Placement of Distribution Generators in IEEE 14 Bus System with Consumer Benefit Maximization

B. Prasanth, G. Sai Surya, G. Sai Vinay, K. Deepa, P. V. Manitha, and V. Sailaja

Abstract The utilization of electrical appliances all over the world has been increased, which thereby increases the consumption of electricity. For ensuring the continuity in power supply, distributed generators (DG) play a vital role and are placed in parallel with the system. The important factor that influences the DG which is inappropriate placement which may increase the energy losses. The placement of the DG should be done so that the losses are reduced, and the consumer is benefited. With respect to that, an objective function is designed for which the consumer benefits are maximized. For knowing the optimal placement and customer benefit maximization, load flow analysis has been performed with two conventional methods like fast decoupled and newton Raphson load flow analysis. A comparative study has been done to put forth the best load flow method for locating the DG at the optimum position. The factors like the optimum size, optimum placement, voltage deviation index are analyzed from the aforementioned analysis, which thereby reduces the energy losses and maximizes the customer benefit for the placement of the DG. The whole analysis is done for IEEE 14 bus system and is evaluated in MATLAB software.

Keywords Distributed generators (DG) · Fast decoupled load flow analysis (FDLF) · Newton Raphson method (N-R method) · Customer benefit maximization (CBM) · Voltage deviation index

1 Introduction

Consumption of electricity has been expeditiously growing around the world. To continue the power generation without interruption, utilization of distributed generators (DG) in parallel with distribution system will possibly satisfy the expedient growth in electricity. Installing DG outworths in reduction of energy losses, enhancing the reliability, and augmenting the voltage profile. Fewer cost of operation

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and flexibility to install has been an added advantage to DG. Moreover, introduction of DG may disturb the distribution network's characteristics because of the power being bi-directional [1]. If the amount of power injected by DG is too high, then there may be voltage spikes because of reversible power flow. Additionally, inappropriate placement and improper sizing of the DG lead to the increment in power losses in the system compared to the one without DG connection. Consequently, there may be conflicts in operation of distribution network due to the integration of significant amount of distributed energy resources. The aspects that play the key role in distribution system operation, and planning is reliability. Enhancing the reliability includes minimizing the service duration. Another key aspect is the stability which includes the stability of the voltage and angle of the rotor, long term and short-term stability, large and small disturbance stability. Stability has been one of the major challenges for the integration of DG [2]. Correspondingly, to ensure the efficient, stable and reliable operation of a power distribution system, planning for the placement of DG is required [3]. For the reliable, efficient and stable operation of distribution system, the optimal value of distributed generation capacity has to be decided which is dependent on time and location. The location has to be optimized which otherwise increases risk and may cause positive impact on the feeder if the feeder is overloaded. The factors influencing the DG planning are technical, economical, regulatory, and commercial issues. The initial aim in the DG planning is calculation of the cost function which represents the operating cost of the DG planning. During the process of the planning, the technical parameters are represented in terms of cost, and a cost minimization function is determined [4].

A detailed expression for determining the size and the optimal location of the DG unit for the better efficiency is conferred with various techniques [5]. Also, power flow algorithms have been developed to define optimal size of the DG at each bus. Many computational and analytical methods have been developed for locating the optimal placement of the DG [6]. The methods based on artificial neural network and genetic algorithms for locating the multiple DG units aiming at minimizing the cost and power loss, adhering the limits of voltage specified at each bus have been developed [7]. Hybrid methodology have also been introduced such as particle swarm optimization and genetic algorithm for enhancing the voltage stability (i.e., less voltage deviation index) and voltage profile along with target to minimize the power losses phenomena. Certain algorithms like particle swarm optimization are developed for multiple objectives based to locate the appropriate location for multiple DGs, and optimal size is found in the varying load distribution system [8].

For the determination of optimal size and optimal DG placement, load flow study like Newton Raphson has been used [9]. Objectives of the problem pertaining to minimization of cost and power losses, an equation have been developed for the customer benefit. Customer benefit maximization equation is quadratic expression with generation and demand terms. Voltage deviation index plays a major role in the placement of DG [13]. To have comparative analysis of better load flow method in determining the best optimal size and placement of DG, fast Decoupled load flow analysis has been used with same customer benefit maximization equation. A detailed study for the values of the cost coefficients has been analyzed [10]. The load flow analysis has been done for IEEE 14, IEEE 30, and IEEE 57 bus system [11]. There are some of conservation strategies proposed for the DC motor applications which are helpful for efficient operation of the DG [12]. The paper does a comparative analysis to put forth the best method for the optimizing the size, location, and minimizing losses [14]. Anyways the placement of the DG does not ensure the power quality on the load, which has to be ensured by initiating well harmonic reduction techniques [15].

2 Methodology

In this paper, for solving a system of non-linear algebraic equations for the computation of power flow, a conventional Newton Raphson and fast decoupled load flow analysis are utilized. To incorporate the DG effect, bus data has been changed. Whenever the bus is connected with a DG, the bus corresponding to it is a PV bus.

2.1 Newton Raphson Method

Newton Raphson method is an iterative technique used for solving non-linear algebraic equations and a practical method of load flow solution of large power networks. It can be solved either by taking the variables in polar or rectangular coordinates. The bus voltages are given by Eqs. (1, 2)

$$V_i = V_i \mathrm{e}^{j\delta_i} \text{ then } V_i^* = V_i \mathrm{e}^{-j\delta_i} \tag{1}$$

$$V_k = V_k \mathrm{e}^{j\delta_k} \text{ and } Y_{ik} = Y_{ik} \mathrm{e}^{-j\theta_{ik}} \tag{2}$$

where δ is the phase angle of the bus voltages, and θ_{ik} is the admittance angle.

The complex power injected into the bus is given by Eq. (3)

$$P_i - jQ_i = V_i^* \sum_{k=1}^{n} Y_{ik} V_k \tag{3}$$

The equality constraints are given by Eq. (4, 5)

$$P_i = V_i^* \sum\nolimits_{k=1}^{n} Y_{ik} V_k \cos(\theta_{ik} + \delta_k - \delta_i) \tag{4}$$

$$Q_i = -V_i^* \sum\nolimits_{k=1}^{n} Y_{ik} V_k \sin(\theta_{ik} + \delta_k - \delta_i) \tag{5}$$

where $i = 2, 3, 4 \ldots, n$, where bus 1 is the slack bus, and n is the number of buses.

The above equation is now written in the polar form as follows

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} \tag{6}$$

where J_1, J_2, J_3, J_4 are the elements of the Jacobian matrix and

$$\Delta P_i = \Delta P_i(\text{specified}) - \Delta P_i(\text{calculated}) \tag{7}$$

$$\Delta Q_i = \Delta Q_i(\text{specified}) - \Delta Q_i(\text{calculated}) \tag{8}$$

From the given bus data, the Y bus is formed, and the initial bus voltages and load angles are assumed. Thereby, computing the reactive and real power of each bus using Eqs. (4, 5). Then, the process includes the calculation of the error using Eqs. (7, 8). For the PV buses, based on limits mentioned for Q_i, ΔQ_i is calculated. The PV buses are considered as load buses where DG is installed. Based on the connection to DG, appropriate bus data is changed. Hereby, computing the elements of the Jacobian from (6). Thus, obtaining $\Delta\delta_i and \Delta V_i$. These unknown variables are updated after every iteration given in (9, 10).

$$\Delta V_i^{r+1} = \left|V_i^r\right| + \Delta\left|V_i^r\right| \tag{9}$$

$$\Delta\delta_i^{r+1} = \delta_i^r + \Delta\delta_i^r \tag{10}$$

The process is continued till all the load buses are within the tolerance limit such that.

$\Delta P_i^r < \varepsilon and \Delta Q_i^r < \varepsilon$, where ε is a tolerance level for the load buses.

2.2 Fast Decoupled Load Flow Analysis

There is strong relationship between the voltage angles of the buses and real powers and also between magnitude of the voltage and reactive power exists in any power transmission network. As the property of this feeble coupling between Q–V and P-δ gives a proper ides to derive decoupled load flow methods.

If the Jacobian obtained in the Newton method is considered, then half of the matrix represents the elements of feeble coupling which can be ignored. There may be reduction of the convergence rate, but there may be benefits in the computational efforts. There are many algorithms related to the decoupled analysis. Moreover, the decoupled Newton Raphson method is used here due to its accuracy and convergence rate compared to the other algorithms. The elements to be neglected are off-diagonal elements in Jacobian matrix; the resulting decoupled linear equations are

$$[\Delta P] = [H][\Delta\delta] \tag{11}$$

$$[\Delta Q] = [L]\left[\frac{\Delta V}{V}\right] \tag{12}$$

The above equations are written as:

$$H_{ij} = L_{ij} = V_i V_j (G_{ij}\sin(\delta_{ij}) - B_{ij}\cos(\delta_{ij})) \tag{13}$$

where $i \neq j$ and

$$H_{ii} = -B_{ii}V_i^2 - Q_i \tag{14}$$

$$L_{ii} = -B_{ii}V_i^2 + Q_i \tag{15}$$

$$Y_{ij} = G_{ij} + jB_{ij} \tag{16}$$

At every iteration, Eqs. (11) and (12) are formed and equated, thereby updating the $[H] and [L]$ matrices using Eqs. (13–16). By first solving Eq. (7) for Δδ and make use of the updated δ in forming and then equating Eq. (8) for Δ|V| therefore resulting faster convergence rate.

The assumptions made in this method are listed from Eqs. (17–20):

$$\cos(\delta_{ij}) \approx 1 \tag{17}$$

$$\sin\left(\delta_{ij}\right) \approx 0 \tag{18}$$

$$G_{ij}\sin\left(\delta_{ij}\right) \ll B_{ij} \tag{19}$$

$$Q_i \ll B_{ii}V_i^2 \tag{20}$$

With the above assumptions, the values of $[H]$ and $[L]$ will become as shown in Eqs. (21 and 22):

$$H_{ij} = L_{ij} = -V_i V_j B_{ij} for i \neq j \tag{21}$$

$$H_{ii} = L_{ii} = -B_{ii}V_i^2 for i = j \tag{22}$$

Equations (7) and (8) can be written as Eqs. (23–24);

$$[\Delta P] = \left[V_i V_j B_{ij}{}'\right][\Delta\delta] \tag{23}$$

$$[\Delta Q] = \left[V_i V_j B''_{ij}\right]\left[\frac{\Delta V}{V}\right] \tag{24}$$

where $B_{ij}{}'$, $B_{ij}{}''$ are elements of $[-B]$ matrix.

Therefore, with necessary modifications done to the above equation, simplification of fast decoupled load flow analysis is done.

1. There is prominent disturbance in the reactive power because of the elements neglected in the matrix $[B^{'}]$.
2. There is disturbance in phase shifters due to the elements neglected in $[B'']$
3. Assume the value of setting $\left|V_j\right| = 1$ put in Eqs. (23) and (24) and divide it by $|V_i|$.
4. The resistance in the series has to be ignored while calculating the elements of $[B]$, thereby resulting in power flow matrix de-approximation.

With the necessary changes done as mentioned above, the equations for FDLF results in

$$[\Delta P/V] = \left[B^{'}\right][\Delta\delta] \tag{25}$$

$$[\Delta Q/V] = \left[B''\right][\Delta V] \tag{26}$$

In (25) and (26), the matrices $\left[B''\right]$ and $\left[B'\right]$ being sparse, real are having the format of $[L]$ and $[H]$, respectively. The matrix consists of the admittance values making it a constant matrix, and the inversion of the matrix has to be done only at the starting. The matrices $\left[B'\right]$ and $\left[B''\right]$ are consistently symmetrical if the phase shifters are not there, and the calculation of the very few upper triangular elements is done, and storing of those is done only at the starting of the solution. Preferably, Eqs. (25) and (26) are solved and updating the value of the voltages obtained recently, and every iteration gives a solution for [Δδ] and thereby updating [δ] and also gives a solution for [Δ|*V*|], thereby updating [|*V*|] which is termed as $1 - V$ and $1 - \delta$ iteration.

A test for convergence is done to know the mismatch in real and reactive power flow Eq. (27):

$$\max[\Delta P] \le \varepsilon_p \text{ and } \max[\Delta Q] \le \varepsilon_q \tag{27}$$

where ε_p and ε_q are the tolerances.

3 Maximization of Customer Benefit

The summation of surplus of the consumer and excess providers maximizes the customer benefit. The customer benefit can be calculated from Eq. (28).

$$\begin{aligned}\text{Maximized customer benefit} = {} & (\text{customer utility} - \text{electricity cost}) \\ & + (\text{sales revenue} - \text{supply cost})\end{aligned} \tag{28}$$

Based on Eq. (28), the objective function is designed for the maximization of customer benefit, which is quadratic equation with demand and generation. The function provides the total assessment of excess in each bus. Thus, the optimal size can be found out by maximizing the objective function which is given by Eq. (29).

$$\text{CBM} = \sum\nolimits_{i=1}^{ND} \left(d_i P_{Di}^2 + e_i P_{Di} + f_i\right) - \sum\nolimits_{j=1}^{NG} \left(a_j P_{Gj}^2 + b_j P_{Gj} + c_j\right) \tag{29}$$

where ND = number of demand buses, NG = number of generation buses, $d_i, e_i, f_i, a_j, b_j, c_j$ are the quadratic coefficients.

The constraints are computed using the Newton Raphson method and fast decoupled load flow analysis.

After the appropriate load flow analysis using the two methods, the total energy management is calculated to indicate the loss in the system which is done using Eqs. (30 and 31)

$$P_L = \sum\nolimits_{k=1}^{N} \sum\nolimits_{i=1}^{N} \left[\propto_{kj}\left(P_k P_j + Q_k Q_j\right) + \beta_{kj}\left(Q_k P_j + P_k Q_j\right)\right] \tag{30}$$

where

$$\left.\begin{aligned} \alpha_{kj} &= \tfrac{r_{kj}}{v_k v_j} \cos(\delta_k - \delta_j) \\ \beta_{kj} &= \tfrac{r_{kj}}{v_k v_j} \sin(\delta_k - \delta_j \end{aligned}\right\} \tag{31}$$

Which are the kjth element of the $[Z_{\text{bus}}]$ matrix

$$\alpha_k = \frac{\partial P_L}{\partial P_k} = 2\alpha_{kk} P_k + 2\sum\nolimits^{n}_{\substack{j \neq 1 \\ j \neq k}} \left[\left(\propto_{kj}\right) P_j - \beta_{kj} Q_j)\right] \tag{32}$$

The placement of the DG is done based on the ascending order of the voltage deviation index based on the Eq. (32). The proper dispatch brings a positive influence to the disturbed grid. This can be done using different strategies. The one this paper presents is dispatch strategy. Dispatch strategy minimizes power losses, improves flat voltage profiles, increases maximum loading, and also can be used to reduce active and reactive losses by proper allocation of distributive generators in the distribution network. This dispatch procedure is based on continuous power flow (CPF) analysis which reduces convergence problems. Continuous power flow uses successive solution to compute the voltage profile up to a collapse point. It also uses iterative process involving predictor and corrector steps which allow in determining maximum loading for voltage stability for each distributive generator (DG). By calculating losses using power flow program for the distributive generators (DG's) in the priority list formed by using continuous power flow (CPF) method, one can select the appropriate DG with maximum loading and low losses and then install it. This process repeats for dispatching each and every DG.

4 Simulation and Results

Newton Raphson method and fast decoupled load flow analysis have been performed to evaluate the customer benefit maximization function. The bus number with least customer benefit maximization will be suitable for the optimal placement of the DG. The objective function is evaluated for the IEEE 14 bus system which is shown in Fig. 1. The systems consist of 5 PQ buses, 1 slack bus and rest with load buses (PV buses). The load buses are modified with the DG ratings varying from 5 to 20 MW is taken and modified the IEEE 14 bus system. The following parameters are evaluated and identified with the objective function.

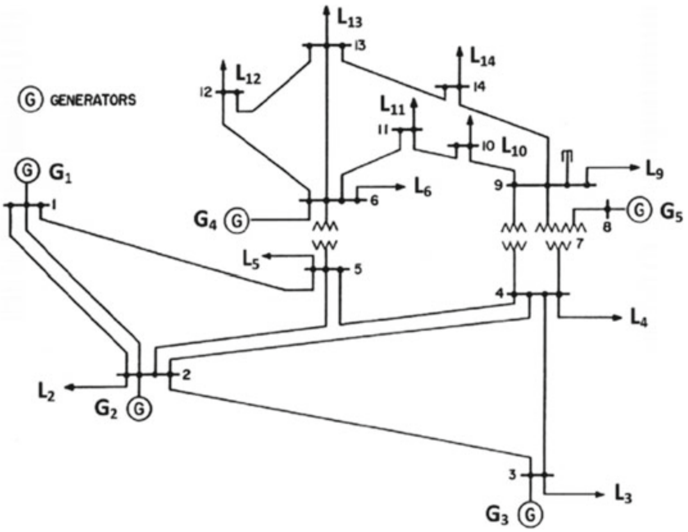

Fig. 1 IEEE 14 bus system

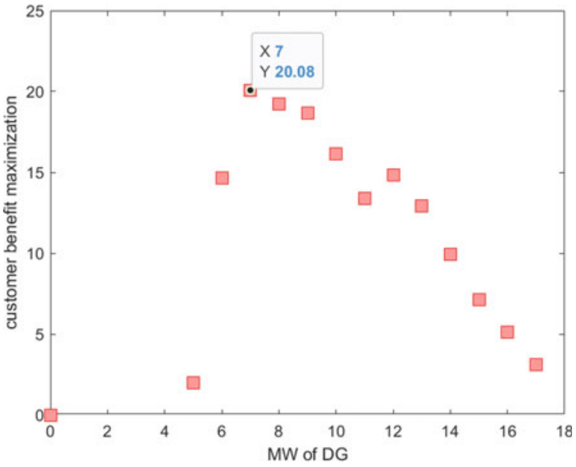

Fig. 2 Variation of CBM with respect to DG rating

4.1 Optimal DG Rating

The optimal DG rating of the system is shown in Fig. 2. According to the figure plotted, the optimal DG rating of the device is 7 MW because of the maximum customer benefits with the value of the maximization function to be 20.08. The optimal DG rating for each analysis converges at the same point as shown in Fig. 2.

4.2 Optimal Location of the DG

The bus with the maximum customer benefits will be considered as the optimum location of the DG. According to Fig. 3, the optimal location of the DG can be found at the bus number 4 with value of customer benefit maximization to be at 20.08 which was the same when identifying the optimal DG rating. In locating the optimum position for the DG, the value obtained with each analysis has been identified to be converging at the same point.

4.3 Voltage Deviation Index

The power loss of the system is calculated from Eq. (27), and the voltage deviation index is calculated from the Eq. (29). The DG is placed according to the voltage deviation index arranged in ascending order. IEEE 14 bus system has been used for evaluating these parameters and is shown in Figs. 4 and 5. Figure 4 has been evaluated using the Newton Raphson method, and the least voltage deviation index is 0.002989 which is at the bus number 7 followed by the bus number 8 which has

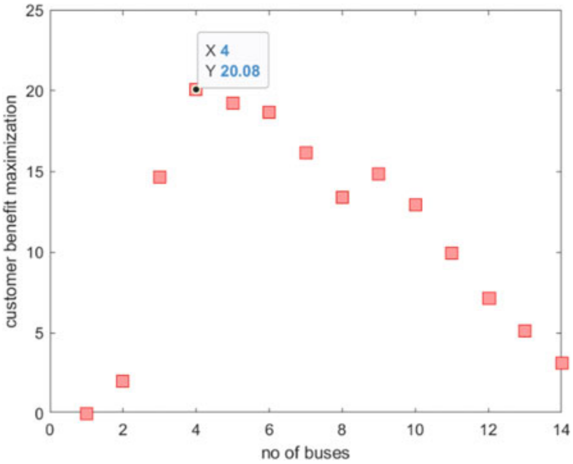

Fig. 3 Variation of customer benefit maximization with respect to number of buses

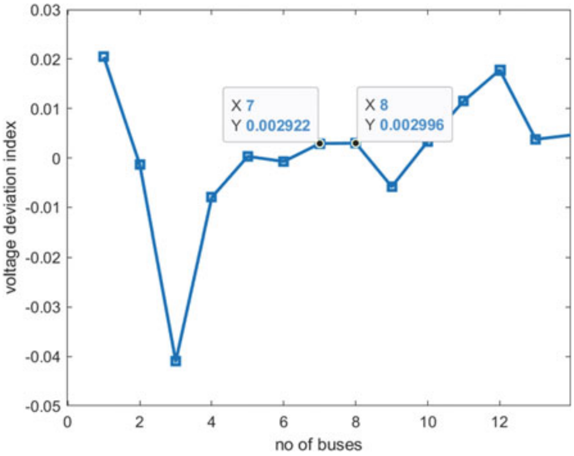

Fig. 4 Voltage deviation index with respect to the number of buses using Newton Raphson method

the value of 0.003055. Figure 5 has been evaluated with fast decoupled load flow analysis and the least voltage deviation index are converged at the bus number 7, with a value 0.002922 which is hereby lesser than the Newton Raphson method. The following bus number with voltage deviation index at 0.002996 is at bus number 8. Considering the voltage deviation index into consideration, the best method for computing the voltage deviation index to find out the optimal placement of the DG is fast decoupled load flow analysis which converges at lesser value compared to that of the Newton Raphson method.

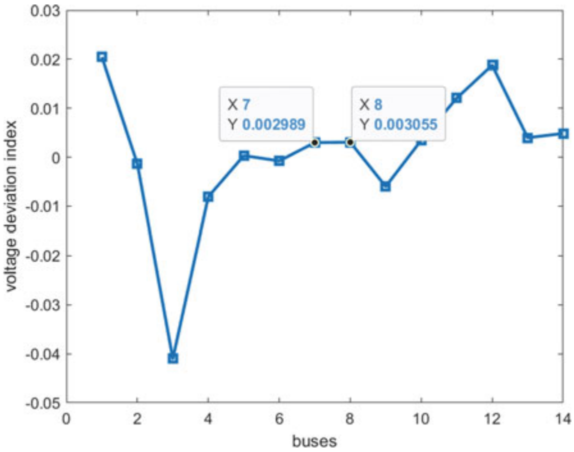

Fig. 5 Voltage deviation index with respect to number of buses using fast decoupled load flow analysis

4.4 Variation of Bus Voltage with DG Size

Figure 6 shows the variation of the bus voltages due to the addition of the DG's into the system. For the modified IEEE 14 bus system, the voltage profile for the buses 2–14 is affected. The bus voltages increase with increase in the DG rating. It increases until it reaches the maximum rating of the DG.

The total line losses for the IEEE 14 system compute to 4.784 + 17.713j when the DG's are inserted into the system. When the DG's are not inserted, the losses compute to 13.476 + 55.797j, which are way higher losses compared to that of the system with DG.

Due to the optimal location of the DG, the losses are minimized to greater extent. The value of the losses proves to be the same with a miniature error. The real losses

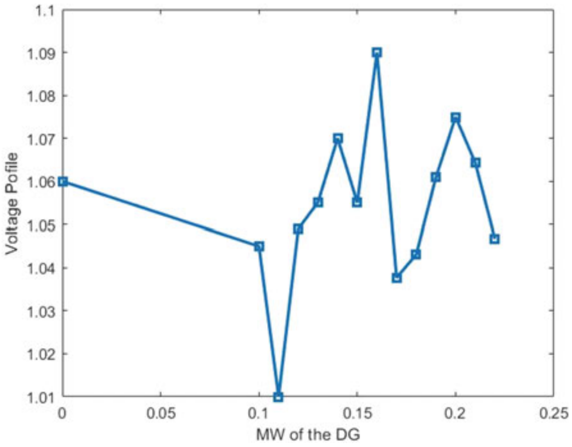

Fig. 6 Voltage profile with respect to DG size

associated with each bus in pu is shown in Fig. 7. According to that, in the IEEE 14 bus system considered, the losses are the bus 3 that are higher compared to the other buses. The reactive power losses with respect to each are shown in Fig. 8.

From Fig. 8, it is observed that the reactive power losses are also higher at the third bus compared to the other buses. The load of the bus 3 is 94.2 + 19j which is highest among the buses present, resulting in amount of losses compared to the other buses. Because of the losses in the buses being higher, there is abrupt decrease in the voltage profile as well as the voltage deviation index. Due to this, the placement of the DG at the bus 3 can be taken as the last option after all the DGs placed at buses with less amount of losses. It is concluded that it is preferable to not have a DG at the bus 3. Based on the above factors, the optimal placement of the DG will be at bus number 4 with optimal size of 7 MW, when customer benefits are of higher

Fig. 7 Real power losses associated with each bus

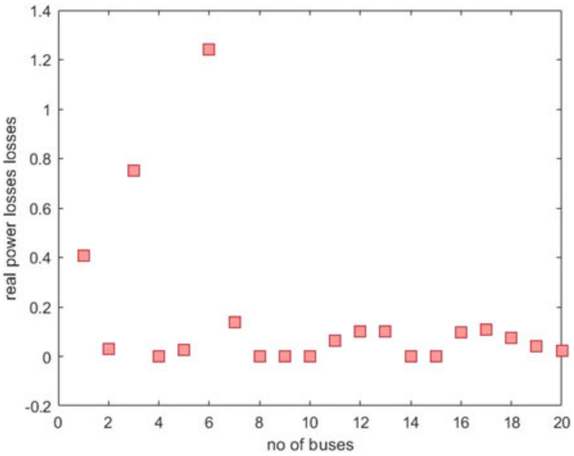

Fig. 8 Reactive Power losses associated with each bus

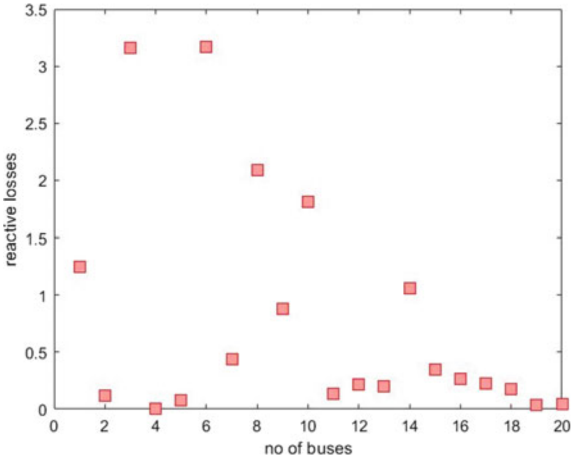

Table 1 Comparative study between the load flow analysis

	N-R method	FDLF method
P loss	0.023	0.021
CBM	0.6599	0.6599
Time elapsed (s)	92.31	32.31
No. of iterations	43	11

priority. When the voltage profile is of higher priority, then the placement of the DG will be optimum at bus number 7. For the analysis to converge to the above factors computing time, no. of iterations play a major role. Therefore, a comparative study has been detailed in Table 1.

According to Table 1, the loss function given by Eq. (27) calculated with FDLF proves to be fewer than the N-R method. The FDLF method converges faster as compared to that of the Newton Raphson method. The simulation time for running tend to be the same as the rate of convergence. The deviation of the voltage with respect to the reference is less in FDLF method compared to that of the Newton Raphson method. Thus, concluding with above considered factors the optimal placement of the DG can be well analyzed in a shorter duration with FDLF method.

5 Conclusion

In this paper, the optimal placement of the DG in the power system network is analyzed using fast decoupled load flow analysis and Newton Raphson method. The objective function has been designed for maximizing the customer benefits. The objective function is evaluated which decides the location of the DG which is optimum, optimal size which can be integrated into the power system network. Voltage deviation index is also calculated for the system considered which is IEEE 14 bus system. Considering the voltage deviation index, the optimal size and placement of the DG are obtained. The time for evaluating the optimal placement of the DGs determines the reliability of the system. A comparative study has been performed between the Newton Raphson and fast decoupled load flow analysis, which results in fast decoupled load flow method to be the best analysis for the load flow and for determining the optimal placement of the DG. The rate of convergence is far less compared to that of the Newton Raphson method. Analysis of the load flow with implementation with the IoT infrastructure can be taken as future scope of study.

References

1. P. Chiradeja, R. Ramakumar, An approach to quantify the technical benefits of distributed generation. IEEE Trans. Energy Convers. **19**(4), 764–773 (2004)

2. J. Jayateertha, A. Balaji, P.V. Manitha, K. Deepa, Automatic control of active and reactive power for stand-alone solar micro-grid. J. Adv. Res. Dyn. Control Syst **11**(04), 1280–1291 (2019)
3. C. Masters, Voltage rise: the big issue when connecting embedded generation to long 11 kV overhead lines. Power Eng. J. **16**(1), 5–12 (2002)
4. R. Dugan, T. McDermott, G. Ball, Planning for distributed generation. IEEE Ind. Appl. Mag. **7**(2), 80–88 (2001)
5. N. Acharya, P. Mahat, N. Mithulananthan, An analytical approach for DG allocation in primary distribution network. Int. J. Electr. Power Energy Syst. **28**(10), 669–678 (2006)
6. K. Nara, Y. Hayashi, K. Ikeda, T. Ashizawa, Application of tabu search to optimal placement of distributed generators, in IEEE PES Winter Meet 2001, pp. 918–23 (2001)
7. A.M. El-Zonkoly, Optimal placement of multi-distributed generation units including different load models using particle swarm optimization. Swarm Evol. Comput. **1**, 50–59 (2011)
8. K. Singh, S.K. Gowsami, Optimum allocation of distributed generations based on nodal pricing for profit, loss reduction and voltage rise issue. Electr. Power Energy Syst. **32**, 637–644 (2010)
9. S. Ghosh, S.P. Ghoshal, S. Ghosh, Optimal sizing and placement of distributed generation in a network system. Int. J. Electr. Power Energy Syst. **32**(8), 849–856 (2010)
10. P. Shanmugapriya, J. Baskaran, C. Nayanatara, D.P. Kothari, IoT based approach in a power system network for optimizing distributed generation parameters. CMES-Comput. Model. Eng. Sci. **119**(3), 541–558 (2019)
11. S. Mishra, P. Debapriya, A simple algorithm for distribution system load flow with distributed generation, in *International Conference on Recent Advances and Innovations in Engineering, ICRAIE 2014* 2014). 10.1109/ICRAIE.2014.6909127
12. U.H. Priya, P. Jyothi, V.V.S.S. Phanipavan, K. Deepa, A. Jain, Energy conservation strategy for DC motor load applications. Intell. Syst. Ref. Libr. **172**, 177–186 (2019)
13. N.S. Rau, Y.-H. Wan, Optimum location of resources in distributed planning. IEEE Trans. Power Syst. **9**(4), 2014–2020 (1994)
14. R. Yokoyama, S.H. Bae, T. Morita, H. Sasaki, Multiobjective optimal generation dispatch based on probability security criteria. IEEE Trans. Power Syst. **3**(1), 317–324 (1988)
15. A. Saxena, K. Deepa, Power quality analysis for electric vehicle charging and its mitigation strategies. Test Eng. Manage. 5409–5418 (2020)