JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

OPTIMAL SIZING AND PLACEMENT OF DG USING MODAL ANALYSIS

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Abstract: The transmission networks are no longer responsible solely for security issues in low voltage distribution networks due to high penetration of distributed generation (DG) in distribution networks. Penetration of DG units in distribution network has increased rapidly, stimulated by reduced network power losses, improved bus voltage profile and better power quality. To maximize the availing benefits, optimal DG planning is necessary. Two critical issues of DG planning: (i) Optimal placement (ii) Optimal sizing. The objective of this work is to demonstrate a simple and fast technique to determine appropriate location and size of DG units. In this project DG placement problem is solved based on voltage stability technique (Modal Analysis). The Modal Analysis determines the critical modes and their associated participating buses, which lead the system to instability. The bus with the biggest participation factor in each mode is selected for allocation of DG units. The effectiveness of this methodology is tested on a well known 33-bus radial distribution network.

***Index Terms* - Distributed Generation, Modal Analysis, Voltage Deviation Index (VDI), Voltage Stability, Participation Factor.**

I. INTRODUCTION

Distributed generation (DG) is going to play a very important role in power systems worldwide [1]. Penetration of DG units in distributed system has a significant impact on system reliability, voltage profile, power flow, stability, and power quality. Since the resources are available locally and in small scale, DG units are mostly connected at the distribution level. When the penetration of DG is high, the generated power of DG units not only alters the power flow in the distribution system, but also in the transmission system. As a consequence, the connection of DG to the network may influence the stability of the power system, i.e., angle, frequency, and voltage stability [2], [3]. It might also have an impact on the protection selectivity, and the frequency and voltage control of the system.

Most of the radial distribution networks suffer voltage instability at feeders. DGs capability can be used to clear voltage stability problems, which are the cause of most recent blackouts. DG units can boost up the low voltage at the end of the feeders. The planned application of DG units can provide the transmission capacity release, reduction in network losses, and avoidance of high investment costs for network upgrades. But, unplanned uses of DG units may increase the problems. Therefore, some tools or techniques are needed to be examined for the allocation and sizing of the DG units to maximize their benefits, which is very important in system design and expansion.

The problem of voltage stability in distribution networks and the analysis of DG units from this point of view are rather new concepts. A new voltage-stability index is introduced by simplified load-flow equations to seek the most sensitive buses to voltage collapse in radial networks [4].A new method for DG placement is introduced using continuation power flow analysis has been proposed by Hedayati et al. [5]. They have not studied about the size of DG units. Kashem et al. have discussed about optimal use of DG units to support voltage in distribution feeders [6]. They have applied sensitivity analysis to determine appropriate location of voltage support. The effect of DG real and reactive power injections for the inclusion of DG units is also investigated. Rafidah et al. [7] have discussed about a methodology to evaluate appropriate DG size and its impact on power losses and voltage profile in distribution system. They have proposed complex artificial immune system optimization algorithm for sizing of DG units. Acharya et al. [8] have derived an expression to calculate size and location of DG units to minimize distribution losses. The size of DG units is calculated updating the loss coefficients of network loss formula. With proposed methodology by Acharya et al., appropriate size of DG units can be estimated after running a number of load flow iterations. A genetic algorithm-based optimal sizing and placement of DG units considering the system energy loss minimization in different load conditions have been presented by Singh et al. [9]. However, this method needs extensive calculations. Analytical approaches to choose optimal location for DG units in radial distribution network to minimize loss have been presented by Caisheng et al. [10]. They have not discussed sizing issue of DG units in the literature. Recent researches focus on the selection of best places for the allocation of DG units in large distribution network, but appropriate size calculation of DG units using simple techniques has not been emphasized yet.

In this paper, a DG placement problem is solved using voltage stability technique *(Modal Analysis)* with an objective to minimize losses and simultaneously improve voltage profile. The next section briefly reviews the technique used for identifying the voltage stability problem. Section 3&4 elaborates on a new algorithm for optimal sizing and placement of DG. Simulation runs are carried out on the well-known 33-bus radial distribution network in Section 5.Finally, Section 6 concludes this paper.

II. VOLTAGE STABILITY PROBLEM IN DISTRIBUTION SYSTEM

2.1 Problem Identification

Voltage collapse usually occurs in heavily loaded systems that do not have sufficient local reactive power sources and consequently cannot provide secure voltage profile for the system. This reactive power shortage may lead to wide-area blackouts and voltage-stability problems. The shortage can be alleviated by an increased share of DGs in low-voltage (LV) distribution systems to improve voltage stability [5].Most DG technologies, such as synchronous machines, power-electronic interface devices (e.g., photovoltaic cells and micro turbines), and new induction generators (doubly fed induction generators), are capable of providing a fast, dynamic reactive power response. This capability can be used by the system operators to enhance system stability. Since a generator location affects the system voltage stability, it is important to identify the most effective buses to install a DG.

2.2 Modal Analysis.

The voltage-stability problem has a dynamic nature in general, but static analysis techniques are promising tools for predicting the problem characteristics [11], [12], [13]. A modal analysis, as a static approach, can discover the instability characteristics .This is achieved by solving the linearized power-flow equations:

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}J_{11} & J_{12}\\ J_{21} & J_{22}\end{bmatrix}\begin{bmatrix}\Delta\theta\\ \Delta V\end{bmatrix} \qquad (1)$$

Considering ΔP=0, the reduced Jacobian matrix is obtained as [13]:

$$J_R = J_{22} - J_{21} * J_{11}^{-1} * J_{12} \ (2)$$

$$\Delta Q = J_R * \Delta V \qquad (3)$$

$$\Delta V = J_R^{-1} * \Delta Q \qquad (4)$$

J_R represents the liberalized relationship between the incremental changes in bus voltage (ΔV) and bus reactive power injection (ΔQ). It is known that, the system voltage is affected by both real and reactive power variations. The focus of study is on the reactive demand and supply problem of the system as well as minimize computational effort, which is achieved by reducing dimensions of the Jacobian matrix J. The real power (ΔP=0) and angle part from the system in Equation (1) are eliminated.

The Eigen values and eigenvectors of the reduced order Jacobian matrix J_R are used for the voltage stability characteristics analysis. Voltage instability can be detected by identifying modes of the Eigen value matrix J_R. The magnitude of the Eigen values provides a relative measure of proximity to instability. The eigenvectors on the other hand present information related to the mechanism of loss of voltage stability.

Eigen value analysis of J_R results in the following:

$$J_R = \Phi\Lambda\Gamma \qquad (5)$$

Where,

Φ = right eigenvector matrix of J_R.
Γ = left eigenvector matrix of J_R.
Λ= diagonal Eigen value matrix of J_R.

Inverting (5) yields:

$$J_R^{-1} = \Phi\Lambda^{-1}\Gamma \qquad (6)$$

Substitute (6) in (4) which gives

$$\Delta V = \Phi\Lambda^{-1}\Gamma\ \Delta Q \text{ or } \Delta V = \sum_i \frac{\Phi_i\Gamma_i}{\lambda_i}\Delta Q \ (7)$$

Where Γ_i is the i^{th} row of left eigenvector of J_R and Φ_i is the i^{th} column of right Eigen vector. λ_i is the i^{th} Eigen value.

The i^{th} modal reactive power variation is defined as:

$$\Delta Q_{mi} = K_i\Phi_i \qquad (8)$$

Where K_i is a scale factor to normalize vector ΔQ_i so that,

$$K_i^2 \sum_j \Phi_{ji}^2 = 1 \qquad (9)$$

With Φ_{ji} is the j^{th} element of Φ_i

The corresponding i^{th} modal voltage variation is:

$$\Delta V_{mi} = \frac{1}{\lambda_i}\Delta Q_{mi} \qquad (10)$$

Equation (10) can be summarized as follows:

If λ_i= 0, the i^{th} modal voltage will collapse because any change in that modal reactive power will cause infinite modal voltage variation.

If λ_i>0, the i^{th} modal voltage and i^{th} reactive power variation are along the same direction, indicating that the system is voltage stable.

If λ_i<0, the i^{th} modal voltage and the i^{th} reactive power variation are along the opposite directions, indicating that the system is voltage unstable.

2.1.1 Identification of the Weak Buses.

The magnitude of λ_i indicates a relative degree of instability of the i^{th} modal voltage. The smaller the magnitude of a positive λ_i, the closer the i^{th} modal voltage is to being unstable.The minimum Eigen values, which become close to instability, need to be observed more closely. The appropriate determination as to which node or load bus participates in the selected modes becomes very important. This necessitates a tool, called the participation factor, for identifying the weakest nodes or load buses that are making significant contribution to the selected modes.

If Φ_i and Γ_i represent the right and left eigenvectors respectively, for the Eigen value λ_i of the matrix J_R, then the participation factor measuring the participation of the k^{th} bus in i^{th} mode is defined as:

$$P_{ki} = \Phi_{ki}\Gamma_{ik} \qquad (11)$$

Participation factors determine the most critical areas which lead the system to instability. Higher the magnitude of the participation factors of a bus in a specific mode, the better the remedial action on that bus in stabilizing the mode.

3 THE PROPOSED ALGORITHM

3.1 Placement Process (Optimal Location)

The DG placement problem can be formulated by many objective functions, including loss minimization, voltage profile improvement, economical revenue, environmental impact reduction, improvement on reliability aspects, etc. [10],[15],[16]. In this section, the problem is formulated and solved by using modal analysis with an objective of loss reduction and voltage profile improvement[14], while the results are compared with the results of the proposed method in [5, Sec. VII]. The Modal analysis can be used to identify the voltage instability characteristics hence used to determine the critical modes and their associated buses. According to the proposed algorithm, the modal analysis is executed and some critical modes and their participating buses are determined. The bus which has the biggest participation factor in each mode is selected as candidates for DG placement. Then, a DG of optimal size is installed at one of the candidates to determine minimum losses and voltage improvement. This procedure is repeated for all the candidates. The bus which has minimum loss and minimum VDI is selected as the best bus for DG placement. If more DGs are allowed to be installed, the procedure will be repeated, taking into account the already installed DG/DGs.

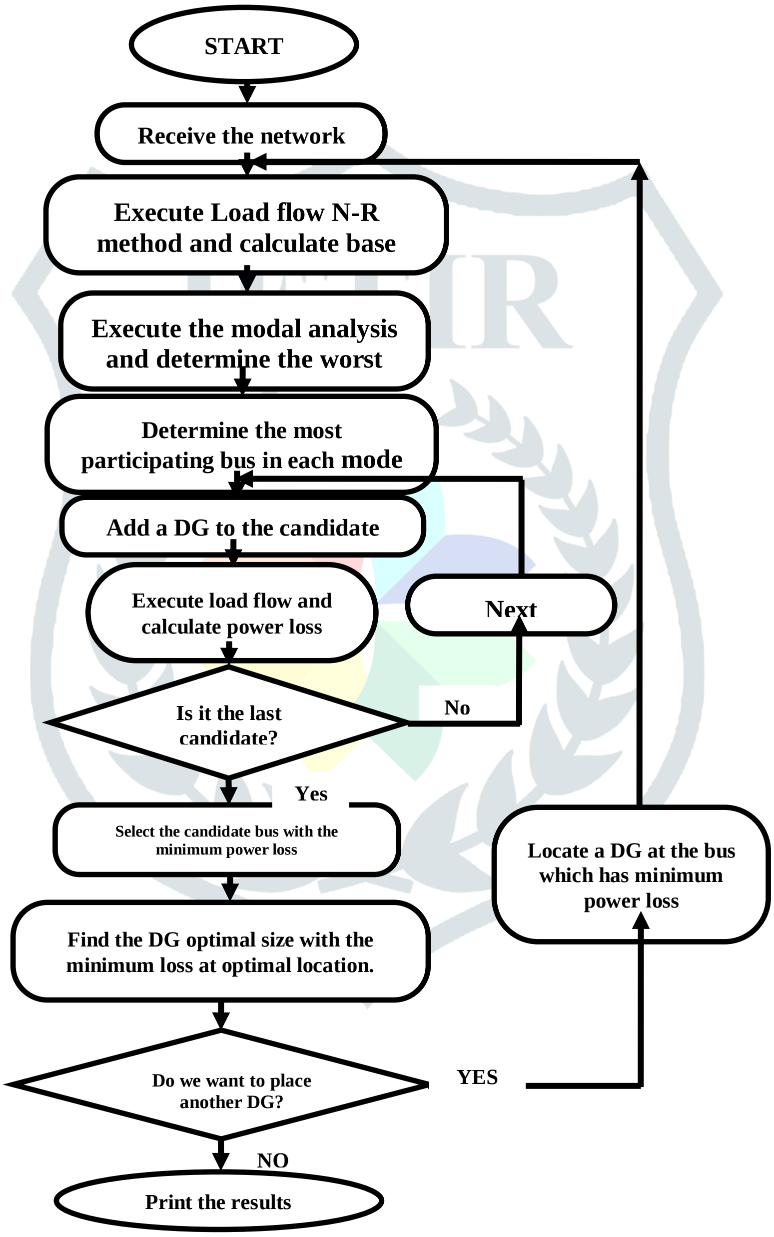

Fig. 1: Flow chart of optimal placement and sizing algorithm.

3.2 Optimal Size.

1. Placing DG at the candidate buses and select appropriate bus for DG placement.
2. Keeping the power factor of DG constant, its size is varied from a minimum value to a value equal to feeder loading capacity in constant steps until the minimum system losses is found.
3. The DG size which results in minimum losses and minimum VDI is taken as optimal.

4 EFFECTS OF ALLOCATION OF DG UNITS ON PLR AND VOLTAGE

4.1 Power Losses.

$$APLR = \frac{P_{loss}-P_{loss}^{DG}}{P_{loss}} * 100\ \% \qquad (12)$$

$$RPLR = \frac{Q_{loss}-Q_{loss}^{DG}}{Q_{loss}} * 100\% \qquad (13)$$

APLR and RPLR show active and reactive power loss reduction after installing DG/DGs [5]. Higher value of APLR and RPLR indicate better performance of DGs in loss reduction.

4.2 Voltage Deviation Index.

$$VDI = \sum_{i=1}^{n}(1 - V_{i,DG})^2 \qquad (14)$$

The Voltage Deviation Index (VDI) is a good indicator of the determination of deviation from bus voltage targets. Lower the VDI better is the performance of DG units.

5 SIMULATION RESULTS AND DISCUSSION

Simulation studies are carried out on33-bus radial distribution network of Fig. 2. The system total apparent load is 4.3694 MVA. Modal analysis is used to identify the voltage instability characteristics by finding the critical modes and their associated buses. Modal analysis determines Buses 18, 33, 22, and 25 as critical buses as shown in Table 2. Table 4 shows bus 33 as the best candidate for DG placement due to lower losses.

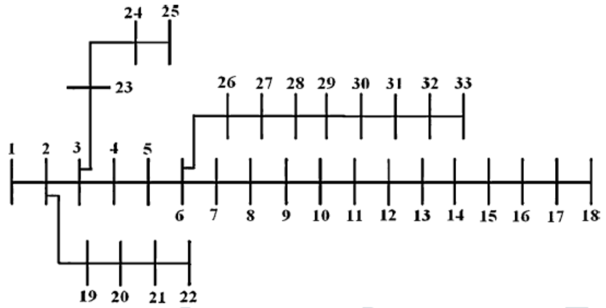

Fig. 2: Single-line diagram of the 33-bus radial distribution network.

5.1 Result of Base Case System

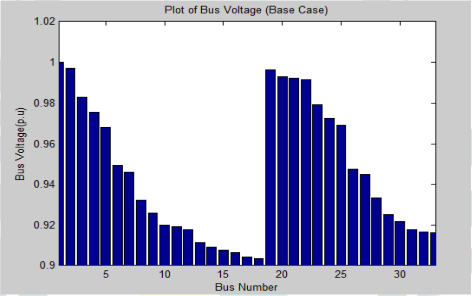

Fig. 3: Plot of Bus Voltage v/s Buses for Base Case

Bus no	Bus Voltage (p.u)	Bus no	Bus Voltage (p.u)	Bus no	Bus Voltage (p.u)
1	1	12	0.9177	23	0.9793
2	0.997	13	0.9115	24	0.9726
3	0.9829	14	0.9092	25	0.9693
4	0.9754	15	0.9078	26	0.9475
5	0.9679	16	0.9064	27	0.9449
6	0.9494	17	0.9043	28	0.9335
7	0.9459	18	0.9037	29	0.9253
8	0.9323	19	0.9965	30	0.9217
9	0.9259	20	0.9929	31	0.9175
10	0.9201	21	0.9922	32	0.9166
11	0.9192	22	0.9916	33	0.9163

Table 1: Bus Voltage of Base Case System

The proposed method is first applied for single DG placement and then it is extended for multiple DG placements.

	Min. Eigenvalues	Base case critical buses
λ_1	0.0215	18
λ_2	0.0698	33
λ_3	0.2255	18
λ_4	0.2743	22
λ_5	0.417	25
λ_6	0.5596	25

Table 2: Critical buses.

5.2 Single DG Placement.

The modal analysis method is applied to the 33-bus radial distribution network. There are 33 buses among which one is slack bus, the total number of Eigen values of the reduced Jacobian matrix J_R is expected to be 32. Note that all the Eigen values are positive which means that the system voltage is stable. Then, the minimum Eigen values of the reduced Jacobian matrix is selected as critical modes. After that, the weakest load buses are identified by computing the participating factors. The results are shown in Fig 4.

For the case of placement of single DG, optimal location of DG for IEEE 33-bus radial distribution system is found to be bus no. 33. As mentioned in Table 3. Optimal size of DG for the same case is 1486 kW and 920 kVAR. From Table 4 it is evident that real power loss of the system is reduced from 211 kW to 93.6157 kW, which amounts for 55.633% reduction in real power loss of system which is exceptional. Most importantly there is improvement in voltage profile of the system which is desirable from the operational point of consumer equipments. Improvement of voltage profile of the system is shown in figure 5.

Optimal Location (Bus No.)	Optimal DG Size	
	kW	kVAR
33	1486	920

Table 3: Location and Size of DG for the case of Single DG Placement

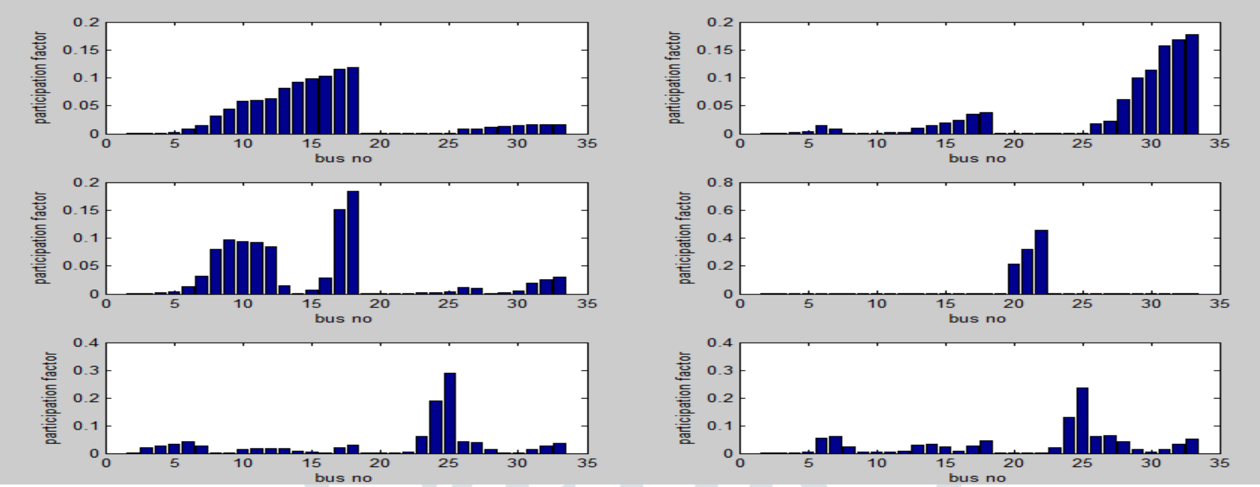

Fig.4: The 33-bus radial networks participation factors for 6 different modes

No. Of Iteration	Candidate Buses by Modal Analysis	P loss kW	Q loss kVAR	Active Power Loss Reduction APLR (%)	Reactive Power Loss Reduction RPLR (%)	Voltage Deviation Index VI	Selected bus for DG placement
Base case	--	211.0036	143.1299	--	--	0.1168	--
1st Iteration	18	125.2685	86.7275	40.632	39.41	0.0403	**33**
	33	93.6157	77.7490	**55.633**	**45.68**	**0.0376**	
	22	208.3767	141.8462	1.245	0.8968	0.1326	
	25	169.9980	120.8265	19.434	15.5826	0.1125	

Table 4: Summary of the placement Algorithm results for one iteration.

No. Of Iteration	Candidate Buses by Modal Analysis	P loss kW	Q loss kVAR	Active Power Loss Reduction APLR (%)	Reactive Power Loss Reduction RPLR (%)	Voltage Deviation Index VI	Selected bus for DG placement
Base case	--	211.0036	143.1299	--	--	0.1168	**--**
1st Iteration	18	125.2685	86.7275	40.632	39.41	0.0403	**33**
	33	93.6157	77.7490	**55.633**	**45.68**	**0.0376**	
	22	208.3767	141.8462	1.245	0.8968	0.1326	
	25	169.9980	120.8265	19.434	15.5826	0.1125	
2nd Iteration	18	76.8193	61.1546	**63.593**	**57.273**	**0.0138**	**18**
	22	102.0146	81.4930	51.653	43.0636	0.0428	
	29	115.1653	90.9862	45.42	36.431	0.0381	
	25	85.5005	71.2245	59.479	50.2378	0.0378	

Table 5: Summary of the placement Algorithm results for two iterations.

5.3 Multiple DG Placements.

Previous section discussed placement of single DG into distribution system, in fact any number of DG's can be integrated into the system and here the task is taken up by inserting 2 DG's into the system. After the placement of first DG the same procedure is repeated with second DG but the system will have first DG with its optimal size at optimal location. Here DG 1 is placed at location 33 having size 1486 kW & 920 kVAR and same procedure is repeated for second DG. After obtaining results for second DG both DG's are placed at their optimal location and procedure will repeat for third DG and it continues so on for remaining DG's. Results are shown in Table 5 & 6. Loss has come down from 211 kW to 76.8193kW at the end of insertion of second DG. Voltage profile improvement is shown in Figure 6.

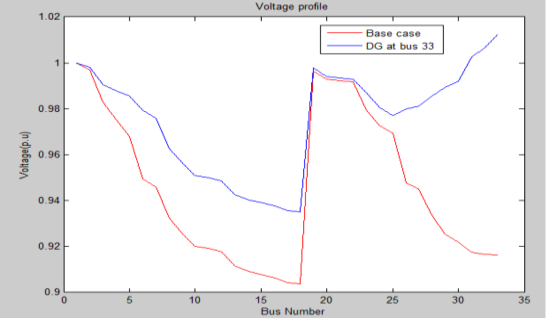

Fig 5: Plot of System Voltage Profile with DG at 33

DG No.	Location	DG Size	
		kW	kVAR
1st DG	33	1486	920
2nd DG	18	371.5	230

Table 6: Location and Size of DG for two DG Placement

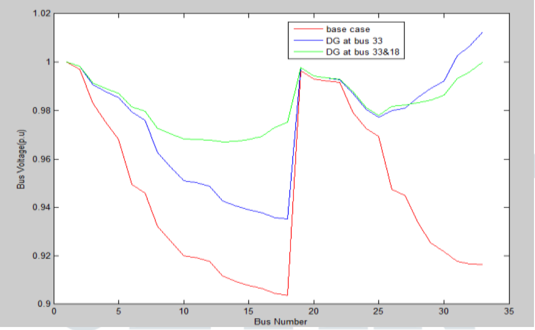

Fig 6: Plot of System Voltage Profile with DG's

6 CONCLUSION

This paper presents a method for optimally allocating distributed generation for reduction of losses and improvement in voltage regulation at buses.Modal analysis is used for determining DG placement candidate buses, while loss reduction and system voltage profile improvement is the comparison index for selecting the best DG places. The present methodology has been tested on 33-bus radial distribution test system and result shows that there is considerable amount of reduction in system power losses and good improvement in system voltage profile.

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