Optimal Placement and Sizing of DG and Shunt Capacitor for Power Loss Minimization in an Islanded Distribution System

Mingu Kang and Ramon Zamora(✉)

Electrical and Electronic Engineering Department,
Auckland University of Technology, Auckland, New Zealand
kangiggs89@naver.com, ramon.zamora@aut.ac.nz

Abstract. Active power loss of transmission lines in a distribution system has been a frequent concern for a great number of researchers. Various approaches have been proposed to minimize active power loss. In this research, two approaches, optimal placement and sizing of distributed generation (DG) and shunt capacitor, are used to reduce the active power loss in a distribution system. Particle Swarm Optimization (PSO) and Newton-Raphson method are integrated to find the optimal location and size of DG and shunt capacitor while maintaining operation constraints. The proposed technique is tested on a radial distribution system based on Vava'u island's distribution system in Tonga. The algorithm is implemented in MATLAB and the results are verified with DIgSILENT PowerFactory. Three case scenarios of the optimal placement and sizing, namely: DG only, shunt capacitor only, and DG & shunt capacitor, were tested. The technique successfully found the optimal location and size of DG and shunt capacitor in three case scenarios and further found the most optimal solution among these three cases.

Keywords: Distributed generation · Shunt capacitor
Particle Swarm Optimization (PSO) · Optimal location · Optimal size
Active power loss

1 Introduction

The current power system is in transition from conventional power system to smart grid. The power system is expected to be more environmentally friendly, secure, reliable, resilient, efficient, and sustainable [1]. The levels of transition and achieved expectation are various among systems; some systems are still at very beginning of transition, while others are already very advanced. Regardless of the current system position in the transition range, the smart grid concept will help the system to improve.

This paper deals with a conventional islanded distribution system, based on Vava'u Island distribution system. The system is expected to be improved in terms of minimizing power loss and maintaining all bus voltages above 0.9 p.u. The improvement is

P. H. J. Chong et al. (Eds.): SmartGIFT 2018, LNICST 245, pp. 43–52, 2018.
https://doi.org/10.1007/978-3-319-94965-9_5

related to two of the defined functions of a smart grid: optimizing assets and operating efficiently [2]. The method to achieve this improvement will be discussed below.

The average electrical power loss is around 8% of output power in transmission and distribution system. The percentage of power loss approximately below 10% which occurs in some countries can be ignored, whereas in some developing countries such as Togo, Libya and Haiti, the power loss is much higher. To deal with the significant power loss in some developing countries, a great number of researchers have proposed different approaches for power loss minimization [3]. In this research, two effective methods will be used to reduce power loss in a distribution system. The first one is the installation of DG and the other one is shunt capacitor as a compensator.

Placing DG has the advantage of reducing the amount of power requested from the transmission system and/or central power plant by supplying local loads. Similarly, placing a shunt capacitor at the load can compensate reactive power loss by supplying reactive current to the load. However, inappropriate placement and sizing of DG and shunt capacitor may increase power loss in a distribution power system. Hence, an optimization method is required to find an optimal solution.

Several methodologies based on analytical and meta-heuristic approaches can be used to find the optimal solution. An analytical calculation by using loss sensitivity factor (LSF) and priority list is implemented in [4]. Zero-point analysis in radial or open loop systems as well as 2/3 rule for power loss are introduced in [5]. Another analytical method for optimal placement of DG based on bus admittance matrix, generation information and load in a radial distribution system is presented in [6]. Genetic Algorithm (GA), Taboo Search (TS), Ant Colony Optimization (ACO), Artificial Bee Colony (ABC) and Harmony Search (HS) have been listed in [7] as heuristic methods for optimal placement of DG or shunt capacitor.

Due to several merits in various applications, Particle Swarm Optimization (PSO) is used in this paper to find optimal location and size of DG and shunt capacitor. PSO requires only a fitness function instead of complex mathematical functions such as gradient or matrix inversion. Due to the simple objective function, the computational time will be short with high quality solutions unlike time consuming algorithms such as TS and GA. Since PSO uses basic mathematical and logic operations as well as has fewer parameters, it is characterized as simple to program and easy to implement. In addition, while some of other algorithms require good initial conditions, it is not necessary to have adequate initial condition for PSO to converge because of population-based characteristics. PSO technique is also so flexible that it can be combined with other optimization techniques [8].

The PSO algorithm will be combined with Newton-Raphson power flow analysis to make sure that the optimal solution satisfies all operation constraints. Three different scenarios, namely: DG only, shunt capacitor only, and DG & shunt capacitor, are simulated in MATLAB and the results from the three scenarios are verified in DIg-SILENT PowerFactory.

2 Proposed Methodology

The methodology for optimal placement and sizing of DG and shunt capacitor is divided into two sections, load flow analysis and optimization. Newton-Raphson method is used for load flow analysis and Particle Swarm Optimization (PSO) algorithm is used to find the optimal solution. Newton-Raphson power flow method is a very common power flow and discussed in detail in power system analysis textbooks, such as [9, 10]. This paper will not discuss about the power flow method, but will just implement it in combination with PSO as shown in Fig. 2.

Particle Swarm Optimization (PSO) algorithm is a nonlinear algorithm motivated by social behavior of flocking birds or schooling fish. PSO is composed of the number of particles (population), the position, and the velocity of particles in the search space [11]. The algorithm begins with the initialization of the population. The next step is based on two processes: computing the particle velocity and updating the particle position. These two processes will give each particle the direction to move toward the final solution. There are several parameters such as w, c_1 and c_2 which should be considered to facilitate the convergence and prevent the explosion of the swarm. Mathematically, the two vectors represent the position and velocity of particle i in N-dimensional search space as shown in Eqs. (1) and (2). The modified velocity can be represented by Eq. (3), while the improved position of particle i is expressed by (4). The PSO concept is shown in Fig. 1.

$$X_i = \left[x_{i,1}, x_{i,2}, x_{i,3}, x_{i,4} \cdots x_{i,n}\right], \tag{1}$$

$$V_i = \left[v_{i,1}, v_{i,2}, v_{i,3}, v_{i,4} \cdots v_{i,n}\right], \tag{2}$$

$$v_i^{k+1} = wv_i^k + c_1 r_1 \left(Pbest_i^k - x_i^k\right) + c_2 r_2 \left(Gbest_i^k - x_i^k\right), \tag{3}$$

$$x_i^{k+1} = x_i^k + v_i^{k+1}, \tag{4}$$

where:

v_i^k is current velocity of particle i at iteration k,
v_i^{k+1} is modified velocity of particle i,
x_i^k is current position of particle i at iteration k,
x_i^{k+1} is modified position of particle i,
$Pbest_i^k$ is personal best of particle i at iteration k,
$Gbest_i^k$ is global best of group,
w is the inertia weight,
c_1 and c_2 are acceleration constants,
r_1 and r_2 are randomly generated number ranged from 0 to 1.

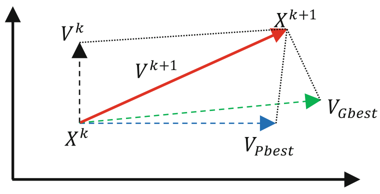

Fig. 1. Concept of PSO search mechanism.

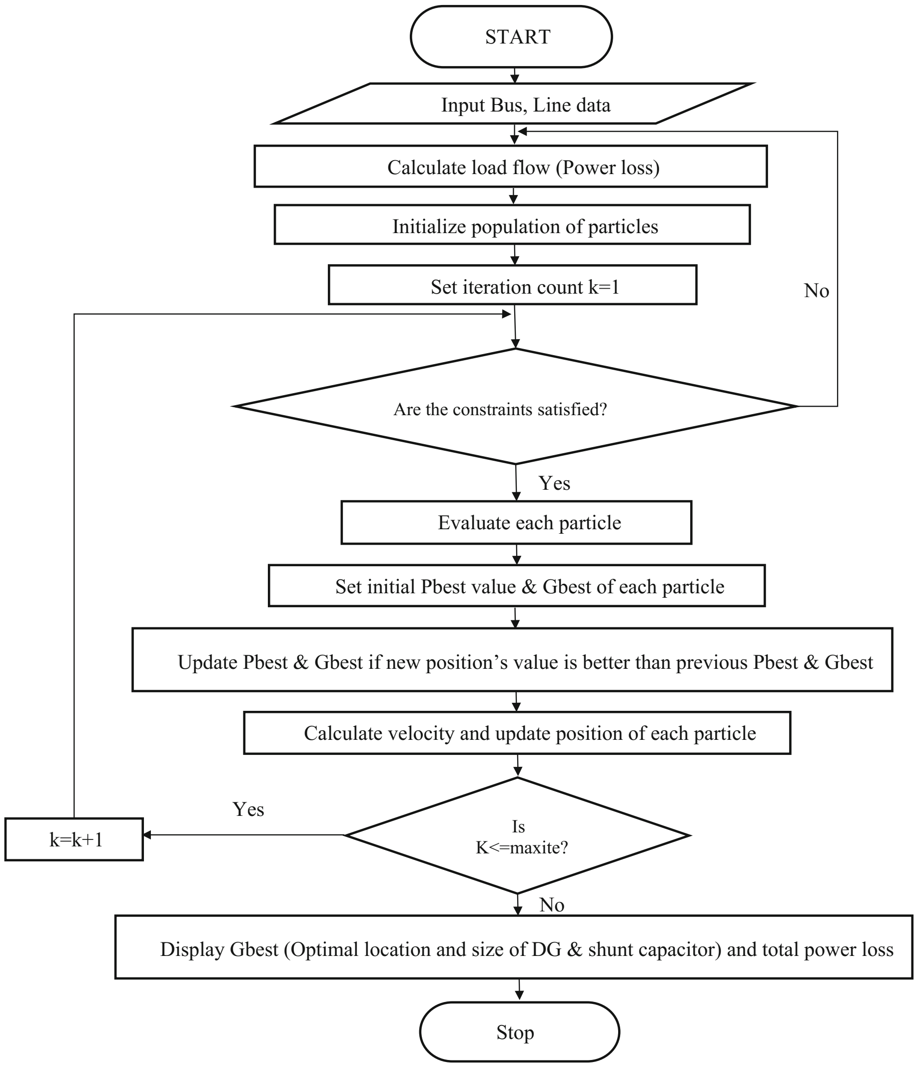

Fig. 2. Proposed PSO flow chart of optimal placement of DG and shunt capacitor.

3 System Design

3.1 Problem Formulation

The simple one-line diagram of radial distribution systems without DG and shunt capacitors is shown in Fig. 3 and with DG and shunt capacitors is shown in Figs. 4 and 5, respectively. The impedance in distribution system represents distribution lines which cause the power loss. The active and reactive power flowing to bus i + 1 is presented in Eqs. (5) and (6).

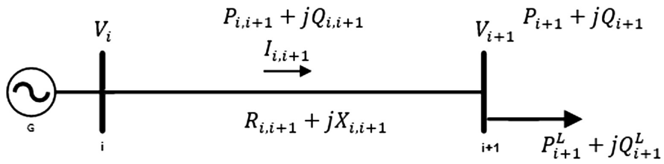

Fig. 3. Simple one-line diagram.

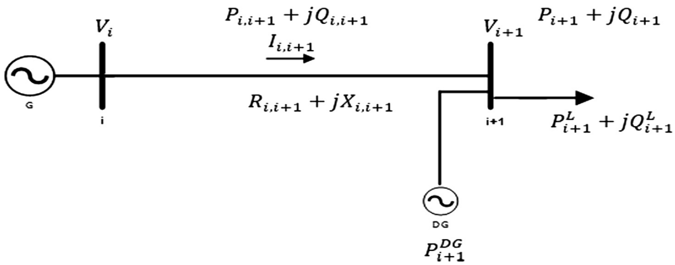

Fig. 4. Simple one-line diagram with DG.

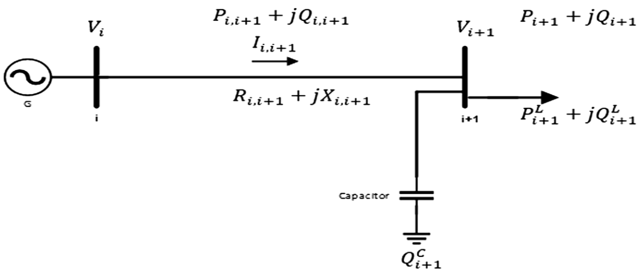

Fig. 5. Simple one-line diagram with capacitor.

$$P_{i+1} = \left[P_{i,i+1} - P_{i+1}^{L} - \left(R_{i,i+1} \frac{P_{i,i+1}^{2} + Q_{i,i+1}^{2}}{|V_i|^2} \right) \right]. \tag{5}$$

$$Q_{i+1} = \left[Q_{i,i+1} - Q_{i+1}^{L} - \left(X_{i,i+1} \frac{P_{i,i+1}^{2} + Q_{i,i+1}^{2}}{|V_i|^2} \right) \right]. \tag{6}$$

The objective function of this problem is to minimize active power loss in distribution network as given in Eqs. (7) and (8). All variables in the equations are from the one-line diagram representations in Figs. 3, 4 and 5.

$$F_{ob} = \min P_{TL}, \tag{7}$$

where:

$$P_{TL} = \sum_{i=1}^{NB} R_{i,i+1} \frac{P_{i,i+1}^{2} + Q_{i,i+1}^{2}}{|V_i|^2}. \tag{8}$$

3.2 Systems Constraints

System constraints are necessary measures to ensure system reliability and safety. Voltage limit constraint, line capacity limit and substation capacity constraints should be satisfied to find the best solution of the optimal DG and capacitor placement and sizing. These constraints are given in Eqs. (9)–(12).

$$|V_{min}| \leq |V_i| \leq |V_{max}|, \tag{9}$$

$$I_i \leq I_i^{rated}, \tag{10}$$

$$P_{DG} \leq P_S, \tag{11}$$

$$Q_C \leq Q_S, \tag{12}$$

where $|V_{max}|$ and $|V_{min}|$ are the maximum and minimum voltage limits at bus i, I_i and I_i^{rated} are the actual current flow and rated maximum current of the conductor, P_{DG} is the active power supplied by DG, Q_C is the reactive power by capacitor, P_S and Q_S are the active and reactive power supplied by substation, respectively.

4 Simulation and Results

The Fig. 6. shows the one-line diagram of the modified 14-bus distribution system based on Vava'u distribution network. It has one central generator. Tables 1 and 2 are the bus data and line data of the system, respectively. The base case analysis is done by Newton-Raphson method to obtain the voltage (p.u), power flow and line loss in the distribution network. The voltage and power loss of base case is shown in Table 3 and Fig. 7.

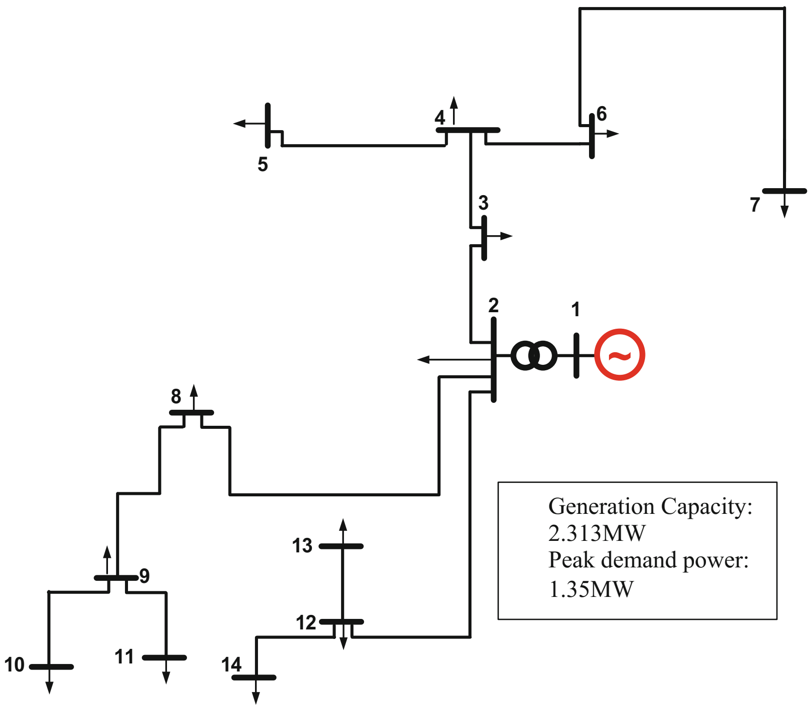

Fig. 6. One-line diagram of the modified 14-bus distribution system.

Table 1. Bus data of the modified 14-bus distribution system

Bus no	Bus code	Voltage mag (p.u)	P(Load) (MW)	Q(Load) (MW)	P(Gen) (MW)	Q(Gen) (Mvar)	Qmin (injected) (Mvar)	Qmin (injected) (Mvar)
1	1	0.0	0.0000	0.0000	0	0	0	0
2	0	0.0	0.5030	0.2436	0	0	0	0
3	0	0.0	0.0451	0.0219	0	0	0	0
4	0	0.0	0.0925	0.0448	0	0	0	0
5	0	0.0	0.1646	0.0797	0	0	0	0
6	0	0.0	0.1306	0.0632	0	0	0	0
7	0	0.0	0.0669	0.0324	0	0	0	0
8	0	0.0	0.0477	0.0231	0	0	0	0
9	0	0.0	0.0547	0.0265	0	0	0	0
10	0	0.0	0.0566	0.0274	0	0	0	0
11	0	0.0	0.0370	0.0179	0	0	0	0
12	0	0.0	0.0873	0.0423	0	0	0	0
13	0	0.0	0.0141	0.0068	0	0	0	0
14	0	0.0	0.0499	0.0242	0	0	0	0

Table 2. Line data of the modified 14-bus distribution system

Line no	Bus no from	Bus no to	Length (km)	R (p.u)	X (p.u)	½ B (p.u)
1	1	2	0.00	0.0000	0.0200	0
2	2	3	1.95	0.0873	0.0336	0
3	2	8	4.92	0.2202	0.0847	0
4	2	12	8.26	0.3698	0.1422	0
5	3	4	1.92	0.0860	0.0331	0
6	4	5	4.75	0.2126	0.0818	0
7	4	6	1.28	0.0573	0.0220	0
8	6	7	8.14	0.3644	0.1402	0
9	8	9	4.63	0.2073	0.0797	0
10	9	10	3.48	0.1558	0.0599	0
11	9	11	3.89	0.1741	0.0670	0
12	12	13	2.55	0.1142	0.0439	0
13	12	14	4.19	0.1876	0.0721	0

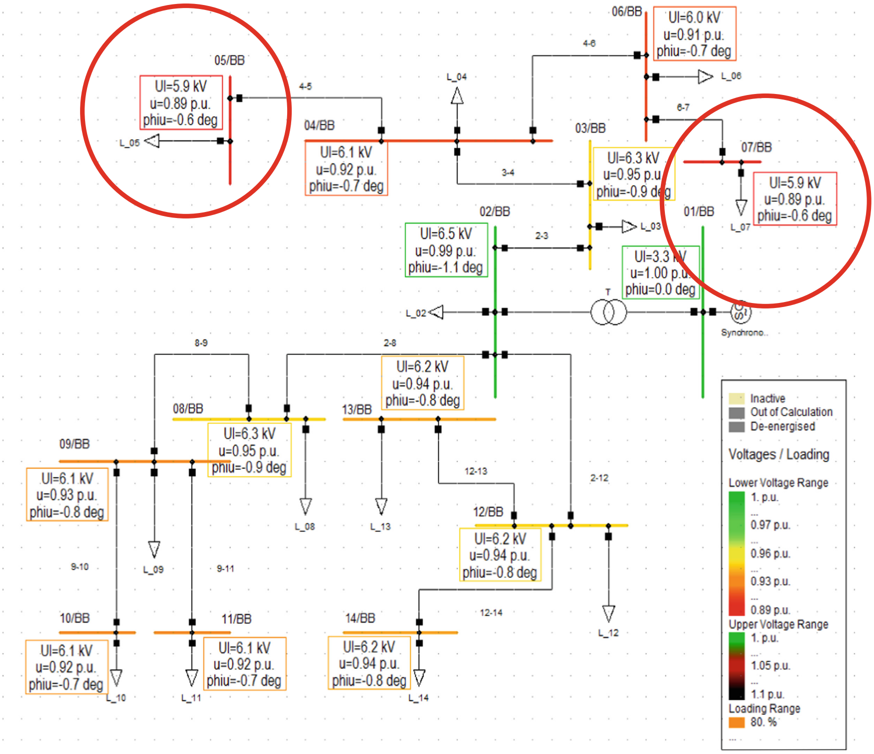

Fig. 7. DIgSILENT PowerFactory result of the modified 14-bus distribution system.

Table 3. Voltage and power flow result of base case

Bus no	Voltage mag (p.u)	Angle (degree)	P(Load) (MW)	Q(Load) (MW)	P(Gen) (MW)	Q(Gen) (Mvar)	Qmin (injected) (Mvar)	Qmax (injected) (Mvar)
1	1.000	0.00	0.0000	0.0000	1.4208	0.7137	0	0
2	0.991	−0.07	0.5030	0.2436	0	0	0	0
3	0.953	−0.89	0.0451	0.0219	0	0	0	0
4	0.918	−0.72	0.0925	0.0448	0	0	0	0
5	0.887	−0.56	0.1646	0.0797	0	0	0	0
6	0.909	−0.67	0.1306	0.0632	0	0	0	0
7	0.887	−0.55	0.0669	0.0324	0	0	0	0
8	0.954	−0.89	0.0477	0.0231	0	0	0	0
9	0.928	−0.76	0.0547	0.0265	0	0	0	0
10	0.920	−0.72	0.0566	0.0274	0	0	0	0
11	0.922	−0.73	0.0370	0.0179	0	0	0	0
12	0.944	−0.84	0.0873	0.0423	0	0	0	0
13	0.943	−0.83	0.0141	0.0068	0	0	0	0
14	0.936	−0.80	0.0499	0.0242	0	0	0	0
Total power			1.3500	0.6538	1.4208	0.7137		
Power loss								0.07082

The maximum DG and capacitor sizes are taken based on the total load demands of 1.35 MW and 0.654 MVAr as shown in Table 3. The variables of population in the PSO algorithm are location and size of DG or shunt capacitor. The randomly initialized variables in each particle are compared and selected for the better position with respect to optimal objective results, the optimal result is the minimum total power loss in the distribution system. The parameters of this PSO algorithm are as follows: maximum number of iteration is 200, population size is 10, inertia weight (w) is 0.9, and acceleration coefficient c_1 and c_2 are 0.5 except for case 3 which has 300 maximum iteration number due to a convergence issue. Table 4 shows the appropriate location and size of DG and shunt capacitor, the total power loss and the voltage improvement at buses 5 and 7, the two buses with voltage below 0.9 p.u in base case, after the installation in different cases. The simulation results show that the proposed algorithm significantly decreased the power loss while improving the weakest bus voltages.

Table 4. Optimal location and size in three cases and total power loss after installation.

Case	Location	DG size (MW)	Capacitor size (MVAr)	Total power loss (MW)	Loss reduction (%)	Bus 5 voltage (p.u)	Bus 7 voltage (p.u)
Base case	-	-	-	0.0708	0	0.887	0.887
Case 1	4	0.5016	-	0.0369	48	0.953	0.953
Case 2	4	-	0.2575	0.0624	12	0.902	0.902
Case 3	4	0.4948	0.2417	0.0298	58	0.967	0.967

5 Conclusion

The optimal location as well as size of DG and shunt capacitor has been applied for power loss minimization in an islanded distribution system. Three case scenarios are presented to compare the active power loss reduction due to the optimal location and size. The Newton-Raphson power flow and PSO are implemented in MATLAB. The results obtained from the Matlab simulations have been verified with DIgSILENT PowerFactory. The results show that the implemented algorithm successfully reduced power loss while maintaining the constraints. The most optimal solution is found for Case 3 with the total power loss of 0.0298 MW. In addition, the lowest bus voltages of 0.887 p.u at bus 5 and 7 in base case are improved to 0.967 p.u in Case 3. Hence, Case 3 is also the best solution for the voltage improvement.

References

1. Zamora, R., Srivastava, A.K.: Controls for microgrids with storage: review, challenges, and research needs. Renew. Sustain. Energ. Rev. **14**, 2009–2018 (2010)
2. Kroposki, B.: Smart grid overview. In: Fall 2012 Federal Utility Partnership Working Group (FUPWG) Meeting (2012). https://www.energy.gov/sites/prod/files/2013/10/f4/fupwg_fall12_kroposki.pdf
3. The World Bank: World Bank Development Indicator (2014). https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS
4. Acharya, N., Mahat, P., Mithulananthan, N.: An analytical approach for DG allocation in primary distribution network. Int. J. Electr. Power Energ. Syst. **28**, 669–678 (2006)
5. Willis, H.L.: Analytical methods and rules of thumb for modeling DG-distribution interaction. In: Power Engineering Society Summer Meeting, pp. 1643–1644 (2000)
6. Caisheng, W., Nehrir, M.H.: Analytical approaches for optimal placement of distributed generation sources in power systems. IEEE Trans. Power Syst. **19**, 2068–2076 (2004)
7. Georgilakis, P.S., Hatziargyriou, N.D.: Optimal distributed generation placement in power distribution networks: models, methods, and future research. IEEE Trans. Power Syst. **28**, 3420–3428 (2013)
8. AlRashidi, M.R., AlHajri, M.F.: Optimal planning of multiple distributed generation sources in distribution networks: a new approach. Energ. Convers. Manag. **52**, 3301–3308 (2011)
9. Saadat, H.: Power System Analysis, 3rd edn. PSA Publishing LLC (2011)
10. Grainger, J.J., Stevenson, W.D., Chang, G.W.: Power System Analysis. McGraw-Hill Education, New York City (2016)
11. Kansal, S., Kumar, V., Tyagi, B.: Optimal placement of different type of DG sources in distribution networks. Int. J. Electr. Power Energ. Syst. **53**, 752–760 (2013)