Optimal Distributed Generation Sizing in Radial Distribution Systems for Stable Voltage and Loss Reduction

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Abstract— Distributed generation (DG) becomes more well-known in the power sector because of its capacity in power loss reduction, low investment cost, increase reliability, and most significant to exploit renewable-energy resources. In this study, a multi-objective index-based approach for optimally determining the size of multi-DG units in distribution systems, including the voltage rise phenomenon is proposed. An analytical method for sizing of distributed generation on power distribution systems for loss reduction is introduced. The analytical method is developed based on a new formulation for the power flow problem, which is non-iterative, direct, and involves no convergence issues even for systems with high R/X branch ratios. Additional, this power flow solution is tremendously useful whenever fast and repetitive power flow estimations are required. Distributed generators (DGs) deals with practical solutions are to reduce total system loss. The proposed method has been tested on 30-bus and compare with genetic algorithm 30-bus distribution systems, which are widely used as examples in solving the placement and sizing problem of DGs. The test results show that the proposed analytical method can lead to optimal or near-optimal solution, while requiring lower computational effort.

Key words: Distributed Generation (DG), Optimization Algorithm, Power Losses Reduction

I. Introduction

Distribution systems have been operated in a vertical and centralized way for many years for best control and coordination of their shielding devices. Distribution systems are characterized by high R/X branch ratios with radial or weakly-meshed topological structure. In fact, the radial topological structure makes distribution system as widest part in the entire power system. The poor voltage regulation and the high line resistance both play a significant role in increasing total power losses of distribution systems. Minimization of power losses of distribution systems is constantly achieved by feeder reconfiguration techniques. However, distributed generators (DGs) [1] have been recently proposed to minimize distribution system power losses. The possible benefits of DG installation on distribution networks comprise total system losses reduction, voltage profile enhancement, peak load shaving and reliability enhancement[2].Given such advantages, DG can play vital role in reducing losses and improving voltage profile of distribution systems, if they are correctly located, sized and their diffusion level is also identified. The problem of allocating and sizing of DG is essentially a non-linear complex mathematical optimization problem. Several solutions, with various scenarios, are constantly required while handling the allocation and sizing problem. A great variety of solution techniques are proposed in the literature to handle the problem of placement and sizing of DG on distribution systems. These solution techniques can be largely classified as population-based optimization methods or heuristic and analytical-based techniques. A methodology for optimal allocation of DG in distribution networks based on analytical approach (sensitivity analysis based on equivalent current injection) for loss reduction has been suggested by Gozel and Hocaoglu [3] .Wang and Nehir [4] proposed an analytical method based on pharos current injection method to optimally place DG assuming uniformly, increasingly and centrally distributed load pattern with in radial distribution network to minimize power loss. These assumptions may cause mistaken results. In [5-7] analytical approach based on exact loss formula for optimally allocating DGs was presented. This is followed by the work of Khan and Chaudhary [8] who presented an analytic-based algorithm to site and size DG in distribution network for reducing the power loss and improving the voltage profile. An approach based on exact loss formula and GA for power loss minimisation of distribution feeder was proposed by Shukla et al [9].The loss sensitivity method is used to classify the strategic candidate locations for DG. A technique based on loss sensitivity method for sizing and siting of DG optimally to minimise the power losses in the distribution system was proposed by Kashem et al [10].Most of the above methodologies considered the DG type, which is able of supplying real power only to the network. However, there are other types of DG which can supply real and/or reactive power into the network and progress the performance to still better extent. Further, the majority of the general analytical approaches for DG siting and sizing are based on exact loss formula and require the determination of the bus impedance matrix (Z_{bus})or Jacobian matrix which are computationally challenging. Therefore, because of the size, the complexity and the specific characteristics of the distribution network, the above methods are not suitable. Therefore, the optimal allocation of DG of any type using appropriate solution technique needs further consideration. In this paper, a methodology based on analytical approach is presented for optimal sizing and siting of DG in distribution system so as to minimize real as well as reactive power losses. This paper is the extension of that proposed in [11]. The developed analytical method is based on modify in active and reactive components of branch currents cause by the DG placement. The proposed method has been tested on 30-bus test radial distribution systems and the results are found to support the suitability and benefits of proper DG allocation in power distribution system for network performance improvement. This paper is organized as follows: Section 2 discusses the problem formulation of proposed method, Section 3 presents the solution algorithm and Section 4 presents the results and discussion of the proposed work. Finally, in Section 5, conclusions are summarized.

II. PROBLEM FORMULATION

In this section, the mathematical formulation of the proposed analytical approach is presented. The proposed analytical approach aims to determine the optimal size of DG in a given radial distribution network so as to minimize both real power loss and voltage drop. The proposed approach begins with the following assumptions:

1) The radial distribution network under consideration is balanced.
2) The power factor of DG is known. Consider a typical N-bus radial distribution system as shown in Fig. 1. In this figure, I_k is the phasor current in branch k while I_{LK} is the load phasor current of load linked at node k. When a DG is placed at a bus (say bus k) as shown in Fig. 2, it injects current I_{DG} into the network and there by alters the currents in all the branches connected between sub-station (bus 1) to bus k. However, the currents in the remaining

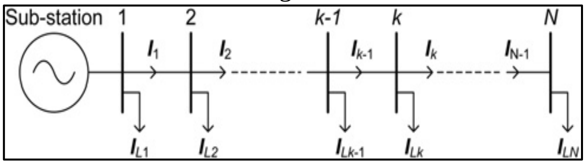

Fig. 1: Typical N-bus radial distribution system

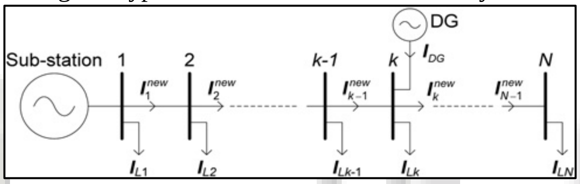

Fig. 2: Typical N-bus radial distribution system with DG placed at bus k

branches are unaltered by the DG placed at bus k. The injected current by DG placed at bus k can be written as

$$I_{DG} = I_{aDG} + jI_{rDG} = I_{aDG}(1 + j\tan\emptyset) \quad (1)$$

Where I_{aDG} and I_{rDG} are the real and reactive components, respectively, of I_{DG} and $\emptyset$ is the phase angle of I_{DG}. Now, the modified current in branch i because of DG placed at bus k can be given as

$$I_i^{new} = I_i - D_i I_{DG} = (I_{ai} - D_i I_{aDG}) + j(I_{ri} - D_i I_{aDG}\tan\emptyset) \quad (2)$$

Where I_i is the phasor current in branch I before DG placement and I_i^{new} is the modified phasor current in branch i after DG placement. The value of D_i is given by the following relation

$$D_i = \begin{cases} 1, & if\ branch\ i\ between\ bus\ 1\ and\ bus\ k \\ 0, & otherwise \end{cases}$$

Extending the above concept for placement of m DGs simultaneously in an N-bus radial distribution network, the modified current through branch I can be given as

$$I_i^{new} = I_i - \sum_{k=1}^{m} D_{ik} I_{DG}^{k} = \left(I_{ai} - \sum_{k=1}^{m} D_{ik} I_{aDG}^{k}\right) + j\left(I_{ri} - \sum_{k=1}^{m} D_{IK}\, I_{aDG}^{k} \tan\emptyset^{K}\right) \quad (3)$$

Where $I_{new}i$ is the modified phasor current in branchi; I_k DG is the phasor current injected current by kth DG;$I_{aDG}^{k}$and $\emptyset^k$ are the active component and phase angle, respectively, of I_k DG and the value of $D_{ik}$is given by the following relation

$$D_{ik} = \begin{cases} 1, & \text{if branch i is between bus 1 and bus at which kth DG placed} \\ 0, & \text{otherwise} \end{cases}$$

A. Exact Loss Formula

The total real power loss in power systems is represented by (4), popularly known as "exact loss formula" [12]

$$P_L = \sum_{i=1}^{N}\sum_{j=1}^{N}\left[\alpha_{ij}\left(P_iP_j + Q_iQ_j\right) + \beta_{ij}\left(Q_iP_j - P_iQ_j\right)\right] \quad (4)$$

Where

$$\alpha_{ij} = \frac{r_{ij}}{V_iV_j}\cos\left(\delta_i - \delta_j\right),$$

$$\beta_{ij} = \frac{r_{ij}}{V_iV_j}\sin\left(\delta_i - \delta_j\right);$$

$V_i\angle\delta_i$ The complex voltage at the bus ith; $r_{ij} + jx_{ij} = Z_{ij}$ the ijth element of $[Z_{bus}]$impedance matrix; $P_i$and P_j the active power injections at the it hand jth buses, respectively; Q_i and Q_j the reactive power injections at the ith and jth buses, respectively; N the number of buses.

B. Real Power Loss Saving

The total active power loss [13], that is, P_L in a typical N-bus radial distribution system as shown in Fig. 1, can be given as

$$P_L = \sum_{i=1}^{N-1} I_i^2 R_i = \sum_{i=1}^{N-1}(I_{ai}^2 + I_{ri}^2)R_i \quad (5)$$

Where I_i is the current through branch i with I_{ai} and I_{ri} being its real and imaginary components, respectively, and R_i is the resistance of the branch. Now, using (3), the total real power loss after placement of m DGs is given by

$$P_L^{new} = \sum_{i=1}^{N=1}(I_i^{new})^2 R_i = \sum_{i=1}^{N=1}\left[\left(I_{ai} - \sum_{k=1}^{m} D_{ik}I_{aDG}^{k}\right)^2 + \left(I_{ri} - \sum_{k=1}^{m} D_{ik}I_{aDG}^{k}\tan\emptyset^{K}\right)^2\right]R_i \quad (6)$$

Using (4) and (5), the normalised loss saving P_S associated with multiple DG placement can be given as (see (6)).

C. Reactive Power Loss Saving

The total reactive power loss, that is, $Q_L$in a typical N-bus radial distribution system as shown in Fig. 1, can be given as

$$Q_L = \sum_{i=1}^{N-1} I_i^2 X_i = \sum_{i=1}^{N-1}(I_{ai}^2 + I_{ri}^2)X_i \quad (7)$$

Now, using (3), the total reactive power loss after placement of m DGs is given by

$$Q_L^{new} = \sum_{i=1}^{N=1}(I_i^{new})^2 X_i = \sum_{i=1}^{N=1}\left[\left(I_{ai} - \sum_{k=1}^{m} D_{ik}I_{aDG}^{k}\right)^2 + \left(I_{ri} - \sum_{k=1}^{m} D_{ik}I_{aDG}^{k}\tan\emptyset^{k}\right)^2\right]X_i \quad (8)$$

Using (7) and (8) are the normalised reactive power loss saving Q_S associated with multiple DG placement.

D. Objective Function and Constraints

The objective function of the problem aims at minimising the real power loss and getting better the voltage outline at all system buses. Mathematically, the problem can be posed as

$$Total\ loss = \left(\sum_{k=1}^{N_b}|I_k^2| \times R_k\right) \quad (9)$$

Subject to

1) *Real and reactive power injections*

$$B'\delta - GV + P_G = P_D$$
$$G'\delta - BV + Q_G = Q_D \quad (10)$$

2) *Voltage limits constraints*

$$\left|V_k^{min}\right| \le |V_k| \le \left|V_k^{max}\right| \quad (11)$$

3) Feeder capacity constraints

$$|I_F| \leq |I_F^{max}| \qquad |I_R| \leq |I_R^{max}| \qquad (12)$$

4) DG real and reactive power constraints

$$P_{DG}^{min} \leq P_{DG} \leq P_{DG}^{max}$$

$$Q_{DG}^{min} \leq Q_{DG} \leq Q_{DG}^{max} \qquad (13)$$

Where N_b is number of buses, I_k is the current flowing out of branch k, R_k is the resistance of branch k. Further, B′, B, G′ and G are as developed in Section 2.4 with dimensions ($N_b \times N_b$), δ represents the bus voltage angles ($N_b \times 1$), V_{max} and V_{min} represent the maximum and minimum permissible voltages ($N_b \times 1$), PG and QG represent the real and reactive power generation of the substation ($N_b \times 1$),PD and QD represent the real and reactive power loads ($N_b \times 1$), P_{min}DG and Q_{min}DG represent the available real and reactive power capacities of the DGs ($N_b \times 1$), Imax F and Imax R represent the forward and reverse flow capacities of distribution lines ($N_f \times 1$), with N_f being the number of distribution feeders.

In the above formulation represents the sum of the power at any arbitrary bus, which is simply the power balance equation for real and reactive power. The formulation of this constraint is given below.

III. Solution Algorithms

The developed formulation as discussed in the previous section can be used to resolve the optimal sizes and locations of DGs in a given radial distribution network. For placement of m DGs in an N-bus radial distribution system, there are C_m^N possible combinations of different buses. If m≪N, the number of combinations becomes very high and thus it is computationally monotonous to analysis all the combinations. Hence, the computational procedure of proposed algorithm can be divided into the following two broad steps:

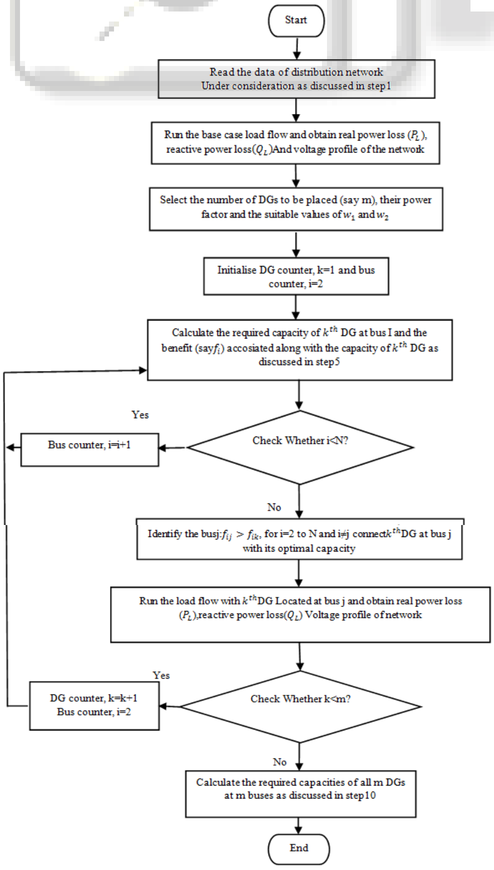

Fig. 3: Flowchart for the proposed algorithm for the optimal sizing and siting of DGs

– Firstly, a sequence of m buses suitable for DG connection is identified. For this, first the optimal size of a DG (say kth DG) is calculated at a bus using the following equation which is obtained from (18) by substituting m = 1

$$I_{aDG}^{k} = \frac{\sum_{i=1}^{N-1} D_i (I_{ai} + I_{ri} \tan \emptyset^k) \left(w_1 \left(\frac{R_i}{P_L} \right) + w_2 \left(\frac{X_i}{Q_L} \right) \right)}{\sum_{i=1}^{N=1} (D_i \sec \emptyset^k)^2 \left(w_1 \left(\frac{R_i}{P_L} \right) + w_2 \left(\frac{X_i}{Q_L} \right) \right)} \qquad (14)$$

At the same time, the advantage associated kth DG is also computed using (8) and this procedure is repetitive for all other buses. The bus which gives the highest benefit is selected as the candidate bus and kth DG is connected with this bus. Then the above procedure is repeated to recognize next and subsequent candidate buses.

– The optimal sizes of all the DGs at m buses, identified during previous step, are then determined simultaneously by using above equation.

Various steps involved in the proposed method are as follows:

1) Read the data concerning number of buses (N), configuration/connectivity, resistances and reactances of different branches, real and reactive power demand at different buses of distribution network under consideration.
2) Run the base case load flow using backward and forward sweep method [14] and obtain real power loss(P_L), reactive power loss (Q_L)and voltage profile of the network.
3) Select the number of DGs to be placed (say m) and their power factors (DGs may have different power factors). Also, select the suitable values of the weights w_1 and $w_2$considering (11).
4) Initialise DG counter, k = 1 and bus counter, i = 2.
5) Calculate the required capacity of kth DG at bus I using equation and then compute and store the benefit (sayf_{ik}) associated using (10) along with the capacity of kth DG.
6) Check whether i < N, if yes, increment bus counter, i = i + 1 and go to step 5, otherwise go to next step.
7) Identify the bus (say bus j) that provides the highest benefit (f_{jk} > f_{ik}, for i = 2 to N and i ≠ j) for kth DG.Connect kth DG at bus j with the capacity as calculated from step 5.
8) Run the load flow with kth DG located at bus j and obtains real power loss(P_L), total reactive power loss (Q_L)and voltage profile of the network.
9) Check Whether k < m, if yes, increment DG counter, k = k + 1, initialise bus counter, i = 2 and go to step 5, otherwise go to next step.
10) At this step, a sequence of m buses is known, which are suitable for DG connection. Now, calculate the required capacities of all m DGs at m buses using equation. A flowchart for the proposed algorithm to determine the optimal sizes and locations of DGs in a given radial distribution network is given in Fig. 3.

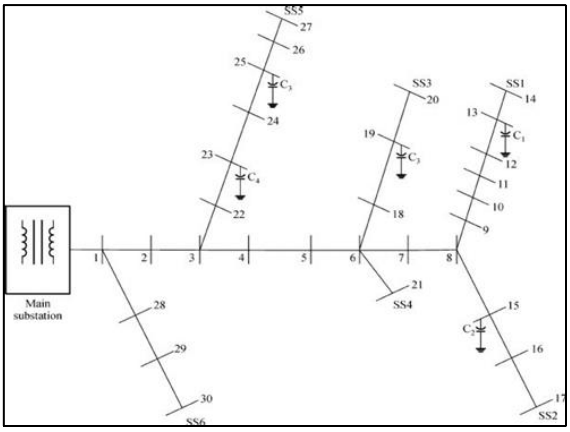

Fig. 4: Single line diagram of 12.66 kV, 30-bus radial distribution System

IV. RESULTS AND DISCUSSION

The developed algorithm has been implemented under MATLAB environment and applied on two test systems to determine the optimal sizing and sitting of DGs. For each test system, different values of w_1 and w_2 have been considered as (a) $w_1 = 1$; and $w_2 = 0$; (b) $w_1 = 0.5$; and $w_2 = 0.5$; and (c) $w_1 = 0$ and $w_2 = 1$

Apart from this, two different values of DG power factors have also been considered as: (a) all DGs are operating at unity power factor; and (b) all DGs are operating at a power factor equal to the power factor of total load of the system [15].The following test systems have been measured for the optimal placement and sizing of DGs by the developed algorithm.

The proposed method is tested on three different test systems with different sizes, to show that it can be implemented in distribution systems of various configurations and sizes. The parameters of the first test system are given in Appendix. The second test system is 30-bus system [16], the total real power and reactive power loads on this system are 3.72 MW and 2.3 Mvar. The initial real and reactive power losses in the system are 0.211 MW and 0.143 Mvar. The third system is a Genetic algorithm 30-bus system [17], the total real power and reactive power loads on this system are 3.80 MW and 2.69 Mvar. The initial real and reactive power losses in the system are 0.225 MW and 0.102 Mvar. Based on the method described previously, the optimal sizes of DG are calculated at all buses for the two test systems. Fig. 5, and Fig. 6 show the optimal sizes of DG unit at all buses for 30 and Genetic algorithm 30 bus distribution test systems, respectively. With the help of FIS editor optimal location of DG unit is found where real power loss is more and voltage is low. The optimal locations of DG unit are bus 5,6 and bus 7 for 30 and Genetic algorithm 30 bus distribution test systems where total power losses attain the minimum value.

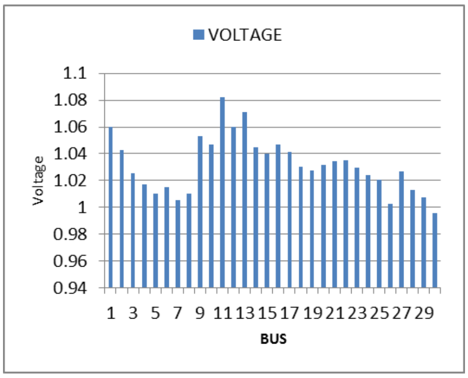

Fig. 5: Voltage profile for PSO 30-bus radial distribution System

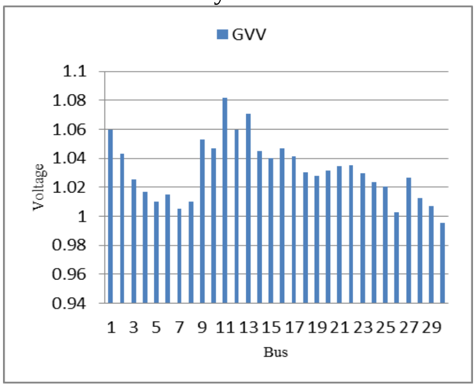

Fig. 6: Voltage profile for Genetic algorithm 30-bus radial distribution System

The Total losses for the corresponding optimal DG unit sizes are shown in Fig. 7 and Fig. 8 shows Elapsed time.

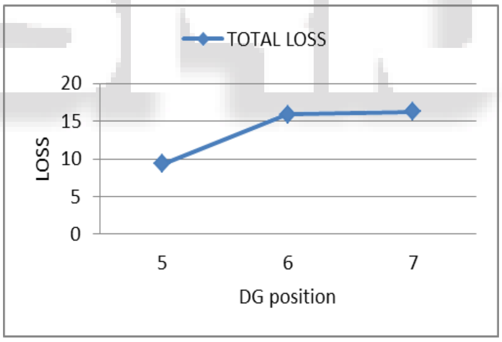

Fig. 7: Total Loss of DG of 30 bus system at 5, 6, 7 position

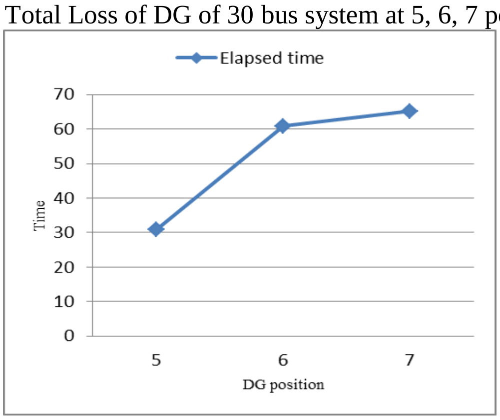

Fig. 8: Elapsed time 30 bus system at 5, 6, 7 position

Results obtained are tabulated in Table 1. For three different test systems, the results of proposed method, total power losses, max and min voltage and Elapsed time, are tabulated. It is seen that the total power losses are significantly reduced for all test systems.

System Type	30 BUS			Genetic algorithm 30 BUS system
	With 5 DG	With 6 DG	With 7 DG	
Maximum Voltage	1.0820	1.0820	1.0820	1.0820
Minimum voltage	0.9957	1.0053	1.0036	0.9957
Total loss	9.3755	15.9384	16.2409	9.3851
Elapsed time in Second	30.860467	60.932063	65.139822	109.946283

Table 1: Results of proposed method for test systems and Genetic algorithm

V. CONCLUSIONS

The size of DG unit is decisive factors in the planning and operation of active distribution networks. This study presents a new methodology which can be used to determine the optimal size and of DG. This method is easy to be implemented and faster for the given accuracy. It is proved that the proposed method can save huge amount of power and achieve significant improvement in voltage stability. Installation of DG unit at one location at a time is proved to be a valid assumption in the present study. However, this paper does not consider the other benefits of DG as well as economics of it.

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