Sizing of DG Units Using Exact Loss Formula to Improve Efficiency of Radial Distribution System

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Abstract: Loss reduction in distribution systems has been a subject of great concern since the evolution of the interconnected power system. In the recent past, with increasing interest in climate change and energy security, renewable energy integration and energy efficiency, including loss reduction, have been considered as twin-pillars of sustainable energy solutions. When renewable energy is integrated by considering loss reduction as an additional goal, it would lead to multi-fold benefits. This paper presents the application of distributed generation for loss reduction. The two key issues of the most suitable location and appropriate size of distributed generation for loss reduction have been discussed. Analytical expressions have been developed for finding the appropriate size of different types of distributed generations. Methodologies are presented for locating the DG in primary distribution network, assuming primary energy resources are evenly distributed along the network. The analytical expressions and placement methodologies have been tested on IEEE 33 bus system.

Keywords: Distributed Generation (DG), Exact Loss Formula, Optimum Location, Power Factor, Power Loss

I. INTRODUCTION

Distributed generation is an approach that employs small-scale technologies to produce electricity close to the end users of power. DG technologies often consist of modular (and sometimes renewable-energy) generators, and they offer a number of potential benefits. In many cases, distributed generators can provide lower-cost electricity and higher power reliability and security with fewer environmental consequences than can traditional power generators.

With large amount of DG penetration it is critical that the power system impacts be assessed accurately so that DG can be applied in a manner that avoids causing degradation of power quality, reliability and control of utility system. The penetration of DG like wind generators, solar panels and small combined heat and power units causes a change in the classic definition of the electricity grid. In the new scenario power flow will not only vary in amount but also in direction. For DG implementation the consumers' interest would be reliability, Power quality and safety where as network operator interests would be customer interests, usage of the grid components, grid losses, safety, stability of the grid and profitability.

Distributed generation (DG) devices can be strategically placed in power systems for grid reinforcement, reducing power losses and on-peak operating costs, improving voltage profiles and load factors, differing or eliminating for system upgrades and improving system integrity, reliability and efficiency.

Distributed Generation has many benefits, including increasing the reliability of electric power, reducing electric utility bills, improving the payback of required generation systems, making power marketable to sell to utilities, generating environmental friendly power and ancillary services like voltage control and loss reduction [1].

II. DG TECHNOLOGIES

Distributed generation takes place on two-levels: the local level and the end-point level. Local level power generation plants often include renewable energy technologies that are site specific, such as wind turbines, geothermal energy production, solar systems (photovoltaic and combustion), and some hydro-thermal plants. These plants tend to be smaller and less centralized than the traditional model plants. They also are frequently more energy and cost efficient and more reliable. Since these local level DG producers often take into account the local context, the usually produce less environmentally damaging or disrupting energy than the larger central model plants.

The technologies used for distribution generation are reciprocating engines, gas turbines, micro turbines, fuel cells, photovoltaic systems, wind Energy, hydro electric resources, bio mass etc., DG technologies can meet the needs of a wide range of users, with applications in the residential, commercial, and industrial sectors. Decision makers at all levels need to be aware of the potential benefits that DG can offer. In some instances, DG technologies can be more cost effective than conventional solutions. Among other things, DG can be used by utilities to enhance existing systems and to delay the purchase of transmission and distribution equipment. In addition, DG units can help to meet the changing demand of end users for premium, reliable or "green" power.

Depending on the operating scheme and relative performance of the DG system and the power plants supplying the grid, fuel consumption, carbon and other pollutant emissions and noise pollution can all increase or decrease with DG adoption [2]. For these reasons, DG policy needs to encourage applications that benefit the public, while discouraging those from which the public incurs a net cost. By considering the capital DG costs, maintenance cost, size range, start-up capability, efficiency, influence on public etc., the technology that will be suitable for particular application should be adapted.

III. LOAD FLOW APPROACH

Four variables associated with each node are Bus voltage magnitude (V), Voltage angle (δ), Real power (P) and Reactive power (Q). Each node introduces two equations, namely the real and reactive power balance equations.

The minimum data required to fully specify system conditions are impedances (usually in per-unit) for all series and shunt branches of the distribution network. Network elements are represented as lumped complex impedances at rated frequency (e.g. distribution lines, in-phase transformers, series and shunt reactors and capacitors). Distribution lines with non-negligible charging capacitance are represented by their simple equivalent π networks and active-power and reactive-power generations and loads at each node.

Distribution load flow solution typically provides voltage magnitude and angle at each bus bar, real and reactive power loss at each bus bar, power flows and MVA loadings at both ends of each branch of the distribution system, power generation or consumption of each static shunt- compensating device and total system losses.

There are many solution techniques for load flow analysis. The solution procedure and formulations can be precise with values adjusted or unadjusted. The acceptable load flow analysis method should meet the following requirements:

- They should have high speed and low storage requirements, especially for real time large system applications, as well as multiple case and interactive applications.
- They should he highly reliable, especially for ill-conditioned problems, outage studies and real-time applications.
- They should have acceptable versatility and simplicity.

The approach utilized forward and backward sweep algorithm based on Kirchoff's Current Law (KCL) and Kirchoff's Voltage Law (KVL) for evaluating the node voltages iteratively. In this approach, computation of branch current depends only on the current injected at the neighboring node and the current in the adjacent branch. This approach starts from the end nodes of sub lateral line, lateral line and main line and moves towards the root node during branch current computation. The node voltage evaluation begins from the root node and moves towards the nodes located at the far end of the main, lateral and sub lateral lines [3].

Voltage at any node is given by

$$V_n = V_{n-1} - I_b Z_b \tag{1}$$

Where V_{n-1} = voltage at $(n-1)^{th}$ node.
b = (n-1)
I_b = Current in the branch b
Z_b = Impedance of the branch b

The real and reactive power loss in the network is given by,

$$\text{Real power loss, } P = \sum_{b=1}^{N_b} |I_b|^2 R_b \tag{2}$$

$$\text{Reactive power loss, } Q = \sum_{b=1}^{N_b} |I_b|^2 X_b \tag{3}$$

IV. DG SIZING AND PLACEMENT

Even though power contribution to the transmission system by DG is small, it is necessary in the present power scenario as many power companies are focusing on reduction of losses in the system and maintaining good voltage profile. In a large transmission system network with high power losses, it is difficult to select a particular bus from many buses so as to place a DG unit for loss reduction. Power losses are present at every bus and identification of bus with highest power loss is important because losses at that bus includes majority of total losses in the system .The cost of power transmission is reduced by minimizing power losses. This can be partially accomplished by DG unit placement in the network.

By considering the above points into consideration, we must consider another important point, which is power reversal in the network. Because if DG size at a bus exceeds certain value, power loss at that bus becomes negative. This situation must be avoided. The exact location and size of DG is calculated by using exact loss formula. Using the exact loss formula sensitivity factors is calculated and bus with highest sensitivity factor is selected as bus with highest power loss.

A. *Problem Formulation*

In order to place the DG unit in the network, we must calculate the loss coefficients by using Exact Transmission Loss Formula and it is derived below. The bus power S_i injected into bus can be represented as generated power minus the bus load. By adding all n bus powers, we therefore obtain the total generated power minus the total load. i.e., we obtain the network losses.

$$P_L + jQ_L = \sum_{i=1}^{n} S_i = \sum_{i=1}^{n} V_i I_i^* \tag{4}$$

Where
P_L → Total transmission loss
Q_L → Total reactive power loss
S_i → Bus power injected into j^{th} bus
V_i → Bus voltage at i^{th} bus
I_i → Bus current vector of i^{th} bus

The total real power loss in power systems is represented by (5), popularly known as "exact loss formula" [4]

$$P_L = \sum_{i=1,j=1}^{n} [\alpha_{ij}(P_iP_j + Q_iQ_j) + \beta_{ij}(Q_iP_j - P_iQ_j)] \tag{5}$$

$$\text{where } \alpha_{ij} = \frac{r_{ij}}{V_iV_j} Cos(\delta_i - \delta_j)$$

$$\text{and } \beta_{ij} = \frac{r_{ij}}{V_iV_j} Sin(\delta_i - \delta_j)$$

i and j in the suffix indicates values at i^{th} and j^{th} nodes respectively.

B. *Types of DG*

DG can be classified into four major types based on their terminal characteristics in terms of real and reactive power delivering capability as follows:

1. DG capable of injecting P only.
2. DG capable of injecting Q only.
3. DG capable of injecting both P and Q
4. DG capable of injecting P but consuming Q.

Photovoltaic, micro turbines, fuel cells, which are integrated to the main grid with the help of converters/inverters, are good examples of Type 1. Type 2 could be synchronous compensators such as gas turbines. DG units that are based on synchronous machine (cogeneration, gas turbine, etc) fall in Type 3. Type 4 is mainly induction generators that are used in wind farms. Type 3 DG is studied in this paper.

C. *Sizing at various locations*

Assuming a = (sign) tan ($\cos^{-1}$ (PF_{DG})), the reactive power output of DG is

$$Q_{DGi} = a\, P_{DGi} \quad (6)$$

in which

sign = +1: DG injecting reactive power;

sign = -1: DG consuming reactive power:

PF_{DG} is the Power factor of DG.

The active and reactive power injected at bus i, where the DG located are

$$P_i = P_{DGi} - P_{Di} \quad (7)$$

$$Q_i = Q_{DGi} - Q_{Di} = aP_{DGi} - Q_{Di} \quad (8)$$

The active power loss can be rewritten and the total active power loss of the system is minimum if the partial derivative of with respect to the active power injection from DG at bus i becomes zero. After simplification and rearrangement we get the optimal size of DG at each bus i [5] for minimizing loss can be written as

$$P_{DGi} = \frac{\alpha_{ii}(P_{Di} + Q_{Di}) + \beta_{ii}(aP_{Di} - Q_{Di}) - X_i - aY_i}{a^2\alpha_{ii} + \alpha_{ii}}$$

where (9)

$$X_i = \sum_{j=i, j\neq i}^{n} (P_j\alpha_{ij} - Q_j\beta_{ij})]$$

$$Y_i = \sum_{j=i, j\neq i}^{n} (Q_j\alpha_{ij} + P_j\beta_{ij})]$$

In the above expression P_{DGI} gives the optimal capacity of DG unit to be placed in transmission system. The power factor of DG depends on operating conditions and type of DG. When the power factor of DG is known, the optimal size of type 3 DG at each bus i for minimizing losses can be found by assuming $0 < PF_{DG} < 1$, sign = +l and "a" is a constant, the optimal size of DC at each bus i for the minimum loss is given by (9) and (6) respectively.

D. *Optimal Location*

For optimal location, first the optimal sizes at various locations have been calculated for different types of DG and the losses were calculated with optimal sizes for each case. The case with minimum losses is selected as the optimal location for each type of DG. Based on this method, one can avoid exhaustive computation and save time, especially for large-scale distribution systems as trend of loss reduction can be captured with α and β coefficients from the bases case.

E. *Optimal Power Factor*

The power factor of the single load [6] is given by

$$PF = \frac{P}{\sqrt{P^2 + Q^2}} \quad (10)$$

It can be proved that at the minimum loss occur when power factor of DG is equal to the power factor of load.

$$PF = PF_{DG} = \frac{P_{DG}}{\sqrt{P_{DG}^2 + Q_{DG}^2}} \quad (11)$$

V. COMPUTATIONAL PROCEDURE

When power factor of DG is set to be equal to that of combined total loads, computational procedure to find optimal size and location of one of four types of DGs is described in the following.

Step l: Run load flow for the base case.

Step 2: Find the base case loss using (5).

Step 3: Calculate power factor of DG using (11).

Step 4: Find the optimal size of DG for each bus using (9) and (8).

Step 5: Place DG with the optin1al size obtained in step 4 at each bus, one at a time. Calculate the approximate loss for each case using (5) with the values α and β of the base case

Step 6: Locate the optimal bus at which the total loss is minimum corresponding with the optimal size at that bus.

Step 7: Run load flow with the optimal size at the optimal, location obtained in step 6. Calculate the exact loss using (5) and the values α and β after DG placement.

It is noted that when the type and power factor of DG is given; the computational procedure to find the optimal size and location of DG is as described earlier apart from step 3. At this step, the power factor of DG is entered rather than using (11). In Exhaustive Load Flow (ELF) method, optimal location and power factor are obtained with a number of load flow solutions.

VI. RESULTS AND DISCUSSION

This chapter provides the case of IEEE 33 Bus radial distribution system. The single line diagram of IEEE 33 Bus radial distribution system is shown in figure 5.1.

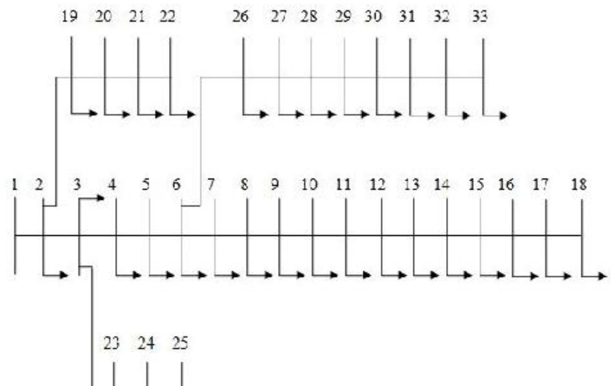

Fig. 1 Single Line Diagram of IEEE 33 Bus System

In the distribution system root node is bus 1, main line has eighteen buses including bus 1 and lateral line emanating from three buses i.e., bus 2, bus 3 and bus 6. There are no sub lateral lines and minor lines present in the system.

The load flow study is conducted on the bus system and the results are carefully noted down. The losses and voltage profile of each bus is noted down, by using the computational procedure mentioned above the optimum power factor and the optimum values of DG to be placed at each bus is obtained. The analysis by placing DG is done and the results are given in this section.

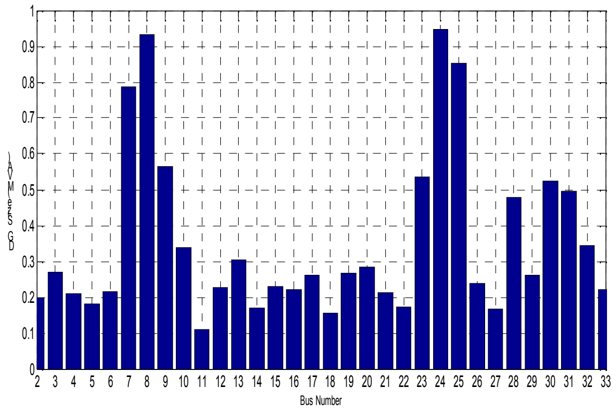

Fig. 2 Optimal DG Sizes at all buses for IEEE 33 Bus System

Figure 2 shows the bar representation of optimal DG Sizes at all buses for IEEE 33 Bus System. From the figure we can observe that the DG size do not follow a regular manner and the size is independent of location of bus (main line or lateral line).

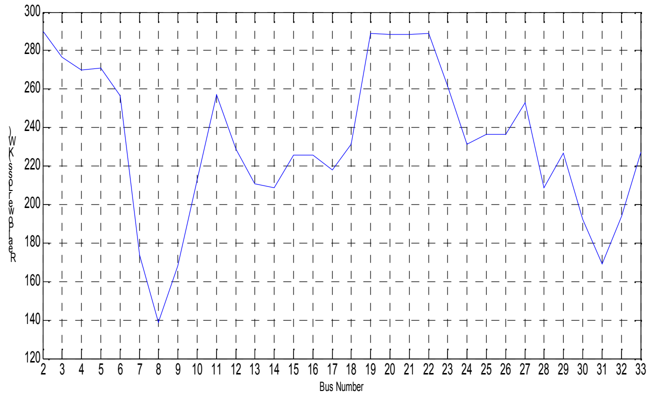

Fig. 3 System Total Real Power Loss with optimum DGs at all buses

Figure 3 shows the graphical representation of system total real power loss with optimum DGs at all buses with optimal DGs placed at each bus. The lowest value of loss is around 140 KW for bus 8. It is clearly seen from graph the optimal location is bus 8 as total losses of system is less. DG of size 0.932 MVA is placed at bus 8 and the graphs are plotted using MATLAB.

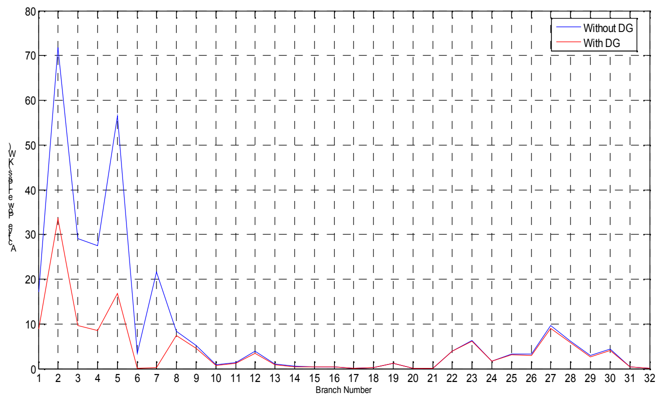

Fig. 4 Line Active Power Loss with DG at bus 8 and without DG

Figure 4 shows line active power loss with DG at bus 8 and without DG. The losses are reduced and it can be seen as difference between the lines blue and red, loss is considerably reduced for buses one to eight excluding 6. Losses are not decreased for the other buses as the branch impedances comes into action.

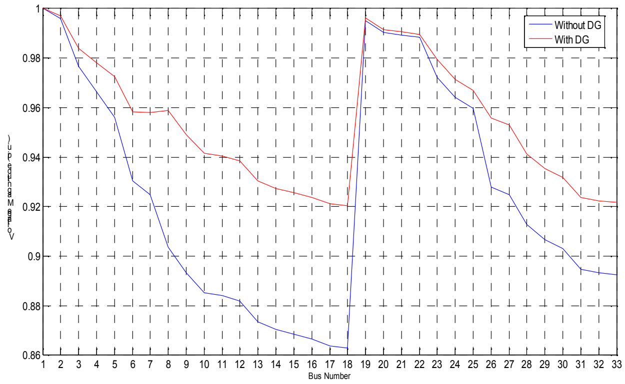

Fig. 5 Voltage at all buses with DG at bus 8 and without DG

Figure 5 shows voltage at all buses with DG at bus 8 and without DG. The voltage profile was improved and it can be seen as difference between the lines blue and red. The bus with more voltage improvement is 18 and bus with less voltage improvement is bus 2.

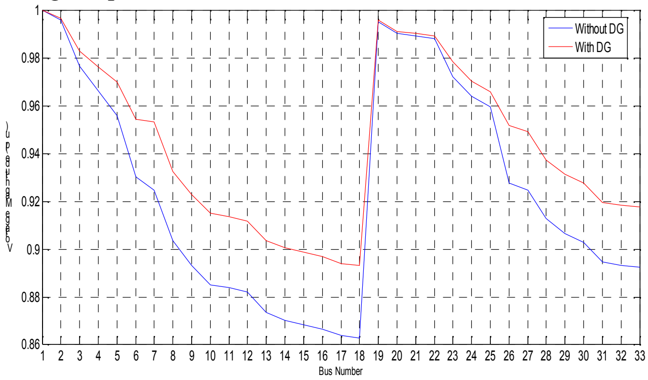

Fig. 6 Voltage at all buses with DG at bus 7 and without DG

Figure 6 shows voltage at all buses with DG at bus 7 and without DG. The voltage profile was improved and it can be seen as difference between the lines blue and red. The buses with more voltage improvement are 17 and 18 and buses 19, 20 and 21 are with less voltage improvement.

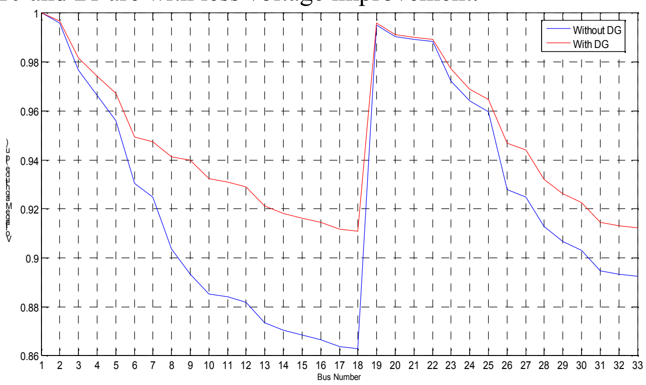

Fig. 7 Voltage at all buses with DG at bus 9 and without DG

Figure 7 shows voltage at all buses with DG at bus 9 and without DG. The voltage profile was improved and it can be seen as difference between the lines blue and red. The bus with more voltage improvement is 18 and bus with less voltage improvement is bus 2.

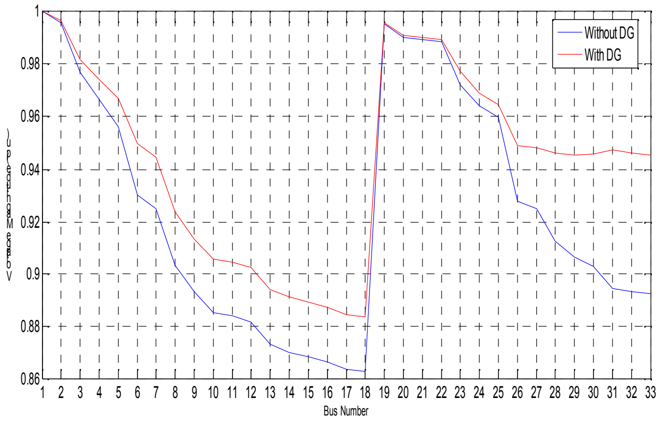

Fig. 8 Voltage at all buses with DG at bus 31 and without DG

Figure 8 shows voltage at all buses with DG at bus 31 and without DG. The voltage profile was improved and it can be seen as difference between the lines blue and red. The bus with more voltage improvement is 33 and bus with less voltage improvement is bus 2.

Table : Summary of Results for IEEE 33 Bus System (PF_{DG}=0.83)

Bus No	TPL (KW)			TQL (KW)			Voltage (p.u)		
	*	#	%	*	#	%	*	#	&
7	292.4	173.7	40.5	196	113.3	42.2	0.925	0.958	3.57
8	292.4	146.2	50.0	196	93.8	52.1	0.903	0.958	6.11
9	292.4	167.8	42.8	196	107.9	44.9	0.893	0.949	6.24
31	292.4	169.0	42.1	196	117.7	39.9	0.894	0.924	3.24

* without DG # with DG
% Percentage Loss reduction & Voltage increment

Table shows the summary of results for IEEE 33 bus system. The voltage increment is more at bus 9 compared to bus 8, but the loss reduction is very less so choice of optimal bus is justified. DG placement improves voltage profiles of the adjacent buses more compared to the buses far away from the installation; this is also seen from the figures. DG at 7 or 8 or 9 improves voltage of bus 18 but DG at bus 31 improved the voltage of bus 33.

VII. CONCLUSION

DG has the potential to play a major role as a compliment or alternative to the electric power grid under certain conditions. DG is fundamentally distinct from the traditional central plant model for power generation and delivery in that it can deliver energy close to loads within the power distribution network. The need for new capacity and DG technology advancements, are collectively laying the groundwork for the possible widespread introduction of DG.

The operating conditions of a power system after connecting DG sources can change drastically as compared to the base case. The planning of DG installations should therefore, consider several factors: the best technology to be used, the number of units of DG and capacities, where should they be installed and type of connection should be used etc.,

The problem of DG allocation and sizing should be approached carefully. If DG units are connected at non optimal locations, the system losses can increase, resulting in increased costs. This shows that all the sites are not practicable for DG implementation and it is necessary to determine the optimal location among the buses present in the network. The reliability of electric power systems can be enhanced by distributed generation, as the system is less dependent on centralized facilities. The use of distributed generators at selected locations can also help distributors overcome local bottlenecks.

A. Future Scope

The proposed method can be extended for a network with large number of buses. An ideal power system, which has the benefits of DG as well as grid, can be formulated by accommodating these DGs into the grid along with central power units so that surplus power generated by DGs can easily sent to the regions as backup power and as peak load sharing.

Since India is a developing country, with availability of huge amount of renewable energy sources like solar, biomass, wind and wave energy. So some amount of energy is contributed to meet the power demands. Therefore it is necessary to locate more DGs and they must be connected to the distribution system.

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