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Impact of DG Placement and Sizing on Distribution System

Tanmoy Malakar* and Nidul Sinha**

Distributed Generation (DG) technology has emerged as a key important issue in distribution system planning, reliability and optimization for quite sometime now. Apart from economic power generation and its efficient transfer, major interests have been observed to plan the distribution system with the presence of small energy sources. This paper addresses a novel technique for optimal placement and sizing of DG into electric power distribution systems. Emphasis has been made to find the impact on voltage profile and power loss of the distribution network with different DG locations and sizes subject to satisfaction of network security constraints. A power flow based simple mathematical formulation has been made. Programs were developed in Matlab for solving the problem. Results reveal that while finding the optimal location and sizing of a DG in a distribution system, both power loss and network security aspects of the network must be considered in addition to minimum voltage deviation as they influence the optimal results significantly.

Keywords: *Distributed Generation, Optimal Size, Optimal Location, Power Loss, Voltage Control*

1.0 INTRODUCTION

Distributed Generation (DG) will play a major role in the near future in the electric power system infrastructure and market. Because of the global warming, there has been a consensus worldwide to cut the emission level for quite sometime now. Clean natural energy generation, cogeneration system of high thermal efficiency etc are the need of the hour. Exploration of renewable energy sources like wind, solar, hydro, geothermal can be an alternative mode of power generation to meet the power growth locally. As these generators are smaller in size and are set up in the vicinity of the customer, they are called Distributed Generation. In distribution systems, DG can provide benefits for the customers as well as for the utilities, especially in sites where the central generation is impracticable or where there are deficiencies in the transmission system. However, DG can never be a substitute of central generation.

The other reasons for the DG technology to become popular is that it reduces considerable amount of transmission costs, power distribution losses, voltage sags and can act as an immediate backup during sustained utility outages. So, the technological achievements of using DG results into improvement of power system reliability and because of widespread use of renewable sources, it is also environment friendly.

The proper choice of DG location and size has a significant impact on the performances of the distribution system. Distributed generation

Electrical Engineering Department, National Institute of Technology, Silchar, Assam-788010, INDIA.
*email: m_tanmoy1@rediffmail.com
**email: nidulsinha@hotmail.com

benefits are site and size specific. Several researches have been carried out recently for improving the flexibility of power distribution systems. Ref [1] discussed about the revolutionary approach of DG technologies in terms of placement, size, practical limitations etc and their impact on the system operation. J. A. P Lopes et al in [2] discussed about the main drivers behind DG growth and presented different challenges that must be overcome in the integration of DG into electric power system. A study highlighting both technical and economical aspect of renewable and distributed generation has been presented in [3]. The problem of finding optimal location and size of DG in a distribution network has been investigated by the previous works in [4], [5], [6], [7], [9], [10]. Ref. [4] discussed the voltage optimization considering optimal DG allocation and sizing, which is most economic. In [5], optimal allocation of DG's have been investigated with the consideration of voltage profile and power losses for fixed DG size. A price based study has been reported to find a suitable location of DG in [6]. Sujatha Kotamarty in [7] proposed a simple formulation to determine optimal location of DG under different network conditions. The impact of both site and size of DG's on system performance has also been reported in their works. Coordinated control of DG with other voltage regulating devices for optimal control of voltage distribution has been presented in [8]. Emphasis has been given to power losses only to determine optimal siting and sizing of DG in [9]. Here a loss sensitivity factor is formulated as performance index. Multiobjective optimization process has been carried out to get a best compromised DG size and location in [10].

Most of the work reported above considers voltage deviation minimization or power loss minimization or both as criterion for finding optimal DG location and size but have ignored the other network security aspects. It is reported in [7] that with the increase in DG penetration, cumulative voltage deviations also get reduced. But, increase in DG penetration may also invite overloading of certain lines in the immediate vicinity of the DG node. In addition, it may result into variation in power losses. It is worth investigating whether the optimal solutions obtained with the approach as in ref. [7] results into minimum power loss or not in addition to satisfaction of network security aspects. Therefore, the objective of the present work is to develop an approach for finding the best DG location considering better voltage profile and minimum power loss in such a manner that the derived DG location and size will satisfy different network security aspects. As security aspect, the line thermal limits and bus voltage magnitude limits have been considered in the present work.

2.0 PROBLEM FORMULATION

A. Objective Function

For finding optimal location of DG together with sizing in terms of voltage profile and power loss; the objective function as used in [5] is modified with elimination of the term related to reactive power loss as it will be taken care of by the minimization of voltage deviation. The objective function consists of two parts: first part is related to change in voltage magnitude and second part is related to change in active power losses.

$$Objective = Max\left[k1\left\{\frac{1}{n}\sum_{i=1}^{n}(V_{i\,with\,DG}-V_{i\,without\,DG})\right\}+ k2\left\{\sum_{j=1}^{m}(P_{j\,without\,DG}-P_{j\,with\,DG})\right\}\right] \quad (1)$$

Subject to,

$$P_{Gi}-P_{Di}-|V_i|\sum_{k=1}^{n}|V_k|\{G_{ik}\cos(\theta_i-\theta_k)+B_{ik}\sin(\theta_i-\theta_k)\}=0$$
$$Q_{Gi}-Q_{Di}-|V_i|\sum_{k=1}^{n}|V_k|\{G_{ik}\sin(\theta_i-\theta_k)+B_{ik}\cos(\theta_i-\theta_k)\}=0 \quad (2)$$

and
$$S_{ij} < S_{ij\,\max}$$
$$|V_{i\,\min}|\le|V_i|\le|V_{i\,\max}| \quad (3)$$

Here k1 and k2 are weighting factors. Values chosen for k1 and k2 are 0.6 and 0.4 respectively. $V_{i\ withDG}$ and $V_{i\ without\ DG}$ are the p.u. voltages at i^{th} bus with and without DG respectively. $P_{j\ with\ DG}$ and $P_{j\ without\ DG}$ are active power losses in j^{th} branch with and without DG respectively. $G_{ik,}$ B_{ik} are real and imaginary part of bus admittance matrix. 'n' is the number of buses, 'm' is the number of branches, S_{ij} and S_{ijmax} are the MVA flow between i^{th} and j^{th} node and its maximum limit respectively. $|V_{i\,\min}|\,\&\,|V_{i\,\max}|$ are minimum and maximum values of the bus voltages at i^{th} bus respectively.

B. Pseudo Code

1. % Initialize the case (normal or contingency) %

    % Read system data. Run Power Flow and save results %

2 % Set DG size (1/3rd, 1/2 and 2/3rd of total load) %

3. **for** i = 2 : node_max (%Insert DG from node 2 %)

    % Run Power Flow and calculate following %

    % i) MVA flow of all branches;

    % ii) Real power loss;

    if (for no limit violations)

    % Calculate the objective function;

    % Insert DG to the next node or bus;

    else (for limit violations)

    % Insert DG to the next node or bus;

    end

    if (Node≤ Node_max)

    % Show results %

    end

    end.

4. **if** (all DG sizes considered)

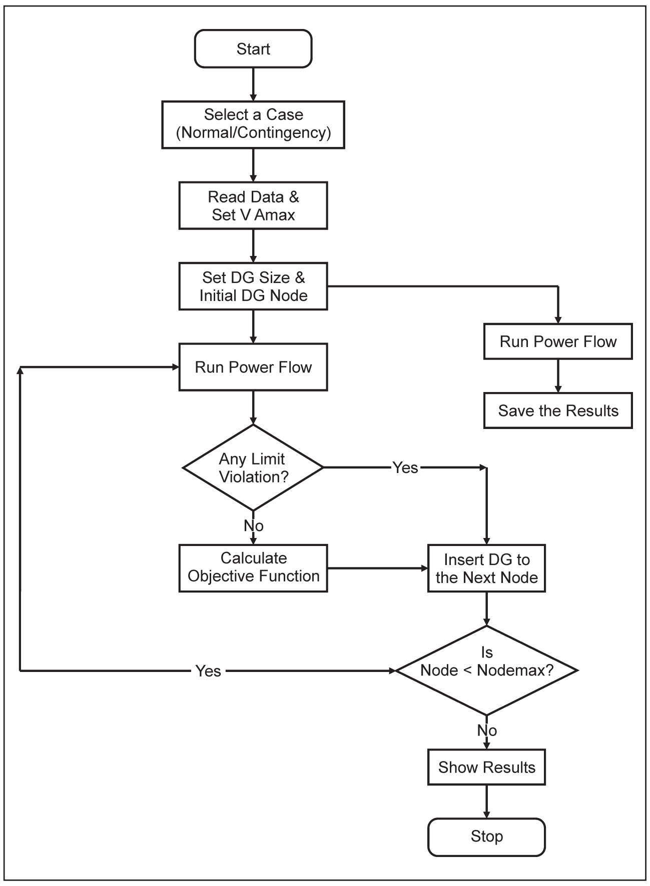
    % Stop %

    else

    % Set next DG size and go to step-3;

    end

C. Flowchart



3.0 PERFORMANCE STUDY

A. Test System

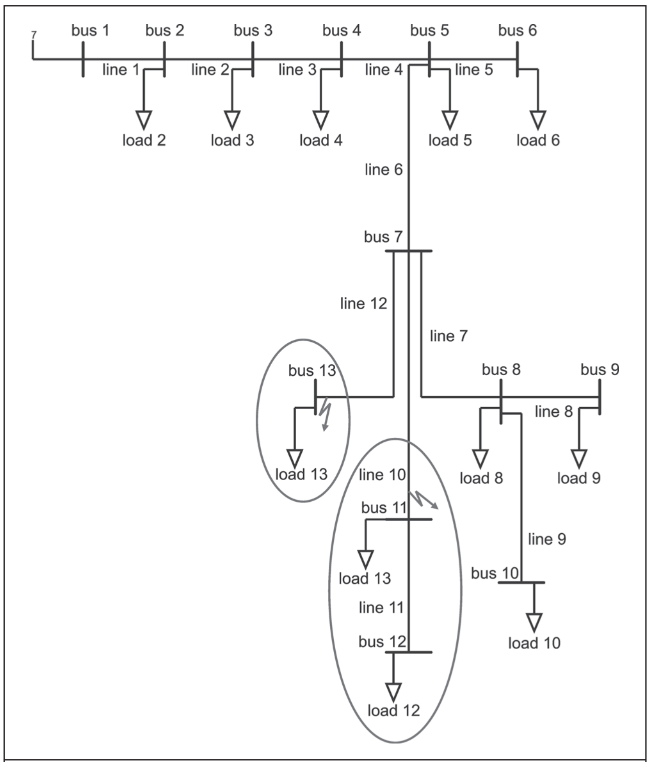


FIG. 1 13 BUS RADIAL DISTRIBUTION SYSTEM

Fig. 1 shows the 13 bus radial distribution system and has been taken as a test system from [5]. Here bus 1 is considered as slack bus is being connected with the substation and all the other buses are PQ type as loads are connected with all of them. A single DG is inserted from bus 2 to maximum available bus for three different DG sizes. The objective function values are recorded for all possible cases. Here the DG node is modeled as PV type with sufficient reactive power support and algorithm is followed to find the performance indexes.

In this paper, three different cases have been considered for the test system, such as normal case, contingency case-1 and contingency case-2. The circled part in the test system represents contingency cases. In contingency case-1, it is assumed that fault has taken place at bus 13 and line-12 has been tripped off. Similarly, in contingency case-2, the assumption is the outage of line-10 in the event of fault at bus 11. The distribution network is reconfigured in each case at the beginning of the algorithm where Newton Raphson power flow is conducted to redistribute the power to reduce its mismatches. In the present work the line thermal limits are considered to be 1.5 times of the base case flow.

B. Impact of DG Placement

In this section, the impact of DG placement on voltage profile and power loss has been investigated subject to satisfying different network constraints. According to the proposed algorithm, the best location for a particular size of DG is the bus at which the maximum value of objective function is reported. This ensures an improved voltage profile in the entire system along with minimized power distribution loss. To investigate the comparative performance of the proposed approach, cumulative voltage deviations at each possible DG nodes have also been calculated and shown in Tables 1-5.

1. DG Size : One Third

In this case, the DG size is assumed to be one third of total load demand. Three different cases have been considered. Under normal case, DG size of 3.512 MW has been tested. In contingency cases, DG sizes are considered as 3.13 MW and 2.8513 MW respectively. In each case, a single DG is inserted from node 2 to maximum available node and the performance indices are recorded. The detail results are depicted in Table 1. It is observed that the objective function values are different when DG is inserted at different buses in all the three cases. The value of objective function is maximum at bus 8 under normal, contingency case-1 and case-2 respectively. The thermal limit violations were reported on some of the other nodes as DG nodes. Hence under such circumstances, objective values were not calculated. For example, limit violation at line-5 (L-5) connecting bus 5 and 6 were reported when DG was inserted at bus 6 under normal, contingency case-1 and case-2. The other DG nodes, where limit violations were reported, may be seen from Table 1 for detail.

In order to verify the results obtained from the proposed algorithm, cumulative voltage deviations as reported in [7] has also been determined for all the three cases and presented in Table 1. It is found that cumulative voltage deviation is minimum when DG is inserted at bus 8. Hence, the best DG location is at bus 8 for all the cases when DG size is one third of the total load.

2. DG Size : Half

When DG size is made half of the total load, the detail results are presented in Table 2. It is observed that the value of objective function is maximum when DG is inserted at bus 8 for normal and contingency case-1. Alternatively minimum value of cumulative voltage deviations has been reported at bus 8 for both normal and contingency case-1 respectively. Therefore, the best location of the DG under both normal and contingency case-1 is bus 8. However, in contingency case-2, the best DG location is at bus 7 as limit violation was reported in line-7 (L-7) when DG was inserted at bus 8.

TABLE 1

IMPACT OF DG PLACEMENT OF SIZE 1/3RD AT DIFFERENT LOCATIONS UNDER DIFFERENT CASES

DG Node	Normal Case			Contingency Case – 1			Contingency Case – 2		
	Objective Value (p.u)	Cumulative Voltage Deviation (p.u)	Thermal Limit Violation	Objective Value (p.u)	Cumulative Voltage Deviation (p.u)	Thermal Limit Violation	Objective Value (p.u)	Cumulative Voltage Deviation (p.u)	Thermal Limit Violation
2	—	—	L-1	—	—	L-1	—	—	L-1
3	0.0015	0.3226	No	0.0021	0.2652	No	0.0047	0.1984	No
4	0.0052	0.2692	No	0.0011	0.2245	No	0.0017	0.1721	No
5	0.0108	0.1922	No	0.0061	0.1692	No	0.0028	0.1406	No
6	—	—	L-5	—	—	L-5	—	—	L-5
7	0.0160	0.1347	No	0.0105	0.1337	No	0.0067	0.1292	No
8	0.0161	0.1275	No	0.0110	0.1266	No	0.0075	0.1258	No
9	—	—	L-8	—	—	L-8	—	—	L-8
10	—	—	L-9	—	—	L-9	—	—	L-9
11	0.0156	0.1337	No	0.0105	0.1308	No	OUT	OUT	OUT
12	—	—	L-11	0.0102	0.1311	No	OUT	OUT	OUT
13	—	—	L-12	OUT	OUT	OUT	—	—	L-12

TABLE 2

IMPACT OF DG PLACEMENT OF SIZE 1/2 AT DIFFERENT LOCATIONS UNDER DIFFERENT CASES

DG Node	Normal Case			Contingency Case – 1			Contingency Case – 2		
	Objective Value (p.u)	Cumulative Voltage Deviation (p.u)	Thermal Limit Violation	Objective Value (p.u)	Cumulative Voltage Deviation (p.u)	Thermal Limit Violation	Objective Value (p.u)	Cumulative Voltage Deviation (p.u)	Thermal Limit Violation
2	—	—	L-1	—	—	L-1	—	—	L-1
3	0.0012	0.3226	No	0.0025	0.2651	No	0.0051	0.1983	No
4	0.0049	0.2691	No	0.0008	0.2244	No	0.0021	0.1720	No
5	0.0106	0.1920	No	0.0058	0.1690	No	0.0024	0.1404	No
6	—	—	L-5	—	—	L-5	—	—	L-5
7	0.0159	0.1345	No	0.0103	0.1335	No	0.0064	0.1289	No
8	0.0160	0.1271	No	0.0108	0.1264	No	—	—	L-7
9	—	—	L-8	—	—	L-8	—	—	L-7, L-8
10	—	—	L-9	—	—	L-9	—	—	L-7, L-9
11	—	—	L-10	—	—	L-10	OUT	OUT	OUT
12	—	—	L-10,L-11	—	—	L-10, L-11	OUT	OUT	OUT
13	—	—	L-12	OUT	OUT	OUT	—	—	L-12

TABLE 3

IMPACT OF DG PLACEMENT OF SIZE 2/3RD AT DIFFERENT LOCATIONS UNDER DIFFERENT CASES

DG Node	Normal Case			Contingency Case – 1			Contingency Case – 2		
	Objective Value (p.u)	Cumulative Voltage Deviation (p.u)	Thermal Limit Violation	Objective Value (p.u)	Cumulative Voltage Deviation (p.u)	Thermal Limit Violation	Objective Value (p.u)	Cumulative Voltage Deviation (p.u)	Thermal Limit Violation
2	—	—	L-1	—	—	L-1	—	—	L-1
3	0.0006	0.3225	No	0.0031	0.2650	No	—	—	L-2
4	0.0044	0.2689	No	0.0003	0.2243	No	0.0026	0.1718	No
5	0.0102	0.1917	No	0.0053	0.1687	No	0.0019	0.1401	No
6	—	—	L-5	—	—	L-5	—	—	L-5
7	0.0154	0.1340	No	0.0098	0.1329	No	0.0058	0.1283	No
8	—	—	L-7	—	—	L-7	—	—	L-7
9	—	—	L-7, L-8	—	—	L-7, L-8	—	—	L-7, L-8
10	—	—	L-7, L-9	—	—	L-7, L-9	—	—	L-7, L-9
11	—	—	L-10	—	—	L-10	OUT	OUT	OUT
12	—	—	L-10	—	—	L-10, L-11	OUT	OUT	OUT
13	—	—	L-12	OUT	OUT	OUT	—	—	L-12

TABLE 4

VARIATIONS OF CUMULATIVE VOLTAGE DEVIATION UNDER DIFFERENT CASES IN P.U.

Cumulative Voltage Deviation Without DG			Cumulative Voltage Deviation With DG Size 1/3rd			Cumulative Voltage Deviation With DG Size 1/2			Cumulative Voltage Deviation With DG Size 2/3rd		
Normal	Case-1	Case-2	Normal	Case-1	Case-2	Normal	Case-1	Case-2	Normal	Case-1	Case-2
0.3522	0.2409	0.1626	0.1275 at bus 8	0.1266 at bus 8	0.1258 at bus 8	0.1271 at bus 8	0.1264 at bus 8	0.1289 at bus 7	0.1340 at bus 7	0.1329 at bus 7	0.1283 at bus 7

TABLE 5

VARIATIONS OF REAL POWER LOSSES UNDER DIFFERENT CASES IN MW

Real Power Loss Without DG			Minimum Real Power Loss With DG Size 1/3rd			Minimum Real Power Loss With DG Size 1/2			Minimum Real Power Loss With DG Size 2/3rd		
Normal	Case-1	Case-2	Normal	Case-1	Case-2	Normal	Case-1	Case-2	Normal	Case-1	Case-2
0.7129	0.5502	0.4458	0.2875 at bus 7	0.2798 at bus 8	0.2788 at bus 8	0.3140 at bus 7	0.3378 at bus 8	0.3646 at bus 7	0.4291 at bus 7	0.4637 at bus 7	0.4903 at bus 7

3. DG Size : Two Third

As has been presented in Table-3 that when DG penetration is increased to two third of the total load, the best DG location is found when DG is inserted at bus 7, where objective function value becomes maximum and the cumulative voltage deviation is found to be minimum. It is also observed from the table that the trend has been maintained for all the three different cases under consideration.

C. Impact of DG Penetration

It is reported in ref. [7] that with the increase in DG penetration, the cumulative voltage deviation reduces and based on this fact, the suitable size of DG was determined. In this work, it is felt important to investigate the changes in power loss with the change in DG penetration. For this purpose, the active power losses have been traced along with cumulative voltage deviations for three different sizes of DG under normal and contingency cases. The variations of cumulative voltage deviations have been reported in Table 4 for different sizes of DG at its best locations. Similarly, the variations of minimum active power losses are presented in Table 5 for three different sizes of DG. It is observed from Table 1 through Table 3 that cumulative voltage deviation decreases as DG penetration level is increased. But the best DG location (based on minimum cumulative voltage deviations) may change with increase in DG penetration, as some of the security constraints may be violated. For example, under normal case when DG size is increased from one third to half, the value of cumulative voltage deviation decreases from 0.1275 p.u to 0.1271 p.u at best DG location (bus 8). However, as the DG penetration is further increased to two third; security limit violation occurs with DG at bus 8 and the best DG location with this injection is now at bus 7 with cumulative voltage deviation of 0.1340.

Similarly, it is observed from Table 5 that there is significant change in real power losses with the change in DG penetration. It is evident that the power loss decreases progressively when DG penetration is raised up to one third of total load. However, for further DG penetration, the power loss starts increasing. For example, without DG under normal case, the power loss is 0.7129 MW; which decreases to 0.2875 MW for one third of DG penetration and the corresponding DG node is at bus 7. But, the power loss increases to 0.3140 MW and 0.4291 MW for DG penetration of half and two third respectively even when the DG is inserted at the same node. This is due to the fact that power flow in the reverse direction increases with corresponding increase in DG penetration.

4.0 CONCLUSION

Algorithms are developed for finding the impact of DG siting and sizing on a distribution system. Performance indices were selected for finding optimal location and sizing of DG units with the objectives of improving voltage profiles and reduction of power loss subject to satisfying network security constraints like bus voltage magnitude limit violation; line thermal limit violation etc. The following conclusions are drawn from the study.

1. Optimal placement of DG is size dependent and system topology dependent. Moreover, different network security aspects must be considered while determining optimal location and size for a DG. In a distribution network, the best DG location derived under normal case may not necessarily be the same under contingency cases.

2. With the increase in DG size, the voltage deviation from the desired value (1.0 p.u) decreases sharply. But this cannot be a sole criterion to get a suitable size of DG unit as changes in power loss must also be taken into consideration.

3. When DG is inserted at any node of a distribution network, the power flow no more remains radial in all parts of the network. As a result, there are changes in power loss.

4. Unlike voltage deviation, real power loss does not decrease continuously with increase in DG size. Investigation reveals that minimum power loss is size dependent. For higher degree of DG penetration, the real power loss increases because of increase in reverse power flow.

5. It is observed that the best DG location does not always associate with minimum power loss. However, more stresses must be given on power loss to determine an optimal size of DG.

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