Allocation and Size Evaluation of Distributed Generation

Partha Kayal and C. K. Chanda

Abstract Recently technological innovation, environmental concerns and market liberalization help to penetrate Distributed Generation (DG) of significant number and capacity into power distribution system. This paper represents technique to minimize power losses in a distribution feeder by optimizing DG model in terms of size and location. A novel Voltage Stability Indicator (VSI) is proposed that can identify critical buses in distribution system. Based on VSI, the suitable location of distributed generator is identified. Desired size of DG is evaluated by simulating ANN model with proper training. The proposed methodology is tested by checking through 15 bus radial distribution and 52 bus practical distribution systems. There are considerable improvements of voltage profiles of the buses after appropriate allocation of DG. Appreciable reductions of distribution power losses for both the systems are also obtained.

Keywords Voltage stability indicator · ANN model · Priority list · DG size

1 Introduction

Worldwide there is growing interest in Distributed Generation (DG) for supplying electrical power to consumers. Integration of DG can have an impact on the practices used in distribution systems, such as the voltage profile, power flow, power quality, stability, reliability, and protection. In addition, with the small scale

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capacity, time of DG installment and some uncertainties in economic planning and construction are reduced. Therefore, the DG projects contain less risk compared with central power plant ones. Most of the radial distribution systems suffer with voltage stability [1, 2] problems at feeders. DG can provide voltage support to boost up the low voltage at the end of feeder. Additionally, DG also promotes greater competition in electricity supply market, because of its short payback period in comparison with transmission and central generation station projects, and its supply power directly to the local distribution network and the local utility. But, unplanned uses of DG while solving some problems may cause additional problem. Therefore some tools or techniques [3–6] are needed to be examined for allocation and sizing of DG.

Recent researches focus on selection of best places for installation and preferable size of DG units in large distribution system. Kashem and Ledwich [7] have discussed about optimal use of voltage support distributed generation to support voltage in distribution feeders. They have applied sensitivity analysis to determine appropriate size of DG. Analytical approaches to choose optimal location for DG in radial network with an objective of loss minimization have been presented by Caisheng and Nehrir [8]. Rafidah and Rahim [9] have discussed about methodology to evaluate DG size and its impact on power losses and voltage profile in distribution system. Acharya et al. [10] have derived an expression to calculate appropriate size and location for DG placement to minimize distribution losses. A G.A based optimal sizing and placement of DG considering the system energy loss minimization in different loading condition have been presented by Singh et al. [5]. However, this method needs extensive calculations. A method for placement of DG units using continuation power flow analysis has been proposed by Hedayati et al. [11]. Devi and Subramanyam [12] have discussed about optimal DG unit placement using fuzzy logic. Ganesan and Subramanyam [6] have optimized cost, emission and reliability of DG using Hopfield Neural Networks (HNN), Particle Swarm Optimization (PSO) and HNN-PSO techniques. These methods take longer time for calculation. Roy and Mandal [13] have studied optimal reactive power dispatch using Quasi Oppositional Biogeography Based Optimization (QOBBO) technique. The methodology determines control variable settings such as generator terminal voltages, tap positions of the regulating transformer and the VAR injection of the shunts compensator, for real power loss minimization in the transmission system.

In this paper, optimal allocation of DG based on determination of most sensitive buses to the voltage collapse in distribution network is analyzed. A Voltage Stability Indicator (VSI) is developed from conventional power flow equation to determine stability condition of buses. Artificial Neural Network (ANN) technique is used to determine the proper capacity of DG to ensure the static voltage of each node within permissible limit. Proposed method is tested on 15 bus and 52 bus radial distribution systems. Through simulation, the impact of DG on static voltage profile is illustrated. The influence of DG on voltage stability and system power losses are also quantified here.

2 Location Selection for DG

In developing countries most of the distribution systems are operated with radial structure. Larger voltage drop in these types of systems are obvious. By analyzing voltage sensitivity of lines, weakness of network voltage may be identified and opportunities for improvement with real or reactive power compensation via DG can be examined.

2.1 Voltage Stability Indicator

Power network are becoming heavily stressed to meet ever increasing load demand. This situation has resulted into deterioration of voltage magnitudes at buses. One of the major problems that may associate with such a stressed system is voltage collapse. From the necessity of accurate analysis of voltage stability a number of analytical and computational tools have been discussed [1, 2, 7]. In this section a simple VSI is formulated for radial distribution system to get a estimation of the distance to voltage collapse. The indicator uses the bus voltage and network information provided by load flow program.

Any branch $r_i + jx_i$ connected between bus:i and bus:i + 1 of the radial distribution system may be represented by an equivalent circuit model as in Fig. 1.

$$I^2 = (P_{i+1}^2 + Q_{i+1}^2)/V_{i+1}^2 \tag{1}$$

Again

$$I^2 = \frac{P_L^2 + Q_L^2}{(V_i - V_{i+1})^2} \tag{2}$$

Here P_L and Q_L are the active and reactive power loss of the line connected between two nodes.

So, from Eqs. (1) and (2) equating I^2 it becomes,

$$\frac{P_{i+1}^2 + Q_{i+1}^2}{V_{i+1}^2} = \frac{P_L^2 + Q_L^2}{(V_i - V_{i+1})^2} \tag{3}$$

Now

$$P_{i+1} = P_i - P_L \tag{4}$$

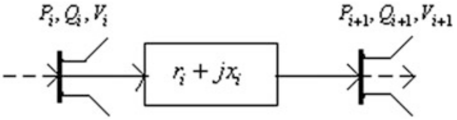


Fig. 1 Two bus power system network

$$Q_{i+1} = Q_i - Q_L \tag{5}$$

$$P_L = r_i\left(\frac{P_{i+1}^2 + Q_{i+1}^2}{V_{i+1}^2}\right) \tag{6}$$

$$Q_L = x_i\left(\frac{P_{i+1}^2 + Q_{i+1}^2}{V_{i+1}^2}\right) \tag{7}$$

As the value of P_L and Q_L from Eqs. (6) and (7) have used in Eq. (3)

$$\left(V_i \cdot V_{i+1} - V_{i+1}^2\right)^2 = \left(P_{i+1}^2 + Q_{i+1}^2\right).\left(r_i^2 + x_i^2\right) \tag{8}$$

Since the positive root of the Eq. (8) is taken,

$$V_{i+1}^2 - V_{i+1}.V_i + \sqrt{\left(\left(P_{i+1}^2 + Q_{i+1}^2\right).\left(r_i^2 + x_i^2\right)\right)} = 0 \tag{9}$$

The roots of the Eq. (9) are real if

$$V_i^2 - 4 \cdot \sqrt{\left(\left(P_{i+1}^2 + Q_{i+1}^2\right).\left(r_i^2 + x_i^2\right)\right)} \geq 0 \tag{10}$$

From Eq. (10) the developed Voltage Stability Index (VSI) is given as

$$L_{i+1} = \frac{4 \cdot \sqrt{\left(\left(P_{i+1}^2 + Q_{i+1}^2\right).\left(r_i^2 + x_i^2\right)\right)}}{V_i^2} \leq 1 \tag{11}$$

In practice, distribution system operators are always try to maintain the system within a given voltage stability margin; so that small contingencies do not make the system unstable. Therefore, L_{i+1} must be less than threshold value for maintaining stability at that bus. The more the value of the indicator nearer to zero the system is more stable.

2.2 Priority List

Voltage stability level of each bus is calculated using the proposed VSI. The buses are ranked in descending order according to their values of VSI to form a priority list. The top ranked bus has chosen first for allocation of DG. Subsequently lower ranked buses are fed with power from DG units. How many number of DG units would be installed depend on sizing issues of DG units. After installation of each DG unit, load flow solution is performed to monitor voltage magnitude of buses, network power losses and voltage stability condition of the system.

3 Sizing of DG

DG is small scale power generation ranging from multi-kW to few MW and usually connected to distribution system. The impact of DG on distribution system may be positive or negative depending upon the size and operating condition of DG. The size at most should be such that it is consumable within the distribution substation boundary. Further increase of size can cause reverse flow of power through substation which will lead to high system losses.

3.1 ANN Model

For a particular bus as the size of DG is increased beyond optimal DG size network losses starts increasing rather than decreasing. So, appropriate size evaluation of DG has become very significant. The use of ANN can capable to indicate the best solution for a given distribution system. This is because of the advantage of high computation rate provided by three layered feed forward ANN in approximating a complex nonlinear mapping. A feed forward ANN works on the basis of propagation of signal in only one direction from an input stage to an output stage through intermediate neurons. Number of hidden layer is chosen to match the complexity of the function. Error Back Propagation Learning algorithm (EBPL) is used as training algorithm for ANN due to faster learning and reliable convergence. The error function chosen for learning process is Mean Square Error (MSE) of outputs. The architecture of three layered ANN is shown in Fig. 2.

Appropriate size of DG unit for a particular bus can be determined for desired voltage profile of that bus. With random change of DG unit at that bus, values of voltage magnitudes are determined from power flow solutions. Feed forward ANN is trained rigorously with DG size correspond to voltage magnitudes at poor voltage stable bus obtained from load flow solution. Then, for any required bus voltage the optimal size of DG unit (MVA) for that particular bus evaluated.

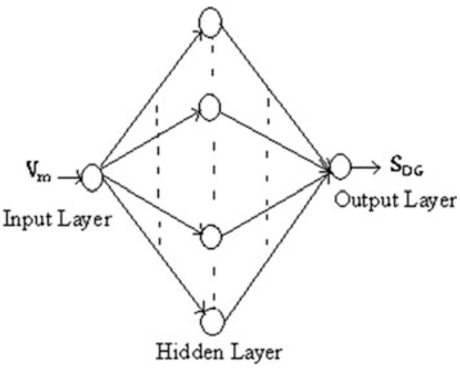


Fig. 2 Architecture of three layered feed forward ANN

3.2 Computational Procedure

Installation of DG of non-optimal size can result in an increase of system losses; implying reduction of voltage magnitudes at buses of network. Computational procedure for proposed methodology is as follows (Fig. 3).

1. Run the power flow solution at base case of the system.
2. Calculate VSI of each bus and store.
3. Arrange VSI of buses in descending order to form priority list.
4. Place DG at top ranked bus.
5. Change size of DG randomly within certain limit and calculate voltage magnitude of the highest priority bus to form training data set.
6. Train three layered feed forward ANN properly with training data set.
7. Evaluate appropriate DG size (MVA) for desired voltage profile at the bus from ANN model.
8. Repeat step-5 to step-7 to allocate DG units subsequently at other weak voltage stable buses till desired voltages at all buses are obtained.

4 Test System

The proposed technique has been tested on 15 bus [14] and 52 bus radial distribution system. Single line diagram of 15 bus system is as shown in Fig. 4.

Load data of the system is given in Table 1.

There are three main feeders of 11 kV, 52 bus practical distribution system supplying a total load of 4.184 + j2.025 MVA [15]. The schematic diagram of the test system is shown in Fig. 5.

Line impedance of the system is 0.0086 + j0.0037 Ω/km.

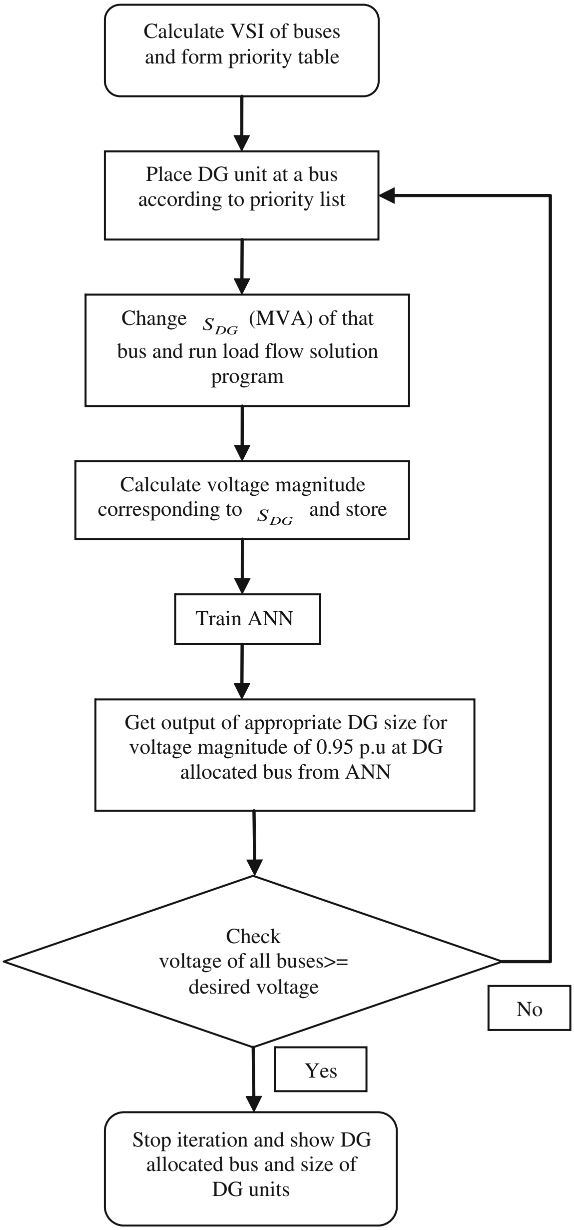
A Newton–Raphson algorithm based load flow solution program is written in MATLAB 7 to solve power flow problem.

5 Simulation Results

VSI of each bus is calculated with system data of base configuration. Priority list is prepared and presented in Table 2.

Obtaining the data from power flow solution, total branch power losses are calculated for 15 bus. Total distribution loss incurred is 79 + j75 kVA. The size of distribution system in term of load (MVA) will play an important role to select the size of DG. To obtain a reasonable solution; the size of DG unit should not be so small or so high with respect to load value. Therefore DG range is chosen as 10 %

Fig. 3 Flow chart for allocation and sizing of DG units



of total load $\leq S_{DG} \leq 30$ % of total load for this system. Optimal size of DG unit is quantified through raising the voltage magnitude of ill voltage stable bus to 0.95 p.u. According to priority list DG is installed at Bus-10. Appropriate size of DG is obtained from ANN model. Figure 6 shows that ANN estimated size of DG is 0.2454 MVA.

Fig. 4 Single line diagram of 15 bus radial distribution system

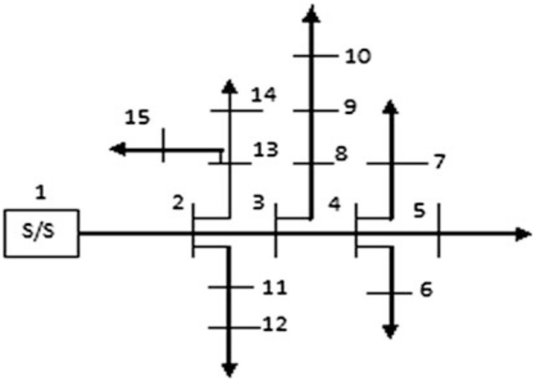


Table 1 Load and generation data of 15 bus distribution system

Bus number	Load		Generation	
	Active (kW)	Reactive (kVAR)	Active (kW)	Reactive (kVAR)
1	–	–	1,305	1,325
2	44	45	–	–
3	70	71	–	–
4	140	143	–	–
5	44	45	–	–
6	140	143	–	–
7	70	71	–	–
8	140	143	–	–
9	70	71	–	–
10	140	143	–	–
11	70	71	–	–
12	44	45	–	–
13	44	45	–	–
14	140	143	–	–
15	70	71	–	–

For 15 bus system one DG is sufficient to boost up the voltage magnitudes of all the lower voltage buses near to 0.95 p.u as shown in Fig. 7.

For 52 bus system active and reactive power losses of the network are obtained as 741 kW and 307 kVAR respectively. Table 3 shows rank of buses to allocate DG.

According to priority list first DG unit is placed at Bus-44 because it is the most sensitive bus to voltage collapse. DG range is chosen as 0.4648 MVA $\leq S_{DG} \leq$ 1.3944 MVA i.e. 10 % of total load $\leq S_{DG} \leq$ 30 % of total load for this system. Based on the proposed methodology, optimum size of DG unit at Bus-44 is calculated using ANN. Figure 8 obtained from simulation of ANN model shows training and target output data at Bus-44. Very low Mean Square Error (MSE = 0.00069) confirms the validation of the proposed model.

Fig. 5 Single line diagram of 52 bus radial distribution system

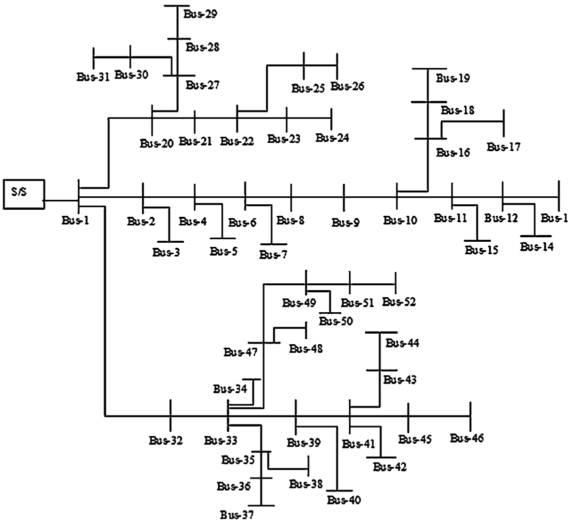


Table 2 Priority list of 15 bus radial system

Rank	Bus number	Value of VSI
1	10	0.222
2	8	0.190
3	9	0.132
4	6	0.124
5	7	0.121
6	11	0.112
7	14	0.107
8	4	0.101
9	13	0.082
10	3	0.067
11	15	0.064
12	12	0.056
13	5	0.051
14	2	0.046
15	1	–

Appropriate DG size at Bus-44 is 0.7123 MVA i.e. 15.06 % of total load.

In the same way another two DG units are installed consecutively at Bus-36 and at Bus-13.

Minimum size of DG i.e. 0.4648 MVA is sufficient to raise the voltage beyond 0.95 p.u at Bus-36.

For Bus-13, size of DG is determined from ANN simulation as shown in Fig. 9.

Appropriate sizes of DG units along with MSEs are tabulated in Table 4.

After installation of three DG units, it is seen that voltage profile of all the buses are raised above 0.90 p.u and that is shown in Fig. 10.

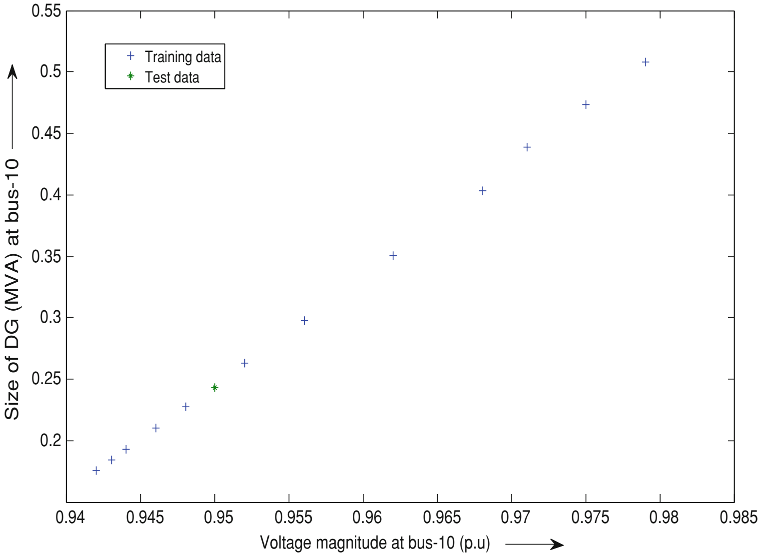


Fig. 6 Training and testing output of ANN for 15 bus radial system

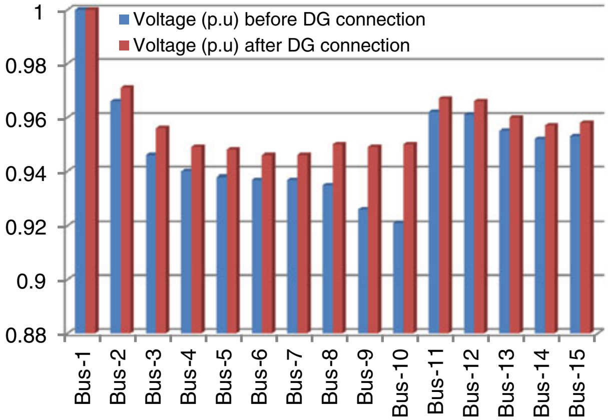


Fig. 7 Comparison of voltage profiles of different buses of 15 bus distribution system

Active and reactive power losses for both the systems are reduced significantly as shown in Tables 5 and 6.

Total power loss is reduced about 76.55 % for 52 bus system and 33.06 % for 15 bus system after proper allocation of DG units.

The optimization techniques for sizing of DGs are iterative process with repetitive solution of power flow problem. So, the processes are time consuming. A number of times, optimization techniques are needed to obtain size of DGs for different required voltage profile at load buses. Once the training has done, ANN

Table 3 Priority list of 52 bus system

Rank	Bus number	Value of VSI
1	44	0.4323
2	36	0.3483
3	13	0.3433
4	18	0.3365
5	03	0.3102
6	33	0.2993
7	15	0.2969
8	47	0.2801
9	17	0.2537
10	23	0.2390
11	50	0.2230
12	19	0.2084
13	31	0.2061
14	46	0.1960
15	42	0.1927
16	10	0.1873
17	08	0.1628
18	39	0.1467
19	40	0.1415
20	14	0.1354
21	37	0.1338
22	25	0.1327
23	09	0.1243
24	24	0.1200
25	30	0.1148
26	28	0.0968
27	45	0.1040
28	22	0.1021
29	34	0.1019
30	02	0.0982
31	28	0.0968
32	35	0.0896
33	38	0.0875
34	43	0.0825
35	26	0.0724
36	05	0.0722
37	29	0.0718
38	04	0.0692
39	32	0.0671
40	41	0.0670
41	49	0.0653
42	16	0.0585
43	21	0.0556
44	07	0.0524
45	27	0.0419
46	20	0.0410
47	48	0.0394
48	52	0.0265
49	11	0.0235
50	12	0.0156
51	06	0.0119
52	1	–

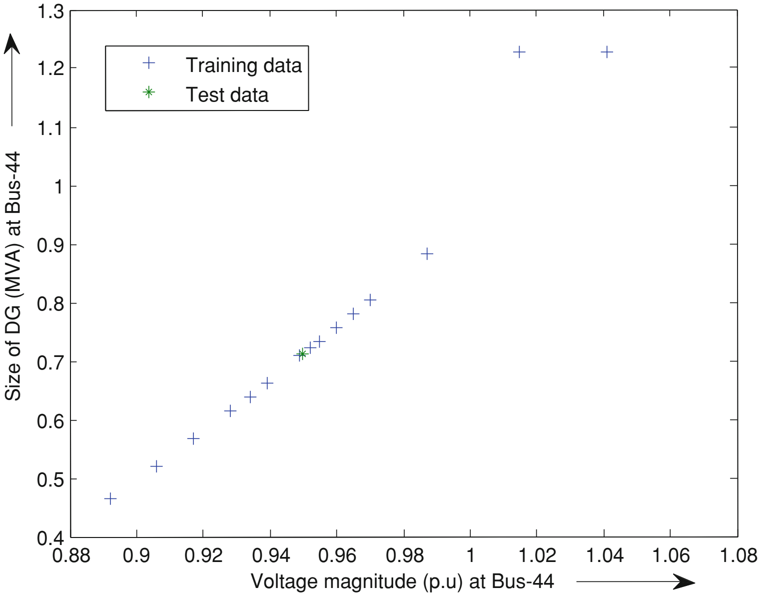


Fig. 8 Graph of test output along with training data for different voltage magnitudes at Bus-44

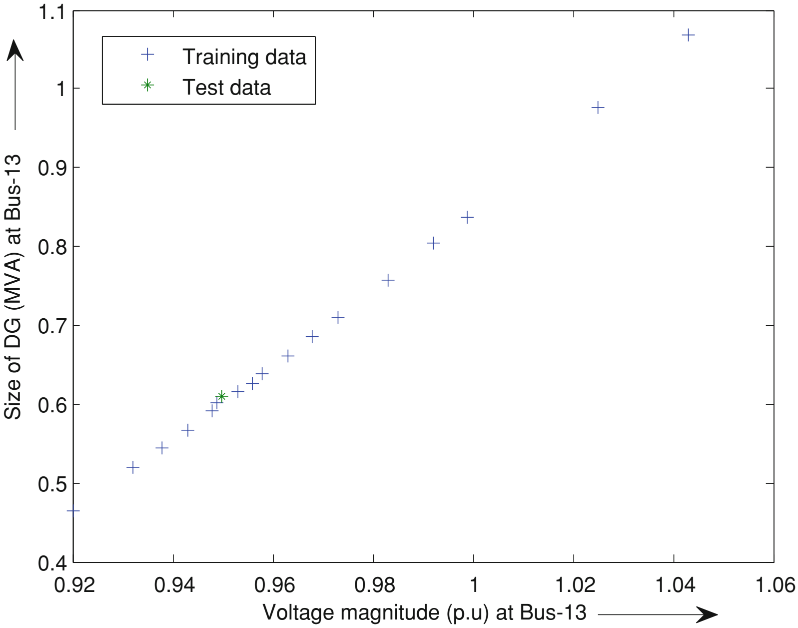


Fig. 9 Graph of training and test output data with respect to voltage magnitudes at Bus-13

Table 4 Size of DG at three vulnerable buses

Bus number	Size of DG		MSE
	(kW)	(kVAR)	
Bus-44	641.4	309.8	0.00069
Bus-36	418.4	202.5	–
Bus-13	547.1	264.3	0.00028

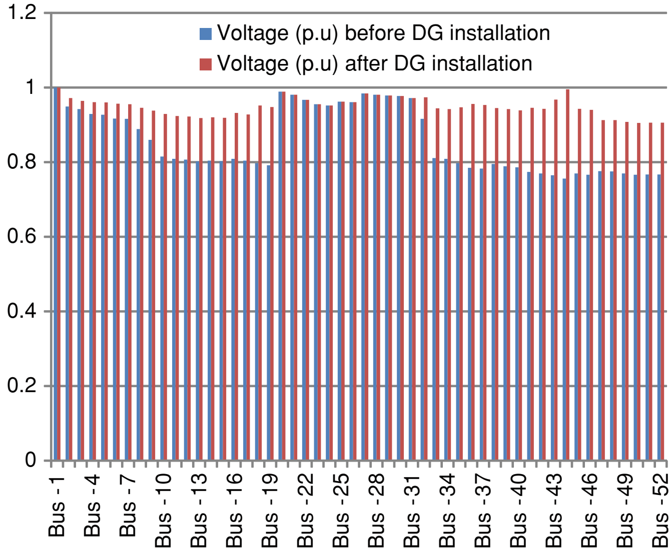


Fig. 10 Comparison of voltage magnitudes of buses before and after DG installation for 52 bus system

Table 5 Losses of the 15 bus system before and after DG installation

	Active power loss (kW)	Reactive power loss (kVAR)
Before DG installation	79	75
After DG installation	53	50

Table 6 Comparative study of power losses before and after DG installation of 52 node network

	Active power loss (kW)	Reactive power loss (kVAR)
Before DG installation	741	307
After DG installation	176	70

technique can directly estimate the size of DG unit for any required voltage profile. So, the technique is quite fast. But, sometimes it may generate sub-optimal solution. The optimization techniques used for the study are complex and difficult to understand. The proposed methodology is rather simple in nature.

6 Conclusion

Priority table is used for easy selection of best location for single or multiple DG units. The buses are ranked using VSI which make priority Table. Appropriate size of DG for desired voltage profile has been evaluated by ANN technique. The proposed algorithm is tested on 15 bus and practical 52 bus radial distribution system. The process is simple and low time demanding. From results obtained, it can be concluded that the optimal sizes of DG units vary from bus to bus, depending on connected loads. Different optimal sizes and locations of DG units are required for different systems depending on their configurations. The results reveal that the integration of DG is highly effective in reducing power losses in the distribution network. Placing DG of appropriate size at optimum location also permit an increase of voltage magnitudes at buses.

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