Chapter 6
Optimal Siting and Sizing of Distributed Generations

Karar Mahmoud and Yorino Naoto

Abstract Recently, the penetration of distributed generations (DG) has been obviously increased in electric distribution networks throughout the world. DGs are small scale generators connected near load centers in networks, thereby avoiding losses in transmission systems and releasing system capacity. At present, there are many types of DG, such as wind power, solar power, fuel cell, biomass, micro-turbines, and diesel engines. DG can play an important role in improving the performance of the networks; therefore, allocating DG optimally is one of the most crucial subjects in DG planning. In this chapter, the DG allocation problem is studied, and an efficient method is presented for accurately solving this optimization problem. The proposed method combines between analytical expressions and an optimal power flow (OPF) algorithm to determine the optimal locations, sizes and the best mix of various DG types for minimizing the total real power loss in electric distribution networks. The proposed analytical expressions are general for directly calculating the optimal sizes of any combination of multi-type DG technologies. The optimal power factors of the various units can be analytically computed, thereby contributing positively to loss reduction. The 69-bus test system is used to test the proposed method. The effectiveness of the proposed method is demonstrated for determining the optimal mix of various combinations of different DG types.

Keywords Electric distribution networks · DG location · DG size
Power loss · Optimal allocation

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6.1 Introduction

The needs for reliable and efficient electric distribution networks have motivated the research on renewable energy sources (RES). RESs, such as wind turbines, photovoltaic (PV), and biomass systems, are clean sources with low investment costs [1]. In electric distribution networks, the penetration of distributed generations (DGs) has steadily increased because of their benefits. DG units are allocated near load centers, reducing the stress on the transmission systems and saving costs [2–5].

The introduction of DG units into electric distribution networks has great impacts on the operation, stability, and protection of the systems. These impacts vary depending on the selected locations, sizes and types of the DG units [6–8]. As most of the losses in the entire power systems are normally dissipated in electric distribution networks, considering DG impacts on losses is important when allocating the DG units. The total active losses are significantly affected by DG, where they can be decreased/increased according to the DG allocation [9, 10]. Voltage rise and reverse power flow are common technical problems associated with the integration of DG in electric distribution networks. These technical problems constraints the allowable penetration of DG. An efficient method is required to allocate DG in an optimal way with considering overall system and DG constraints.

The allocation of DG units in MV electric distribution networks is considered an important issue for system planners. The optimal DG allocation aims at determining the best locations and sizes of DGs to optimize the network operation. Recently, many methods have been presented in the literature for solving the optimal DG allocation problem in networks. These methods are categorized as follows: (1) numerical-based methods, (2) heuristic-based methods, and (3) analytical-based methods. Examples of numerical-based methods are gradient search [11], linear programming [12], optimal power flow [13], and exhaustive search [14, 15]. These methods can determine the optimal DG sizes at candidate locations. To determine the optimal locations of DGs, these numerical-based are applied to solve the optimal DG sizes at all possible combinations of DG locations. The heuristic-based methods utilize artificial intelligence algorithms, e.g., genetic algorithms [16, 17], particle swarm optimization [18], harmony search [19], and tabu search [20]. These heuristic-based methods have the ability to deliver near-optimal solutions of DG sizes and locations but require exhaustive computational efforts. Regarding analytical-based methods, they are simple, easy to be applied, and computationally fast. The analytical-based methods simplify the DG allocation problem by considering only uniformly distributed load types or single DG placements [21, 22]. In [23], an analytical method is presented to deliver the optimal locations of DG units, and their sizes are optimally calculated using the Kalman filter method. In [24, 25], a method based on the concept of load centroid to optimally allocate multiple DGs. An analytical method for allocating a single DG unit is proposed in [26], and then it is improved in [27, 28] by considering the reactive power capability of multiple DG units.

This book chapter is on the optimal siting and sizing of multi-type DG units in electric distribution networks. In this chapter, two efficient methods for the optimal allocation of multi-type DG for loss minimization are presented. The first method is based on analytical expressions that directly can calculate the optimal sizes of multi-type DG units and evaluate the corresponding DG benefits. A second hybrid method is presented which combines the first analytical method and an optimal power flow (OPF) algorithm for solving the DG allocation problem. The presented methods are accurate, general for multi-type DGs, and valid for radial and meshed systems. The performance of the proposed methods is tested and validated using the 69-bus test system.

6.2 DG Models

According to the output scheme of DG units, they can be classified to three models: (1) DG Model A, (2) DG Model B, and (3) DG Model C. First, for DG Model A, its active power is not specified and needed to be optimally computed. Second, unlike DG Model A, the variable in the DG Model B is reactive power, not the active power generation. Third, the DG Model C model has two variables includes both active and reactive power generation, which means that this model is more complex than the other two models to be optimally solved. The mathematical representations of these units are described in Fig. 6.1. As seen in the figure, the different RES technologies have their interfaced devices to the main grid. For each DG type, once the state variable (active and/or reactive power generation), the interfaced device and the configuration of DG technology can be properly designed [29, 30]. It is important to mention that considering the reactive power capability of DG is important to simulate the real situation of employing the DG reactive power

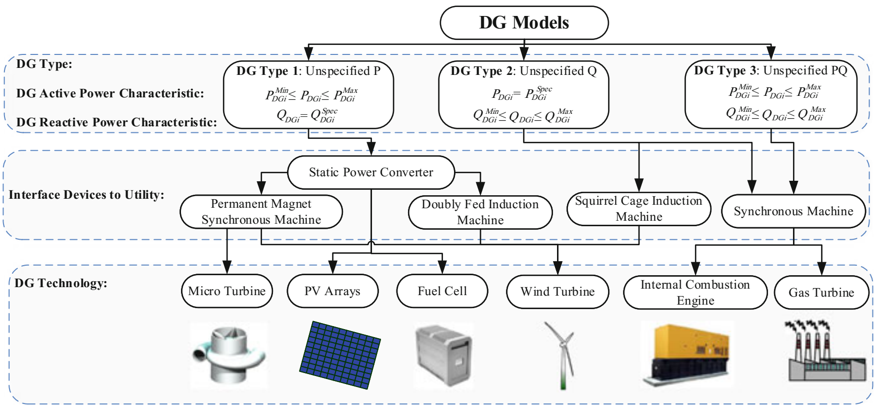


Fig. 6.1 Steady state models of different DG technologies

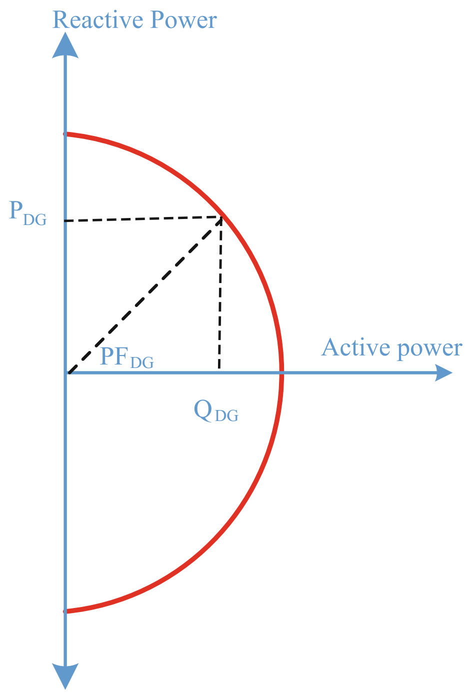


Fig. 6.2 Generation capability curve of PV inverters

injection/rejection for voltage regulations. For example, Fig. 6.2 shows the generation capability curve of PV inverters, where the red circle indicates the rated power of the interfaced inverter.

6.3 DG Impacts on Electric Distribution Networks

DGs have enormous impacts on electric distribution networks according to their locations, sizes, and types. For instance, consider a DG unit is added to a network supplied from the distribution substation (Fig. 6.3). Figure 6.4 shows the variation of power loss with active and reactive powers of the DG unit. At each DG power factor, as the active power of DG is increased, the active losses are reduced to a minimum value and increased again after exceeding a specific DG penetration level (optimal DG penetration). Therefore, to minimize the total systems losses, the optimal power factors of the DG units are required to be accurately computed.

Regarding voltage variation with DG, Fig. 6.5. describes the impact of DG penetration on the voltage profile. The penetration level of DG can be defined as the ratio of the total size of DGs to the total load demand in the system. Normally, the voltage of distribution feeders drops with increasing the distance from the distribution substation. However, if a DG unit with high penetration is added,

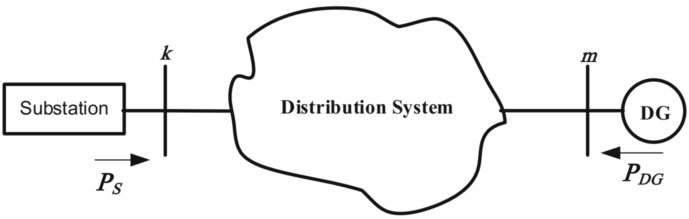


Fig. 6.3 Electric distribution network with DG

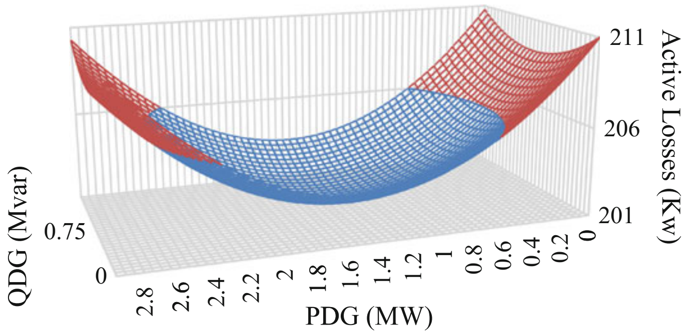


Fig. 6.4 The variation of the active losses with active and reactive powers of DG

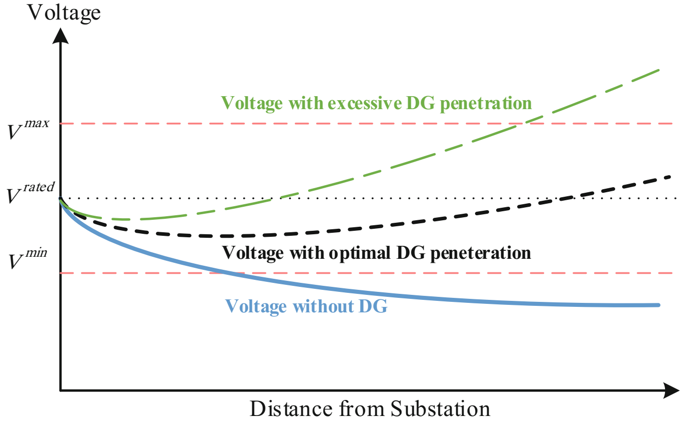


Fig. 6.5 The variation in voltage profile with the penetration level of DG

voltage profile will increase with distance from the substation. For example, the penetration level of the PV units is changed by increasing the number of arrays of the PV units. An optimal penetration of DG is required to ensure that the voltage profiles along the distribution feeder do not exceed lower/upper limits.

Besides losses and voltage profile, overall constraints of the electric distribution network must be considered when allocating DG.

6.4 Description of the DG Allocation Problem

The optimal placement of DG is a complex optimization as the number of alternative solutions (i.e., possible locations and sizes of units) is huge and the electric distribution network is nonlinear. Figure 6.6 shows an example of a network where various components are needed to be placed at some of their recommended sites. These recommended sites for each unit type can be listed according to many factors including fuel distribution, investor strategies, weather conditions (for renewable DG) and etc. Figure 6.7 shows a PV system where its optimal size can be specified by the number of PV models. Therefore, the target of optimal placement is to determine the best set of locations for the various units, according to their recommendation locations. For instance, consider installing N_{DG} DG units in a network with N_B nodes that are eligible for the installation.

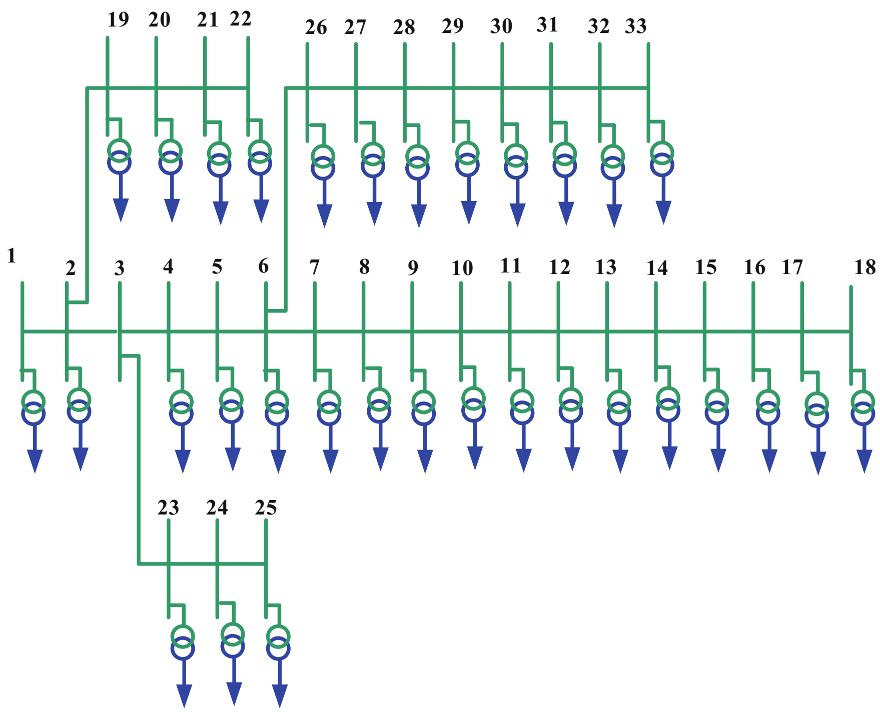
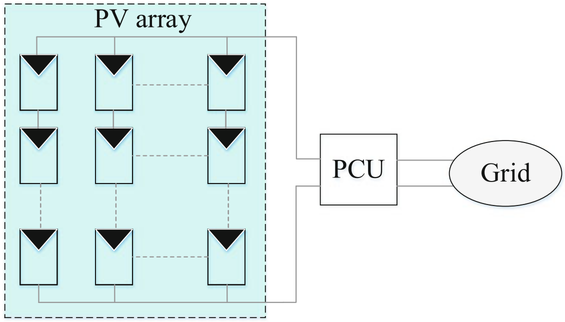


Fig. 6.6 Example of an electric distribution network

Fig. 6.7 PV system model



The DG units of type i, whose number is N_{DGi}, can be installed only in their corresponding nodes N_{Bi}. Thus

$$N_{DG} = \sum_{i=1}^{N_{DGT}} N_{DGi}, \quad N_B = \sum_{i=1}^{N_{DGT}} N_{Bi} \tag{6.1}$$

where N_{DGT} is the number of DG types to be installed. The number of possible combination of DG sites in this case can be computed from

$$N_{Com} = \left(\prod_{i=1}^{N_{DGT}} C_{N_{DGi}}^{N_{Bi}} \right) (N_{DG}!) \tag{6.2}$$

To determine the optimal combination, it is required to evaluate all of these possible combinations of the DG sites. Note that the number of the possible combinations is high, especially when placing different DG types in large-scale distribution networks. This excessive number of combinations will not only increase the complexity of the optimization problem but also degrade the computational performance. A fast method is required to determine the optimal combination among all of these combinations. The main requirements of the DG allocation method can be listed as

- Accurate (proper DG locations with optimal capacities).
- Generic formulations for multi-type DG allocation.
- High computational speed (especially when allocating multiple DGs in large-scale systems).

6.5 Combined Analytical-OPF Method

6.5.1 Losses with DG

The basic formula for calculating the total active power loss P_{loss} is expressed as

$$P_{loss} = \sum_{j \in \phi} \varphi_j \left(P_j^2 + Q_j^2 \right) \tag{6.3}$$

in which

$$\varphi_j = \frac{R_j}{V_j^2}$$

where P_j and Q_j the active and reactive power flows, respectively, through the distribution line j. ϕ is a set of system lines, V_j is voltage magnitude of the receiving bus of the line, and R_j is line resistance. Consider adding a DG or a capacitor, which injects P_g and/or Q_g, at a certain bus in a network, the variation in the reactive power loss can be linearly estimated, whereas it can be computed by

$$P_{loss,DG} = \sum_{j \in \alpha} \varphi_j \left(P_j^2 + Q_j^2 \right) + \sum_{j \in \beta} \varphi_j \left(\left(P_j - P_g \right)^2 + \left(Q_j - Q_g \right)^2 \right), \quad \alpha \cup \beta = \phi \tag{6.4}$$

where α and β represent two different sets of lines whose power flows are not affected and whose power flows are affected by adding the DG, respectively. The above equation can be modified to be in general form for expressing the effect of integrating multiple DG units and capacitors at a set of locations ψ on reactive power loss as follows

$$P_{loss,DG} = \sum_{j \in \alpha} \varphi_j \left(P_j^2 + Q_j^2 \right) + \sum_{j \in \beta} \varphi_j \left(\left(P_j - \sum_{i \in \psi} \Omega_{ij} P_{gi} \right)^2 + \left(Q_j - \sum_{i \in \psi} \Omega_{ij} Q_{gi} \right)^2 \right) \tag{6.5}$$

The Ω matrix can be built based on the radial structure of networks. The binary matrix Ω for a small-scale system shown in Fig. 6.8. when adding PV and wind units, respectively, at buses 11 and 7 can be expressed as follows

$$\begin{array}{c} \textit{System Buses} \\ \begin{array}{cccccccccccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 \end{array} \end{array}$$

$$\Omega = \begin{bmatrix} 1 & 1 & 1 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \end{bmatrix} \begin{array}{ll} 7 & \textit{Wind Bus} \\ 11 & \textit{PV Bus} \end{array} \tag{6.6}$$

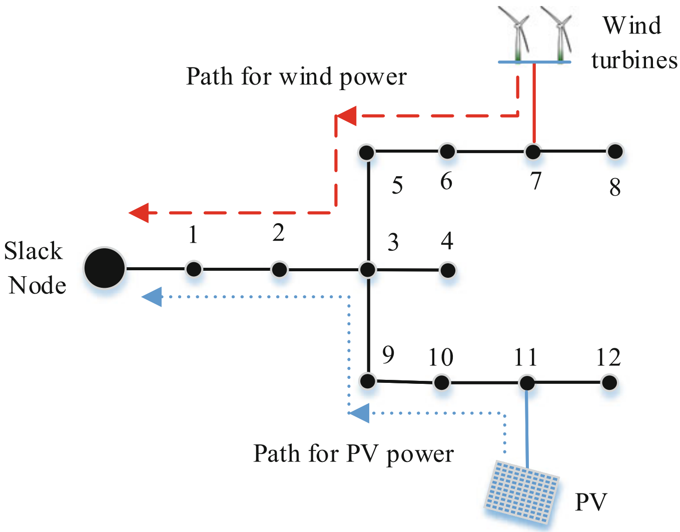


Fig. 6.8 Power flows after adding PV and wind units to an electric distribution network

Equation (6.5) could be expressed in different ways with active or reactive power injection of DG with respect to the power factor PF_g as in (6.7) and (6.8).

$$Q_{gi} = M_{gi} P_{gi} \tag{6.7}$$

where

$$M_{gi} = \frac{\sqrt{1 - PF_{gi}^2}}{PF_{gi}} \tag{6.8}$$

6.5.2 Analytical Expressions for Optimal DG Sizing

The objective of the placement of DG units in electric distribution networks is to minimize the total power loss by selecting best locations and optimal sizes of these units. Since the losses can be represented by (6.5), the objective function can be expressed as minimization of $P_{loss,DG}$. The variable for this optimization problem is the active P_g and reactive Q_g powers of the units. As the variations of $P_{loss,DG}$ with P_g and Q_g are equal to zero at the optimal point,

$$\frac{\partial P_{loss,DG}}{\partial P_{gm}} = 0, \quad \forall m \in \Psi \tag{6.9}$$

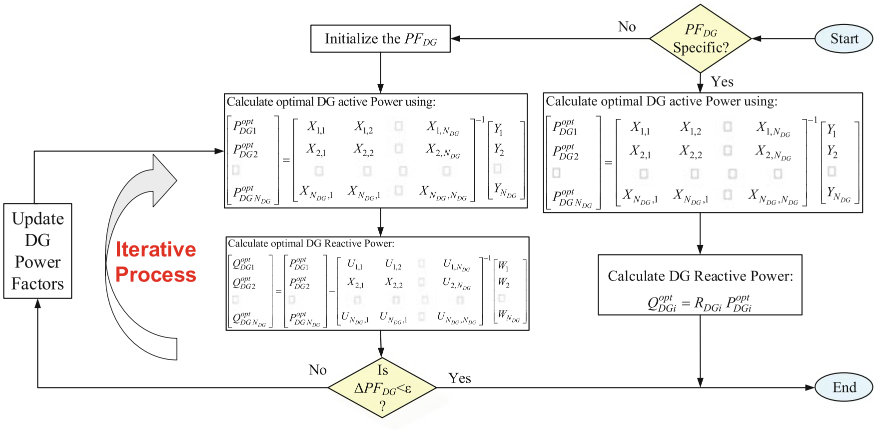


Fig. 6.9 Optimal DG sizing process

$$\frac{\partial P_{loss,DG}}{\partial Q_{gm}} = \frac{\partial P_{loss,DG}}{\partial P_{gm}}, \quad \forall m \in \Psi \tag{6.10}$$

The above two equations can be written for each unit; therefore, their number is equal to double the number of the units to be placed. For the set of (6.9) and (6.10), they can be arranged in matrix form to be as given in (6.11) and (6.12), respectively. With employing the new (6.11) and (6.12), a direct optimal solution of P_g and Q_g for all units (i.e., optimal power factors) can be delivered. Once the combination of the DG and capacitor locations is defined, the optimal sizing for all units can be computed, as shown in Fig. 6.9. The parameters of XYWU matrices in (6.11) and (6.12) can be completely computed directly from the power flow result for the base case without requiring iterative processes. The proposed formulae have been established based on the radial structure of power distribution systems. In order to apply the proposed method to radial systems, it is required to break all system loops and then the DG allocation problem is solved for the resulted radial system [31, 32].

$$\begin{bmatrix} P_{g\Psi_1} \\ P_{g\Psi_2} \\ \vdots \\ P_{g\Psi_N} \end{bmatrix} = \begin{bmatrix} X_{\Psi_1,\Psi_1} & X_{\Psi_1,\Psi_2} & \cdots & X_{\Psi_1,\Psi_3} \\ X_{\Psi_2,\Psi_1} & X_{\Psi_2,\Psi_2} & \cdots & X_{\Psi_2,\Psi_N} \\ \vdots & \vdots & \vdots & \vdots \\ X_{\Psi_N,\Psi_1} & X_{\Psi_N,\Psi_2} & \cdots & X_{\Psi_N,\Psi_N} \end{bmatrix}^{-1} \begin{bmatrix} Y_{\Psi_1} \\ Y_{\Psi_2} \\ \vdots \\ Y_{\Psi_N} \end{bmatrix} \tag{6.11}$$

$$\begin{bmatrix} Q_{g\Psi_1} \\ Q_{g\Psi_2} \\ \vdots \\ Q_{g\Psi_N} \end{bmatrix} = \begin{bmatrix} P_{g\Psi_1} \\ P_{g\Psi_2} \\ \vdots \\ P_{g\Psi_N} \end{bmatrix} - \begin{bmatrix} U_{\Psi_1,\Psi_1} & U_{\Psi_1,\Psi_2} & \cdots & U_{\Psi_1,\Psi_3} \\ U_{\Psi_2,\Psi_1} & U_{\Psi_2,\Psi_2} & \cdots & U_{\Psi_2,\Psi_N} \\ \vdots & \vdots & \vdots & \vdots \\ U_{\Psi_N,\Psi_1} & U_{\Psi_N,\Psi_2} & \cdots & U_{\Psi_N,\Psi_N} \end{bmatrix}^{-1} \begin{bmatrix} W_{\Psi_1} \\ W_{\Psi_2} \\ \vdots \\ W_{\Psi_N} \end{bmatrix} \tag{6.12}$$

where

$$X_{n,m} = \sum_{j \in \beta} \Omega_{nj} \varphi_j \Omega_{mj} (1 + M_{DGm} M_{DGn}), \qquad Y_m = \sum_{j \in \beta} \Omega_{mj} \varphi_j (P_j + M_{DGm} Q_j)$$

$$U_{n,m} = \sum_{j \in \beta} \Omega_{nj} \varphi_j \Omega_{mj}, \qquad W_m = \sum_{j \in \beta} \Omega_{mj} \varphi_j (P_j - Q_j)$$

6.6 Solution Process

The proposed method for determining the optimal mix of DG involves a combination of the proposed analytical expressions and OPF [31–34]. The objective function of OPF is set to be the minimization of the losses with considering equality and inequality constraints (6.13)–(6.17). Since the analytical expressions are general for optimally solving any combination of sites where various units are placed, they can be employed to evaluate all possible combinations of the sites. This evaluation process is essential to select the optimal combination of unit sites (i.e., the optimal mix). The computation burden of the evaluation process is greatly improved using the proposed analytical expressions, as the optimal solution can be directly computed using (6.11) and (6.12). The benefits of employing the OPF formulation are to apply system constraints for the optimal combination obtained by the analytical expressions and slightly correct the unit sizes to the exact optimal solution. The flowchart which illustrates the solution process of the proposed method is given in Fig. 6.10. The backward/forward sweep power flow method presented in [35] is employed as a power flow solver. As clear in the figure, the proposed analytical expressions are needed to calculate the optimal mix, while OPF is employed once for considering system constraints. This combination between these two formulations is efficient; since the proper optimal combination can be obtained with the analytical expressions, and the optimal solution can be accurately computed with including various constraints via OPF.

Minimize:

$$F = \sum_{j=1}^{N_{Line}} P_L^i \tag{6.13}$$

Subject To: (1) Equality constraints

$$P_S - P_D - \sum_{i=1}^{N} |V_j||V_i| \left(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij} \right) = 0 \tag{6.14}$$

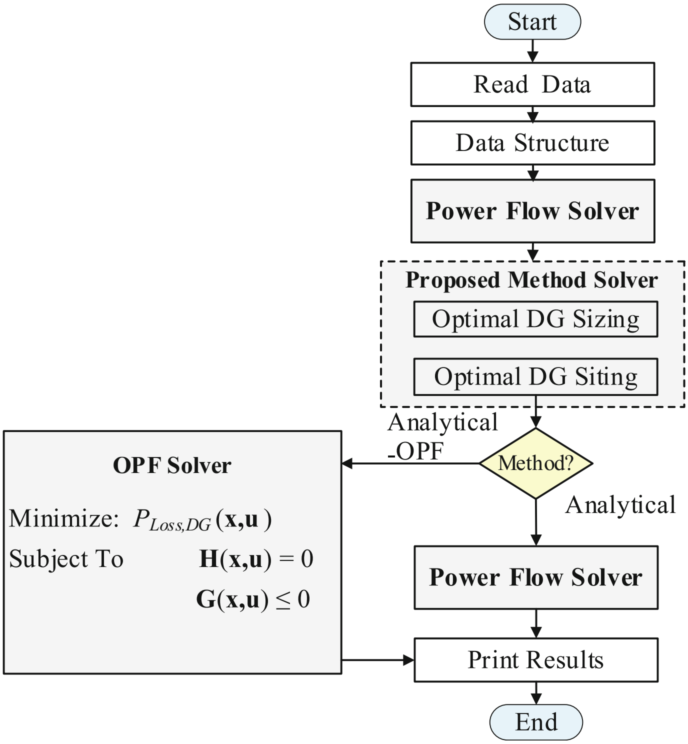


Fig. 6.10 Flowchart of the proposed method for DG allocation

$$Q_S - Q_D - \sum_{i=1}^{N} |V_j||V_i|\left(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}\right) = 0 \tag{6.15}$$

(2) Inequality constraints

$$P_{DGi}^{\min} \leq P_{DGi} \leq P_{DGi}^{\max} \quad \text{for } i = 1, 2, \ldots N_{DG} \tag{6.16}$$

$$V_i^{\min} \leq V_i \leq V_i^{\max} \quad \text{for } i = 1, 2, \ldots N \tag{6.17}$$

6.7 Results and Discussions

6.7.1 Assumptions

- A single DG unit can be placed on each bus in the test system;
- The maximum allowed number of DG to be connected is three units;

- The specified generation values of DG Types A and DG type B are considered to be zero.
- For DG Type C, its power factor is equal to 0.90 lagging.
- The maximum penetration of DG is 100%.
- The minimum and maximum limits of voltages are 0.9 and 1.05, respectively.

6.7.2 Test System

The 69-bus test system is used to test out the proposed method for DG placement. Figure 6.11 shows the system, which is a preferable benchmark test system for several allocation approaches, where the data are given in [36]. This system consists of 68 load buses and a slack bus, and the active and reactive power loss in the base case are 225 kW and 102 kvar, respectively. The proposed method has been implemented by C++ programming. This analysis aims at demonstrating the effectiveness of the proposed method for solving the allocation problem of different DG types. Assume that an area is recommended for each type of DG. To do so, the 69-bus distribution test system is divided into four different areas as

- Area-A: This area contains candidate locations of DG type A.
- Area-B: This area contains candidate locations of DG type B.
- Area-C: This area contains candidate locations of DG type C.
- Area-D: No DG is allowed to be installed in this area.

Table 6.1 shows different studied cases with different combinations of DG types. The first case (Case 0) is the base case without DG while the other seven cases (Case 1–Case 7) involve installing three DG units of different types, as illustrated in the table.

Table 6.1 Number of DG for different cases

Cases	DG Type A	DG Type B	DG Type C
Case 0	–	–	–
Case 1	2	1	–
Case 2	2	–	1
Case 3	1	2	–
Case 4	–	2	1
Case 5	–	1	2
Case 6	1	–	2
Case 7	1	1	1

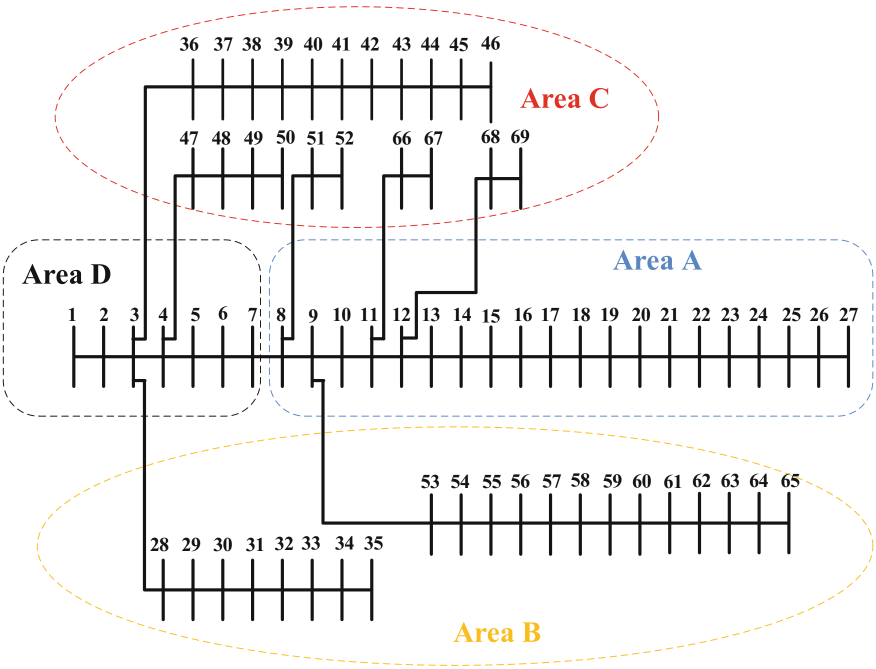


Fig. 6.11 The 69-bus test system

6.7.3 *Analyses*

In this subsection, the benefits of allocating DGs to the test system are discussed. Table 6.2 shows the computed DG sizes and their corresponding buses with using the proposed analytical-OPF method. Note that the calculated DG locations and sizes are almost different for all the cases at which the DG numbers are similar (three units) for the cases. The only difference between the cases is the combinations of the different DG types. These results imply that the type of DG has a significant influence on the DG allocation problem. The major differences between the eight cases can be listed as

- **Total Losses**: Figure 6.12 shows the losses in kW and kVA for the cases after allocating the DG units into the 69-bus test system. It is obvious that there are significant reductions of the total losses for all the cases of DG allocation with respect to the base case, but these reductions are different for the cases. Note that DG type C has a higher effect on loss reduction compared with the other DG types. For example, Case 5 has a high value of loss reduction due to its two DG units of type C. This feature is reasonable since this DG type can inject active and reactive power, thereby contributing heavily in reducing losses. In addition,

Table 6.2 Results for the 69-bus test system

Cases	DG Type A		DG Type B		DG Type C		Total DG size (kVA)
	Bus	Size (kVA)	Bus	Size (kVA)	Bus	Size (kVA)	
Case 0	–	–	–	–	–	–	–
Case 1	9 18	2388.12 451.373	61	1314.6	–	–	4154.0
Case 2	12 21	370.6 312.8	–	–	51	2535.9	3219.2
Case 3	9	2839.5	53 61	652.6 1193.5	–	–	4685.6
Case 4	–	–	61 64	938.9 206.5	51	2640.3	3785.7
Case 5	–	–	61	1138.2	51 68	2007.7 704.3	3850.3
Case 6	21	302.1	–	–	51 66	2129 793.8	3225.2
Case 7	9	2249.6	61	1270.1	68	655.4	4175.2

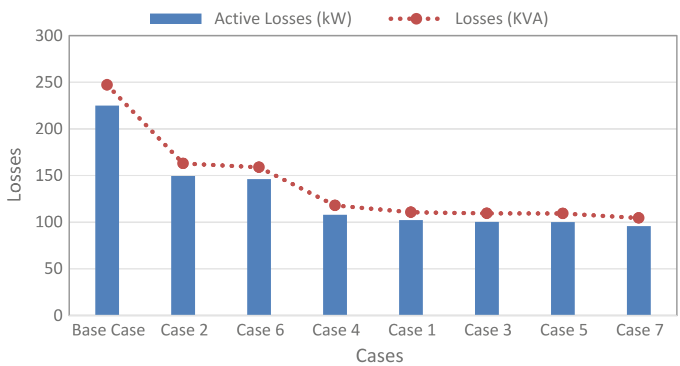


Fig. 6.12 The losses for the different cases

it is noted that Case 7 which involves different three types of DG yields the highest loss reduction.

- **The Total Size of DGs**: The total size of DGs is important in the DG allocation as it can be employed to estimate the installation cost of DG. The higher DG size, the higher cost of DG. The total size of DG units for the case are shown in Table 6.2. It is clear from the table that Case 1 and Case 3 at which DG type C is not included, have the highest capacity. This trend means that the installation costs for these two cases are relatively high. However, this trend can be an advantageous feature if the penetration DG is required to be maximized.
- **Voltage Profile**: Figure 6.13 shows the voltage profile for the different cases. Table 6.3 compares the minimum voltage, maximum voltage, and the value of

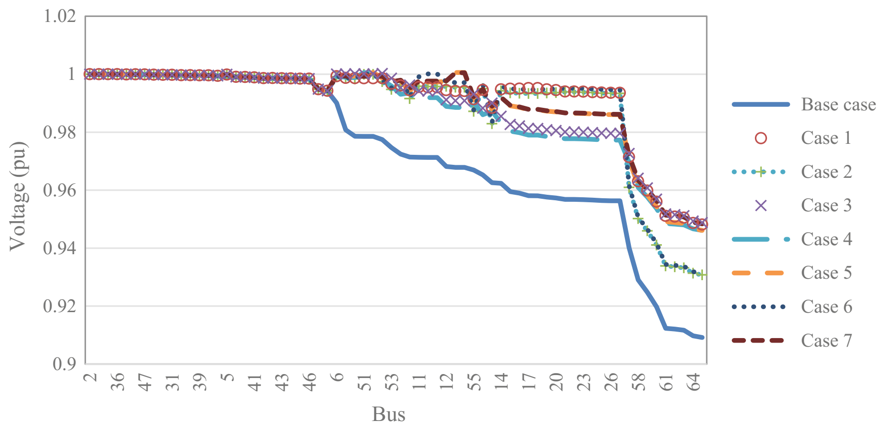


Fig. 6.13 Voltage profile for the different cases

Table 6.3 Voltage for the different cases

Item	Base case	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Maximum voltage	0.9092	0.9481	0.9307	0.9488	0.9461	0.9461	0.9313	0.9484
Maximum voltage	1.0000	1.0000	1.0000	1.0002	1.0005	1.0006	1.0001	1.0005
Voltage deviation	0.0993	0.0193	0.0345	0.0236	0.0278	0.0224	0.0336	0.0207

voltage deviation for the different cases. It is clear that the voltage profile is significantly improved for the cases of DG installation compared with Case 0.

It is important to mention that the proposed method solves the DG allocation problem optimally, and the total losses are reduced for all cases. The proposed method is general, and so it can be applied for solving other cases and electric distribution networks. The proposed method is a helpful tool for optimizing the networks with DG and selecting the optimal mix of the available DG technologies to maximize benefits. Note that the proposed method is very effective for solving the allocation problem of multi-type DG units compared with existing analytical methods in the literature. This superiority is accomplished as the proposed method has high accuracy rates with fast computational speed, and it can directly compute the optimal power factors of different DG types [31, 32].

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