y_{ij}$ : Magnitude of the $i-j^{th}$ element of the bus admittance matrix, $V_i$ : Voltage magnitude at the $i^{th}$ bus, $\gamma_{ij}$ : Angle of the $i-j^{th}$ element of the bus admittance matrix and $\delta_i$ : Phase angle of the voltage $V_i$
The system losses are expressed as:

$$P_L = \sum_{i=1}^{n} P_{G_i} - \sum_{i=1}^{n} P_{D_i} \tag{7}$$

where
$P_L$ : Real power loss, $P_{G_i}$ : Real power generated at $i^{th}$ bus, $P_{D_i}$ : Real power required at $i^{th}$ bus and $n$ : Number of buses.

### E. Distributed Generation System

Distributed Generation (DG) system is an electric generator connected at distribution level rather than transmission level. Distributed Generation also considered as any source of electrical energy of limited size that is connected directly to the distribution system of a power network. These generators are distributed closer to the loads throughout the power system. Interconnection of DG units into electric power networks offers economic, environmental and technical benefits [2], [8], [10], [14].

Distributed Generation is considered as a least-cost planning alternative because of its integration being closer to load centre, thereby brings about reduction of distribution cost and elimination of transmission cost as well as saving of fuel. Another point of economic benefit is that the integration of DG reduces power demand from central plant, which in turn reduces the wholesale power price by supplying excess power to the grid [22]. Also, DGs can be installed in small increments to meet an increase in load growth, by sizing it in small increments to supply the load requirement. DG technologies offer an environmentally friendly source of electrical energy through limiting the sound pollution and the Green House Gas (GHG) emissions. Also, there are practical and aesthetic reason for incorporating DGs, as DGs reduce the tendency of construction of new transmission circuits and large networks is minimized thereby enhancing the aesthetic value [15],.[19], [21], [23].

## II. MATERIALS AND METHODS

In this study, Ladder load flow equation model with incorporation of DG was formulated by calculating the voltage at each bus, beginning at the generator bus to the load buses using currents calculated in backward sweep method. The calculated source voltage was used as mismatch calculation termination criteria to calculate power loss. For effectiveness of this study, script codes were written in MATLAB 7.9.0529(R2009b) version and simulations were carried out to solve the resulting Ladder load flow equation without and with the incorporation of DG. The line, bus, generator and load data for this study was obtained from the Institute of Electrical and Electronics Engineers (IEEE) Distribution System Analysis Subcommittee.

The assumptions in Modified Ladder Load Flow Model is given as:

i. The system is a balanced 3-phase system

ii. The distribution lines was modeled as series impedance, $Z_i = R_i + jX_i$

iii. The load at bus $i$ was modeled as a constant power sink, $S_{Li} = P_{Li} + jQ_{Li}$

iv. Shunt capacitor placed at the nodes of the system was represented as reactive power injections.

v. Distributed generator was represented by PQV model as a negative load referred to a PQ model with constraint power factor.

vi. Generation at bus $i$ was modeled as a constant power given by. $S_{Gi} = P_{Gi} + jQ_{Gi}$

Considering a balanced radial distribution system represented by an equivalent single line diagram in Figure 2 with generator arbitrarily placed at bus$(i+1)$, the Ladder load flow equation model with incorporation of DG was formulated as:

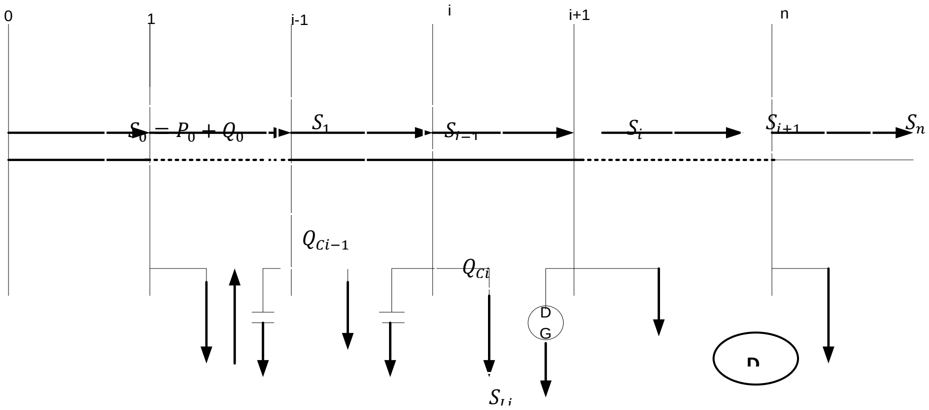

Figure 2: Single line diagram of distribution main feeder with distributed generation

From the line diagram of Figure 2, the equivalent aggregate load power is calculated as follows:

$$P_{i+1} = P_i - P_{Li+1} - R_{i+1}\frac{P_i^2 + Q_i^2}{|V_i|^2} + P_{Gi+1} \tag{8}$$

$$Q_{i+1} = Q_i - Q_{Li+1} - X_{i+1}\frac{P_i^2 + Q_i^2}{|V_i|^2} + Q_{Ci+1} + Q_{Gi+1} \tag{9}$$

Also, the voltage magnitude at the sending end is given as:

$$|V_{i+1}|^2 = |V_i|^2 + \left(R_{i+1}^2 + X_{i+1}^2\right)\frac{P_i^2 + Q_i^2}{|V_i|^2} - 2(R_{i+1}P_i + X_{i+1}Q_i) \tag{10}$$

The power loss connecting bus $i$ and $i+1$ is give by:

$$P_{LOSS(i,i+1)} = R_{i,i+1}\frac{P_i^2 + Q_i^2}{|V_i|^2} \tag{11}$$

for$i = 0, 1, 2 \ldots.. n-1$

where;

$R_{i+1}, X_{i+1}$ : Resistance and Reactance at bus $(i+1)$

$P_{i+1}, Q_{i+1}$ : Active and Reactive power at bus $(i+1)$

$P_i, Q_i$ : Active and Reactive power loss at bus $i$

$P_{Li+1}, Q_{Li+1}$ : Active and Reactive power loss at bus $(i+1)$

$P_{Gi+1}, Q_{Gi+1}$ : Active and Reactive power of DG at bus $(i+1)$

$Q_{Ci+1}$ : Reactive power injection on shunt capacitor at bus $(i+1)$

$V_{i+1}$ : Receiving end voltage at bus$(i+1)$

$|V_{i+1}|$ : Voltage magnitude at bus$(i+1)$

Thus, once the mathematical modeling of Ladder Load Flow with DG is developed, the power loss in the distribution system is computed and the system losses are calculated without and with DG incorporation. Then, the simulation was carried out according to the algorithm below using MATLAB.

Step 1: Read the system data and initially set all the voltage to $1.0\ p.u$ and branch current to $0$.

Step 2: Calculate the active and reactive power

Step 3: Calculate the current for all the branches of the system

Step 4: Update the bus voltage using the computed branch current.

Step 5: If the absolute value of the difference between the previous iteration and present iteration at any node is more than some present value, then reset the counter by 1 and go to step 2 else calculate the system loss and stop.

Step 6: Repeat the process for the system with incorporation of distributed generation.

The pictorial representation of the Ladder load flow solution method without and with incorporation of DG is depicted in Figure 3.

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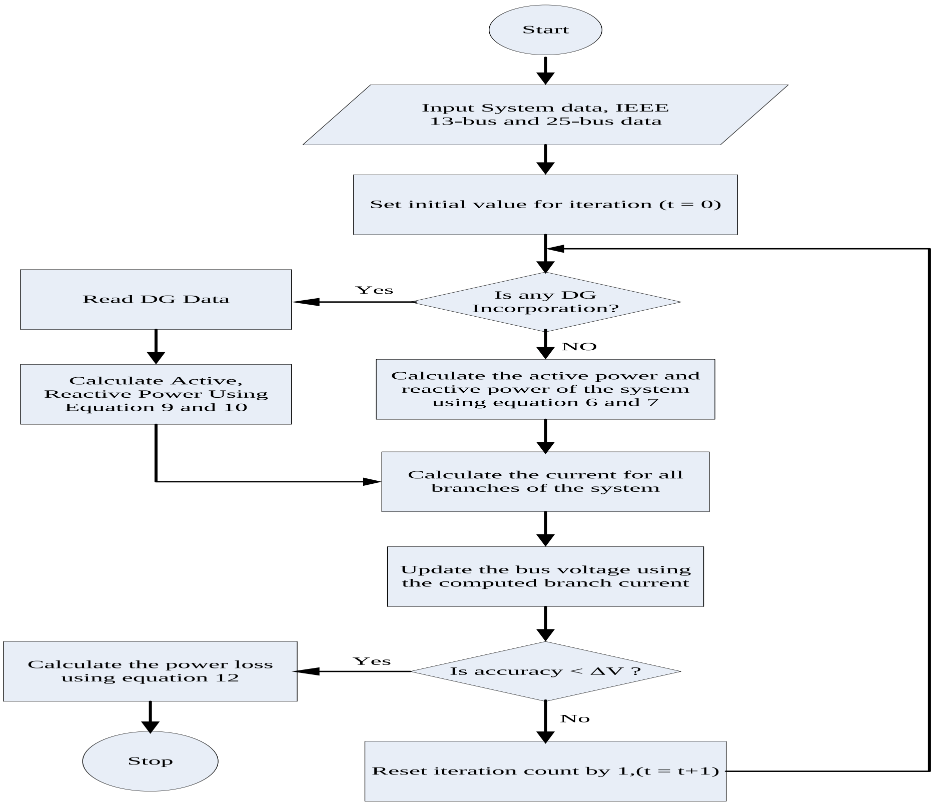

Figure 3: Flowchart of the Ladder Load Flow without and with DG

## III. RESULTS AND DISCUSSION

The simulation results of mathematical modelling of the Ladder load flow with Distributed Generation (DG) are presented and discussed. Distributed Generation unit were place on 13-bus and 25-Bus test feeders using ladder load flow method with assumed constant power factor of 0.85 p.u. Two cases are considered in this study. Test case one discusses Ladder load flow results of 13-bus feeder without and with DG. Case two presents the Ladder load flow results of 13-bus feeder with incorporation of DG. While case two analyses Ladder load flow results of 25-bus feeder without and with DG. The computer simulations and corresponding results are presented in Figures 4 to 9.

### Test Case 1: 13-Bus Ladder Load Flow Results

13-bus test feeder is a radial distribution system feeder fed at one end. The simulation is made with a pre-voltage of 4.16 kV and 100% of nominal voltage of 4.6 kV and base MVA value of 20 (standard value of IEEE 13-bus feeder) and also with a total DG penetration level of 60 MW decentralized DGs of 5 MW which are placed in each bus with a base voltage of 13.8 kV, shunt capacitor of 200 kVar and base value of 40(standard values of DG).. The feeders are reconfigured as bus number 1 to 12.Having carried out Ladder load flow analysis on this feeder, the computed simulations are presented in Figures 4 to 6.

Figure 4 shows how the power loss without incorporation of DG varies with the bus numbers. The power loss for buses 1, 2 and 3 are 0.101, 0.1467 and 0.140p.u. respectively. Buses 4, 5 and 6 also have power loss values of 0.1468, 0.1601 and 0.1035p.u. respectively. Buses 7, 8 and 9 recorded an increase in power loss values of 0.1434, 0.1465, 0.1510p.u. respectively while buses 10, 11 and 12 have the values of power loss of 0.1412, 0.1410 and 0.1418p.u respectively.

Figure 5 illustrates the correspondence between the power loss with Incorporation of DG and the bus numbers. The power loss with incorporation of DG for buses 1, 2 and 3 are 0.0687, 0.0489 and 0.0376 p.u respectively. Buses 4, 5 and 6 have values of power loss of 0.0489, 0.0508 and 0.0232 with DG respectively. The power loss with DG for buses 7, 8 and 9 are 0.041, 0.0431 and 0.0493 p.u. respectively. Buses 10, bus 11 and bus 12 have the values of power loss of 0.0433, 0.0324 and 0.0356 p.u respectively with incorporation of DG.

The comparison of the power losses without and with incorporation of DG with bus numbers is illustrated in Figure 6. The power losses with incorporation of DG for buses 1, 2 and 3 are 0.0687, 0.0489 and 0.0376 p.u. respectively which correspond to power losses of 0.101, 0.1467 and 0.140 p.u. respectively without incorporation of DG indicate a reduction in power losses. This is due to the size of install DGs at the feeders. Buses 4, 5 and 6 also have power losses with incorporation of DG of 0.0489, 0.0508 and 0.0232 p.u. respectively which correspond to power losses of 0.1468, 0.1601 and 0.1035 respectively without incorporation of DG. Buses 7, 8 and 9 have power losses with incorporation of DG of 0.041, 0.0431 and 0.0493 p.u. respectively correspond to power losses of 0.1434, 0.1465 and 0.151 p.u. respectively without incorporation of DG, while buses 10, 11 and 12 have the values of power losses with incorporation of DG of 0.041, 0.0324 and 0.0356 p.u respectively which correspond to power losses of 0.1412, 0.141 and 0.1418 p.u respectively without incorporation of DG.

The results show the total power losses without incorporation of DG were 1.663 p.u and 0.5205 p.u. having installed DG (power losses reduced by 1.1425 p.u, that is, a 68.7% reduction) that is power losses with installation of DG at the feeders are less than the power losses before installing DG. This indicates that the size of distributed generator used is in appropriate.

**Test Case Two: 25-Bus Ladder Load Flow Results**

The 25-bus test feeder is an unbalanced radial distribution system test feeder formed as a result of two pieces of IEEE 13- bus distribution system test feeder. The simulation is made with a pre-voltage of 4.16 kV and 100% of nominal voltage of 4.6 kV and base MVA value of 40(standard value of IEEE 25-bus feeder) and also with a total DG penetration level of 60 MW decentralized DGs of 5 MW which are placed in each bus with a base voltage of 13.8 kV, shunt capacitor of 200 kVar and base value of 40 (standard values of DG). The feeders are reconfigured as bus number 1 to 24. Having carried out Ladder load flow analysis on this feeder, the computed simulations are presented in Figures 7 to 9.

Figure 7 shows the variation of power loss without incorporation of DG with the bus numbers. The power loss for buses 1, 2, 3 and 4 are 0.1501, 0.1567, 0.1701 and 0.1710 p.u respectively without incorporation of DG indicating an increase in power loss as bus numbers are increased. This is due to the resistance and reactance data at each feeder. Buses 5, 6, 7 and 8 have the values of power loss of 0.2145, 0.103, 0.1320 and 0.2145 p.u. respectively. Power loss without incorporating DG for buses 9, 10, 11 and 12 are 0.2145, 0.2014, 0.1845 and 0.2145 p.u. respectively while buses 13, 14, 15 and 16 have the values of power loss of 0.2132, 0.2145, 0.2145 and 0.2145 p.u respectively without incorporation of DG indicating an increase and constant in power loss. This is due to the resistance and reactance data at each feeder. Power loss for buses 17, 18, 19 and 20 are 0.2145, 0.1801, 0.2143 and 0.1124 p.u. respectively while buses 21, 22, 23 and 24 have the values of power loss of 0.2143, 0.1422, 0.2110 and 0.2070 p.u. respectively.

Figure 8 illustrates the correspondence between power loss and bus numbers with incorporation of DG. The power loss with incorporation of DG for buses 1, 2, 3 and 4 are 0.0937, 0.0734, 0.0757 and 0.0760 p.u which correspond to power loss of 0.1501, 0.1567, 0.1701 and 0.1710 p.u respectively without the incorporation of DG. Buses 5, 6, 7 and 8 recorded an increase in power loss of 0.0925, 0.0563, 0.0710 and 0.0925 p.u. respectively when compared to power loss of 0.2145, 0.1030, 0.1320 and 0.2145 p.u. respectively without incorporation of DG. The power loss with DG for buses 9, 10, 11 and 12 are 0.0925, 0.0856, 0.0826 and 0.0922 p.u. respectively which correspond to power loss of 0.2145, 0.2014, 0.1845 and 0.2145 p.u. respectively without incorporating DG while buses 13, 14, 15 and 16 have values of power loss of 0.0917, 0.0925, 0.0925 and 0.0925 p.u respectively with incorporation of DG which correspond to power loss of 0.2132, 0.2145, 0.2145 and 0.2145 p.u respectively without incorporation of DG. The power loss for buses 17, 18, 19 and 20 are 0.0925, 0.0810, 0.0916 and 0.0602 p.u. respectively while power loss at buses 21, 22, 23 and 24 are 0.0917, 0.0710, 0.0858 and 0.0858 p.u respectively.

Figure 9 illustrates the correspondence between the power losses without and with incorporation of DG with the bus numbers. The power losses with incorporation of DG for buses 1, 2, 3 and 4 are 0.0937, 0.0734, 0.0757 and 0.0760 p.u. respectively which correspond to power losses of 0.1501, 0.1567, 0.1701 and 0.1710 p.u. respectively without DG. Buses 5, 6, 7 and 8 also have values of power losses with DG of 0.0925, 0.0563, 0.0710 and 0.0925 p.u. respectively which correspond to power losses of 0.2145, 0.1030, 0.1320 and 0.2145 respectively without DG. The power loses with DG for buses 9, 10, 11 and 12 are 0.0925, 0.0856, 0.0826 and

0.0922 p.u. respectively which correspond to power losses of 0.2145, 0.2014, 0.1845 and 0.2145 p.u. respectively without DG while buses 13, 14, 15 and 16 have values of power losses with DG of 0.0917, 0.0925, 0.0925 and 0.0925 p.u respectively which correspond to power losses of 0.2132, 0.2145, 0.2145 and 0.2145 p.u respectively without DG. The power losses with DG for buses 17, 18, 19 and 20 are 0.0925, 0.0810, 0.0916 and 0.0602 p.u. respectively which correspond to power losses without DG of 0.2145, 0.1801, 0.2143 and 0.1124 p.u respectively while buses 21, 22, 23 and 24 have values of power losses with incorporation of DG of 0.0917, 0.0710, 0.0858 and 0.0858 p.u. respectively which correspond to power losses of 0.2145, 0.1422, 0.2110 and 0.2070 p.u. respectively without DG.

The results also showed that the total power losses with incorporation of DG are 2.0128 p.u.(power losses reduced by 2.4665 p.u, that is, a 55.1% reduction) which are less than total power losses without introduction of DG of 4.4793 p.u. Losses along distribution lines were reduced, hence, an enhanced performance for the power infrastructure. The ladder load flow results have demonstrated the effectiveness and feasibility of the distributed generators power injection model. The results show an appreciable level of electrical power loss in distribution system with the incorporation of DGs.

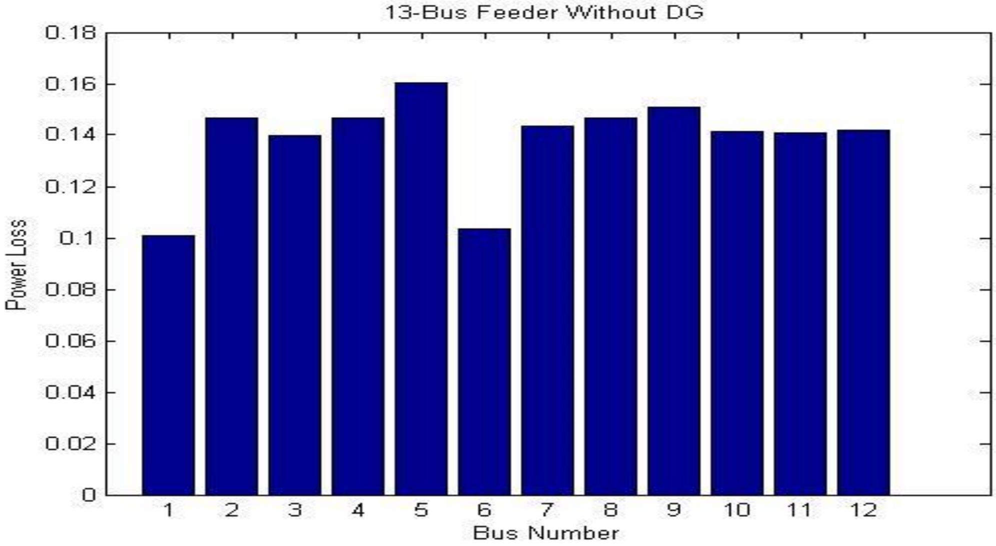

Figure 4: 13-Bus Power loss without Incorporation of DG

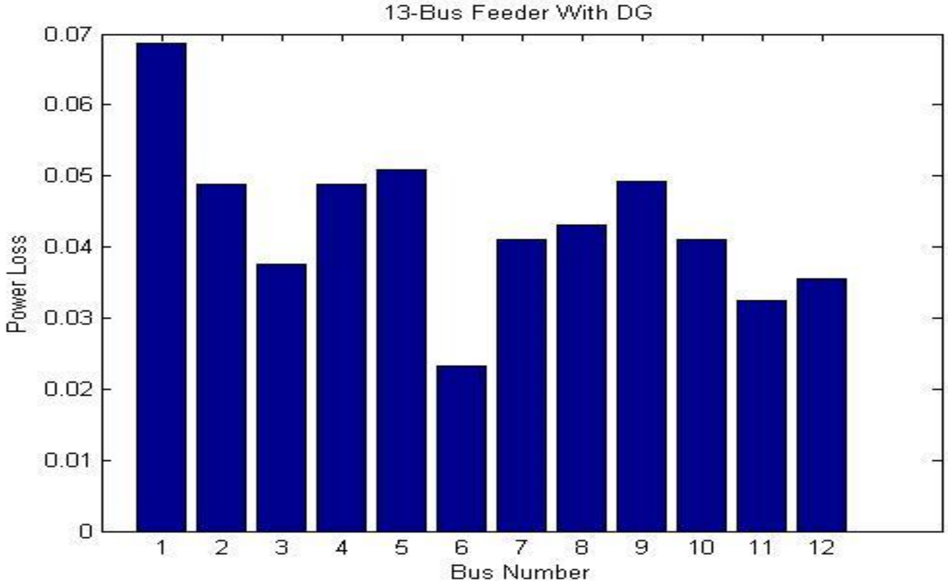

Figure 5: 13-Bus Power Loss with Incorporation of DG

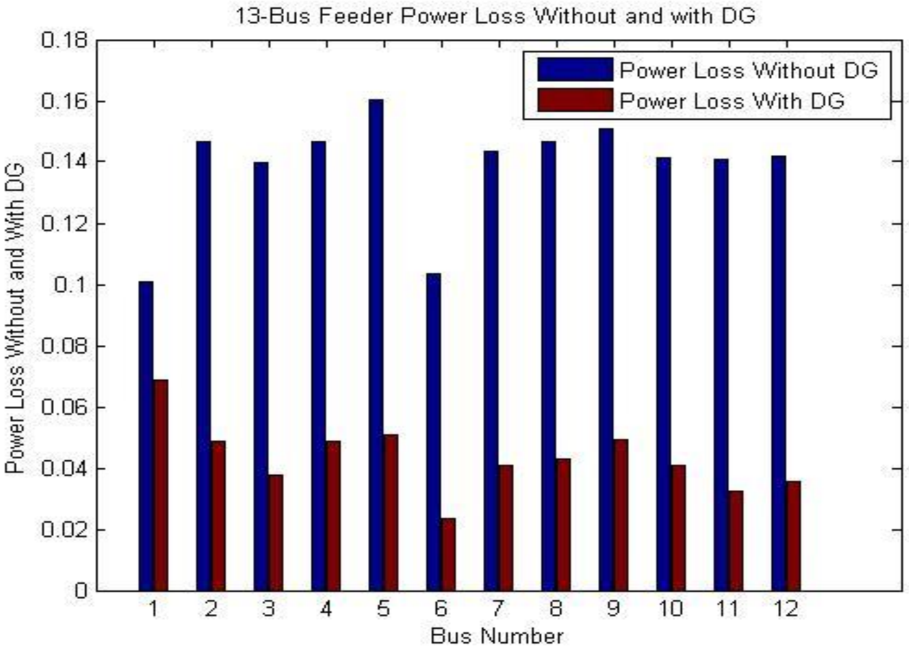

Figure 6: 13-Bus Comparison of Power losses without and with Incorporation of DG

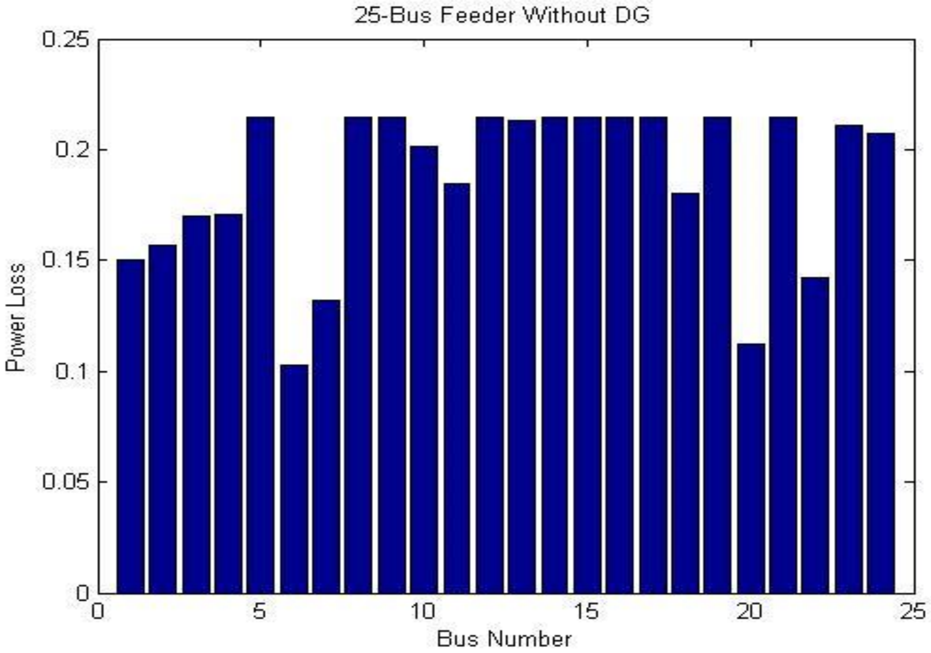

Figure 7: 25-Bus Power Loss without Incorporation of DG

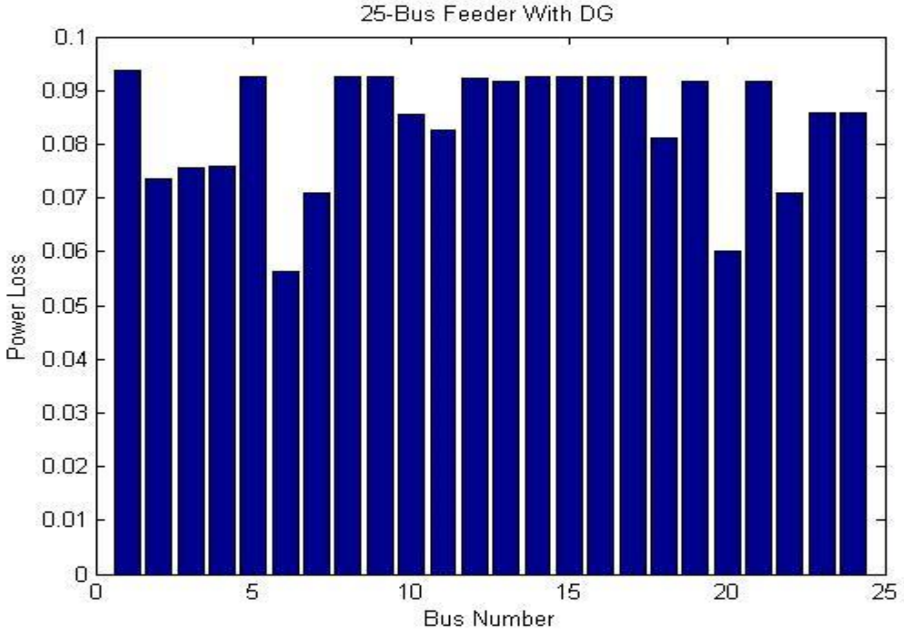

Figure 8: 25-Bus Power Loss with Incorporation of DG

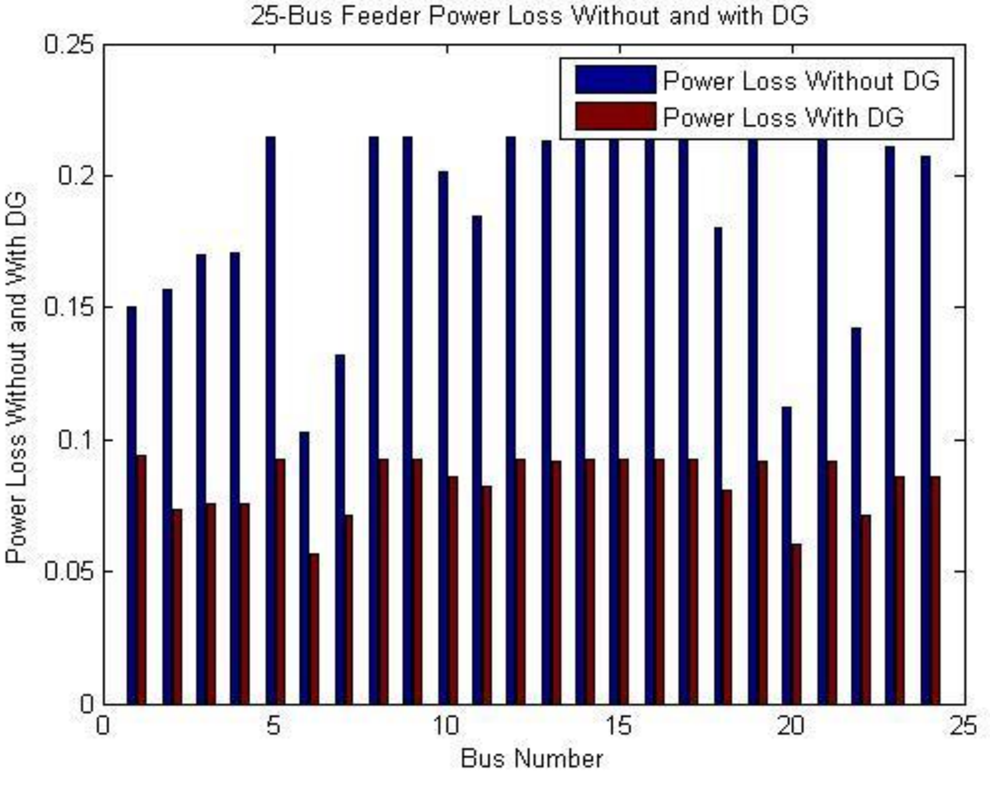

Figure 9: 25-Bus Comparison of Power Loss without and with DG

## IV. CONCLUSSION

This study has discussed load flow simulation approach for power loss minimization in distribution network. The simulations were performed on standard IEEE 13-bus and 25-bus test feeders using the Ladder load flow model with incorporation of DG for distribution system. The power flow results were presented without and with the incorporation of DG. Incorporation of DG into the distribution network has demonstrated technical benefit that compliments the distribution system performance. Results of this study show that installing DG units at appropriate location achieved great improvement for power loss minimization. This study therefore, has developed an enhanced DG improvement power flow model for loss minimization in electrical distribution system.

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