Multiple distributed generation units allocation in distribution network for loss reduction based on a combination of analytical and genetic algorithm methods

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Abstract: Many methods have been proposed to determine the optimal location and capacities of distributed generation (DG) units to reach the lowest value for system losses. In this study, the combination of analytical and genetic algorithm methods is used for optimal allocation of multiple DGs in a distribution network to minimise the system losses. This combination guarantees the convergence accuracy and speed in multiple DG units allocation. In this study, the DGs active power, power factor, and location are simultaneously considered during distribution network losses minimisation. The utility will dictate only the maximum DG power generation if the DG is installed by DG owner. However, both of the size and the location of DG will be determined by the utility if the DG is installed by it. The proposed method is applied to 33-bus and 69-bus test distribution systems. Simulation results show that the proposed method results in lower losses compared with the other methods.

1 Introduction

The newly introduced distributed or decentralised generation units connected to local distribution systems are usually not dispatchable by a central operator, but they can have significant impact on the power flow, voltage profile, stability, continuity, and quality of power supply for customers and electricity suppliers [1–4]. The exact output power of some distributed generation (DG) units such as photovoltaic energy converters and wind turbines depends on the weather conditions and they cannot be accurately anticipated.

Owing to the locally available resources and their small scale, DG units are mostly connected to the distribution voltage level. When the penetration of DG units is high, the generated power of DG units alters the power flow not only in the distribution system, but also in the sub-transmission system [5, 6].

The optimal placement of DG units is one of the major challenges for system designers and various methods have been used for finding the optimal location of DG units. For example, the Lagrange method, two-degree gradient method and sensitivity analysis have been used for DG placement [7–10].

The challenge of identifying the best network locations for DGs has attracted significant research efforts [11–15], albeit referred to by several terms: optimal 'capacity evaluation' [16], 'DG placement' [17], or 'capacity allocation' [18–20]. Although in the literature, a wide range of objectives with a variety of constraints has been suggested, there are two distinct approaches: finding optimal locations for known DG capacities and finding optimal DG capacities at predefined locations.

The first approach aims to site DGs with specified and discrete capacities at the best locations. This problem has generally been tackled using the genetic algorithm (GA) [21, 22] or other methods [17, 23] which can handle discrete problems. For example, in [22] GA has been used to place generators of discrete capacities in order to minimise losses, costs, and network disruption, while El-Khaltam *et al.* [23] adopted a heuristic approach with an investment-based objective function to determine the optimal site and size of DGs which have known capacities. In [24], an optimisation technique based on GA and optimal power flow has been applied to minimise the active and reactive power generation costs considering the DG installation costs. The prejudging for DG capacity means that some solutions that are smaller or larger than the standard one will not be selected in search space, and therefore the solution may be a non-optimal one.

In the second approach, the user should specify the network candidate installation locations and the algorithm will determine the DG capacity at each location while meeting the network constraints. The optimisation methods in this approach use continuous functions of capacity which should be minimised by using analytical methods such as optimal power flow [16–18], linear programming [19], or gradient search [25]. These approaches are robust, well defined, and accepted, and their outcomes are repeatable. A drawback is that in case of having a large number of installation buses, the perceived optimal solution may contain a number of sites with very small DG capacities. While this case is mathematically optimal, the upfront costs of connection suggest a very small plant would not be economic. Specifying minimum capacity at each location would unduly bias the analysis and potentially present the algorithm search to find a feasible solution. As both approaches require capacity or location determination at the beginning of the algorithm, in this paper, a new method is presented that overcomes these limitations. It is a hybrid method that uses the GA to search a large range of combinations of locations and the power factor of DGs and employs an analytical approach to calculate DGs capacity for each location. Although this is achieved at the expense of requiring the number of DG units to be pre-specified, this opens up the potential to examine the benefits of strategic placement of different numbers of DG.

This method is applied to 33-bus and 69-bus test distribution systems and results show the accuracy and effectiveness of the proposed method for optimal allocation of DG units in the distribution network.

The main contributions of this paper are listed as follows:

- Combination of analytical and heuristic search methods for achieving high-speed and accurate convergence simultaneously.
- Considering the dependency of the active power flow of the slack bus to the active power generated by DGs as a new constraint in minimising distribution network losses.
- Analytical solution of the problem for minimising losses of the distribution network using a deterministic equation for DGs optimal output active power in terms of network loss coefficients and network demand.
- Considering the DGs active power, power factor, and location during minimisation of distribution network loss, simultaneously.

The rest of this paper is organised as follows: Section 3 explains the problem formulation and the proposed method. Simulations and results of multiple DG unit placements are investigated and discussed in Section 4. Finally, Section 5 concludes this paper.

2 Proposed method

2.1 Problem formulation

The active power losses in networks can be expressed as the function of the generated power by different units according to the following relationship, called Kron equation [26]

$$P_L = \sum_{j=1}^{n_g}\sum_{i=1}^{n_g} b_{ij}P_iP_j + \sum_{i=1}^{n_g} b_{i0}P_i + b_{00} \tag{1}$$

Equation (1) can be expressed by the following matrix form

$$P_L = P_g^{\mathrm{T}}\boldsymbol{B}P_g + P_g^{\mathrm{T}}\boldsymbol{B}_0 + \boldsymbol{B}_{00} \tag{2}$$

where

$$B = [b_{ij}]$$
$$B_0 = [b_{i0}]$$
$$B_{00} = b_{00}$$
$$P_g^T = [p_1\ p_2 \cdots p_{n_g}]$$

In (2), the matrices $\boldsymbol{B}$, $\boldsymbol{B}_0$, and $\boldsymbol{B}_{00}$ are the loss coefficient matrices calculated according to the method stated in [26]. Generally, these coefficients are not constant and are dependent of values of loads and generations. However, they can be calculated in the base case of the system operation.

The following assumptions are considered in this paper: the distribution network is a radial system fed at the slack bus, which is identified by number 1 and connected to the sub-transmission or transmission networks and DGs have constant power factors.

2.2 Optimal sizing of DGs

Assume n_g units of DGs are installed in the buses k_{n1}, k_{n2}, …, k_{ng} working with the constant power factors (PF_{n1}, PF_{n2}, …, PF_{ng}). Assuming the slack bus as a generation unit, there are $n_g + 1$ generation units in this network. The network losses can be calculated according to (1). It is assumed that DGs are installed at the buses 2, 3, …, $n_g + 1$. The network losses would be minimum, if the derivate of (1) with respect to p_i becomes zero.

It should be noted that P_2 … $P_{ng} + 1$ in (1), indicating the generated power by different DGs, are independent and the generated power by the slack bus, P_1, is dependent of these variables as follows

$$P_L + P_D = P_1 + \sum_{j=2}^{n_g+1} P_j \tag{3}$$

It should be noted that P_D is assumed to be constant in a specific state of the network.

Differentiation of (3) yields

$$\frac{\partial P_L}{\partial P_i} + \frac{\partial P_D}{\partial P_i} = \frac{\partial P_1}{\partial P_i} + \sum_{j=2}^{n_g+1}\frac{\partial P_j}{\partial P_i} \tag{4}$$

Since $\partial P_L/\partial P_i$ and $\partial P_D/\partial P_i$ are equal to zero, (4) can be written as follows

$$\frac{\partial P_1}{\partial P_i}(\text{at optimum point}) = -1 \tag{5}$$

As shown in (5), P_1 is dependent on the generated power by different DGs. On the other hand, in the case with minimum system losses, the ratio of the active power changes generated by the slack bus to the ones generated by DG units is equal to −1.

To minimise (1) subject to (3), the Lagrangian relaxation method is used as follows

$$f = P_L + \lambda\left(P_L + P_D - P_1 - \sum_{i=2}^{n_g+1} P_i\right) \tag{6}$$

The partial differential functions should be equal to zero, that is

$$\frac{\partial f}{\partial P_j} = (1+\lambda)\left(\sum_{i=1}^{n_g+1} 2b_{ij}P_i + b_{j0}\right) - \lambda = 0 \tag{7}$$

$$\sum_{i=1}^{n_g+1} 2b_{ij}P_i + b_{j0} = \frac{\lambda}{1+\lambda} \quad (1 \le j \le n_g + 1) \tag{8}$$

Equation (8) can be written in the matrix form, as follows

$$2\boldsymbol{B}P = \frac{\lambda}{1+\lambda}J^{n_g+1} - \boldsymbol{B}_0 \tag{9}$$

P can be calculated from (9) using the following equation

$$P = xE - F \tag{10}$$

where x, E, and F can be, respectively, calculated based on the following equations

$$x = \frac{\lambda}{2(1+\lambda)} \tag{11}$$

$$E = B^{-1}J \tag{12}$$

$$F = \frac{1}{2}B^{-1}\boldsymbol{B}_0 \tag{13}$$

Each of the elements of P is determined as follows

$$P_i = xe_i - f_i \tag{14}$$

The optimal P_is can be calculated according to (10) for the known value of x. By substituting (10)–(14) in (3), the following equation can be written

$$\begin{aligned}&(xE - f)^{\mathrm{T}}\boldsymbol{B}(xE - F) + (xE - F)^{\mathrm{T}}\boldsymbol{B}_0 + \boldsymbol{B}_{00} + P_D\\ &= x\sum_{j=1}^{n_g+1} e_j - \sum_{j=1}^{n_g+1} f_j\end{aligned} \tag{15}$$

Expanding (15) leads to the following equation

$$ax^2 + bx + c = 0 \tag{16}$$

where the parameters a, b, and c are calculated based on the following equations

$$a = E^{\mathrm{T}}\boldsymbol{B}E \tag{17}$$

By substituting E from (12), (17) can be written as follows

$$a = (B^{-1}J)^{\mathrm{T}}\boldsymbol{B}(B^{-1}J) = J^{\mathrm{T}}(B^{-1})^{\mathrm{T}}J \tag{18}$$

Since $B = BT$, (18) can be simplified as follows

$$a = J^{\mathrm{T}}B^{-1}J = J^{\mathrm{T}}E = \sum_{j=1}^{n_g+1} e_j \tag{19}$$

b is calculated according to the following equation

$$\begin{aligned} b &= -E^{\mathrm{T}}\boldsymbol{B}F - F^{\mathrm{T}}\boldsymbol{B}E + E^{\mathrm{T}}\boldsymbol{B}_0 - \sum_{j=1}^{n_g+1} e_j \\ &= -2E^{\mathrm{T}}\boldsymbol{B}F + E^{\mathrm{T}}\boldsymbol{B}_0 - \sum_{j=1}^{n_g+1} e_j \end{aligned} \tag{20}$$

Considering (13), b can be calculated based on the following equation

$$b = -E^{\mathrm{T}}\boldsymbol{B}B^{-1}\boldsymbol{B}_0 + E^{\mathrm{T}}\boldsymbol{B}_0 - \sum_{j=1}^{n_g+1} e_j = -\sum_{j=1}^{n_g+1} e_j \tag{21}$$

Finally, c can be calculated as follows

$$c = F^{\mathrm{T}}\boldsymbol{B}F + \boldsymbol{B}_{00} + P_D + \sum_{j=1}^{n_g+1} f_j \tag{22}$$

Equation (16) has two roots as follows

$$x_1 = \frac{-b + \sqrt{b^2 - 4ac}}{2a}, \quad x_2 = \frac{-b - \sqrt{b^2 - 4ac}}{2a} \tag{23}$$

Since b is negative [considering (21)], x_1 is a large number and the corresponding P_i has a large value too [according to (14)]. This answer is not acceptable because P_i stated in per unit is too big. Therefore, the following answer is the only acceptable one

$$x = \frac{-b - \sqrt{b^2 - 4ac}}{2a} \tag{24}$$

Using (10)–(24), the optimal value of P_is is determined.

2.3 Using GA for optimal power factor determination and DG allocation

In this section, the DGs power factor and their locations are determined to have the minimum value for the system losses.

GA is a general-purpose optimisation method, which has been used in optimisation problems in different fields [27–29]. GA proceeds in several steps as stated in [30].

In this paper, three variables are considered in optimisation problem for each DG unit. These variables are active power of DG, power factor of DG, and the location of DG. The active power of DG is obtained through an analytical solution and a mathematical approach (24). The power factor and the location of DGs are determined by using continuous and discrete GA, respectively. In GA, chromosomes are problem variables, which are power factor and location of DGs. Thus, assuming the n_g DG units, the length of chromosomes in GA will be equal to $2n_g$ including n_g genes for power factors (PF_1, PF_2, …, PF_n) and n_g genes for the locations of DGs connection (D_1, D_2, …, D_n). In other words, in the first step of GA process, a set of possible answers, which are called scenarios or chromosomes, are randomly produced. A chromosome is considered in this paper in the form shown in Fig. 1.

In the next step, a number will be allocated to each of the chromosomes with respect to its fitness as a possible answer. The mentioned number is determined by fitness function, which will be optimised by GA. Finally, GA chooses some chromosomes for cross-over, mutation, and replacement operators through selection operator and with respect to the fitness of the chromosomes. These operators generate a new population and the procedure will be repeated until reaching the stop condition.

To calculate the fitness function corresponding to a chromosome, the network loss is calculated based on (2) and the DGs optimal power generations are determined by using (24).

After a power flow run, the power system losses are determined based on (1) and assigned to a chromosome as its fitness value

$$\text{fitness} = P_{\text{loss}} \tag{25}$$

The GA should search for the least value of the fitness function by changing the power factor and the location of different DGs.

The problem of the DG optimal allocation is solved in this paper by using the combination of the analytical approach and heuristic searching method as shown in Fig. 2.

The main benefits of using the proposed method are listed below:

- Since the margin of DGs power generations is so wide, GA has convergence low speed and may not lead to an accurate solution. In this paper, the location of DGs installation and their power factors are determined by the GA and the optimal power generated by the DGs are determined by using the analytical method.
- Using solely the analytical method, leads to a complex and non-linear equation because differentiation of loss coefficients with respect to the DGs power factor should be calculated and the loss coefficients are non-linear and complex function of the DGs power factor. Moreover, the DGs location is a discrete parameter and its derivative with respect to the DG location is meaningless. Therefore, the heuristic search algorithm should be used for optimal DG allocation.

Considering these two issues, a combination of analytical and heuristic search methods is proposed in this paper.

3 Simulation results and discussion

The proposed method is applied to two test distribution networks (33-bus and 69-bus systems [31, 32]) shown in Figs. 3 and 4. The algorithm is implemented in MATLAB environment and the MATPOWER software is used for load flow calculations.

Two different modes of DG operation are considered in this investigation as follows: DGs generate only active power (unity power factor mode) and DGs can generate active and reactive powers (non-unity power factor mode).

PF_1	PF_2	....	PF_n	D_1	D_2	....	D_n

Fig. 1 *Form of chromosome considered in this paper*

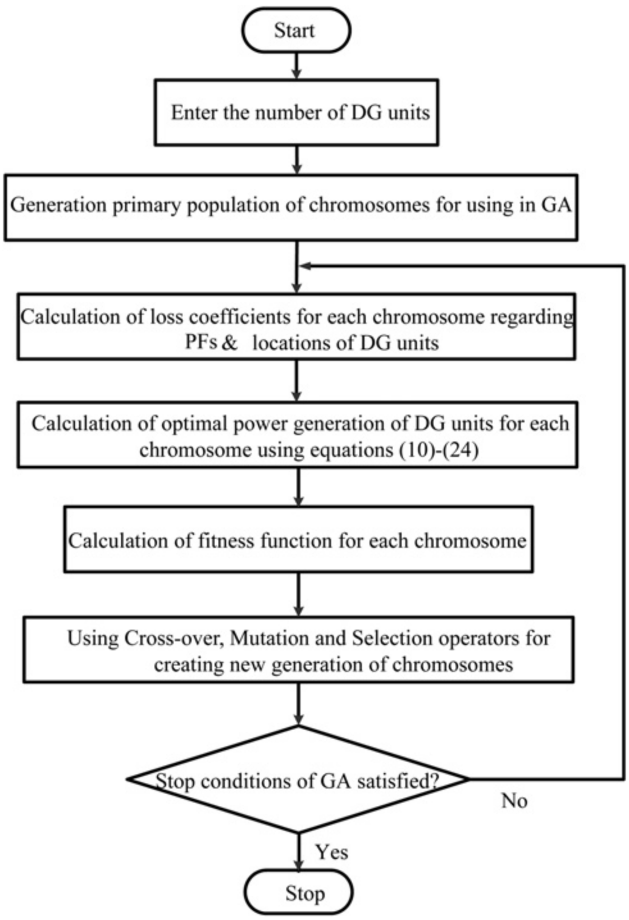

Fig. 2 *Flowchart of the proposed method*

3.1 Simulation of 33-bus test distribution system

In this section, two different modes of the DG operation are considered in the following two scenarios.

3.1.1 Scenario 1: unity power factor mode of DG operation: In this scenario, it is assumed that the DGs generate active power and no reactive power is generated/consumed by them. Different numbers of DGs are allocated in the network using the proposed method. In Table 1, the results of the proposed method are compared with other methods, that is, loss sensitivity factor (LSF), improved analytical (IA), and exhaustive load flow (ELF) methods [33].

As it can be seen in Table 1, the proposed method has better performance in loss reduction over the other methods. In the case of one DG placement, among the four algorithms, three of them propose bus 6 to install the DG. To show the performance of the proposed method in finding the optimal generation of the DG

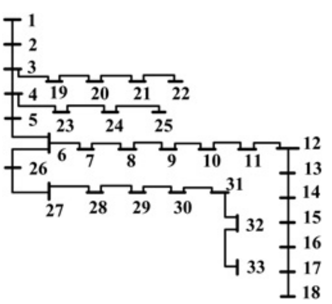

Fig. 3 *33-Bus test distribution system*

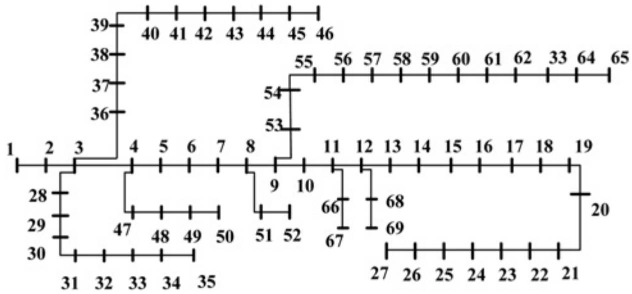

Fig. 4 *69-Bus test distribution system*

installed at bus 6, the network losses are calculated versus the generated power of the DG installed at bus 6 and shown in Fig. 5.

As shown in Fig. 5, the minimum value of losses is achieved (0.09922 MW) if the DG installed at bus 6 generates 2.706 MVA.

As listed in Table 1, the proposed method finds this value for the power, which should be generated by the DG installed at bus 6 to minimise the losses.

3.1.2 Scenario 2: non-unity power factor mode of DG operation: In this scenario, it is assumed that the power factor of DG is not necessarily equal to 1. The simulation results are listed in Table 2. As it can be seen in Table 2, the proposed method reaches the lowest network losses.

In the case of one DG placement, the proposed algorithm suggests installation at bus 30. The installed DG has the power of 1844.85 kVA and lagging power factor of 0.767. Fig. 6 shows the losses versus the location of the DG and its power factor. As shown in this figure, the combination of analytical and GA methods reaches the minimum network losses by installing one DG at bus 30 (Fig. 7) with the lagging power factor of 0.767. To analytically solve the problem, the voltage inequality constraints of the buses (i.e. $V_{\min} < V_{\text{bus}} < V_{\max}$) cannot be included in the optimisation problem. Therefore, the bus voltage and line current can and should be checked after finishing the optimisation procedure, to guarantee the inequality constraints of the bus voltage. Table 3

Table 1 Simulation results for first scenario (33-bus test distribution system)

Number of DG	Method	Location bus	Power, kW	Power factor	Loss, kW
1	LSF [33]	18	743	1	146.82
	IA [33]	6	2601	1	111.1
	ELF [33]	6	2601	1	111.1
	proposed method	6	2706.73	1	99.22
2	LSF [33]	18	720	1	100.69
		33	900	1	
	IA [33]	6	1800	1	91.63
		14	720	1	
	ELF [33]	12	1020	1	87.63
		30	1020	1	
	proposed method	30	1323.19	1	81.752
		13	867.24	1	
3	LSF [33]	18	720	1	85.07
		33	810	1	
		25	900	1	
	IA [33]	6	900	1	81.05
		12	900	1	
		31	720	1	
	ELF [33]	13	900	1	74.27
		30	900	1	
		24	900	1	
	proposed method	30	1180.43	1	67.221
		24	1260.41	1	
		14	709.45	1	
4	proposed method	14	561.56	1	62.46
		6	946.75	1	
		31	774.34	1	
		24	1065.62	1	

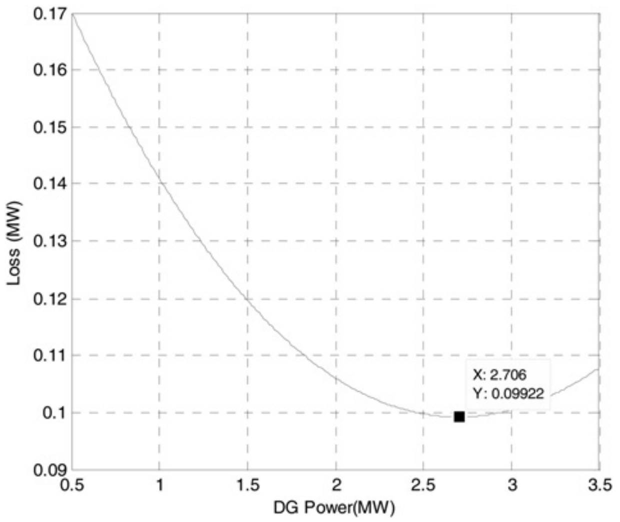

Fig. 5 *Network losses against generated power (DG installed at bus 6)*

Table 2 Simulation results for second scenario (33-bus test distribution system)

Number of DG	Method	Location bus	Power, kW	Power factor	Loss, kW
1	IA [33]	6	3107	0.82	67.90
	proposed method	30	1844.85	0.767	60.29
2	IA [33]	6	2159	0.82	44.39
		30	1098	0.82	
	proposed method	30	1477.28	0.75	26.705
		13	917.74	0.9	
3	IA [33]	6	1098	0.82	22.29
		30	1098	0.82	
		14	768	0.82	
	proposed method	24	1228.45	0.895	10.435
		30	1388.79	0.75	
		14	800.91	0.9	
4	proposed method	8	650.13	0.9	6.41
		24	1143.94	0.9	
		14	606.73	0.9	
		30	1230.57	0.7	
5	proposed method	14	604.44	0.9	5.15
		8	640.50	0.9	
		24	1123.41	0.9	
		30	1227.31	0.7	
		21	326.34	0.9	

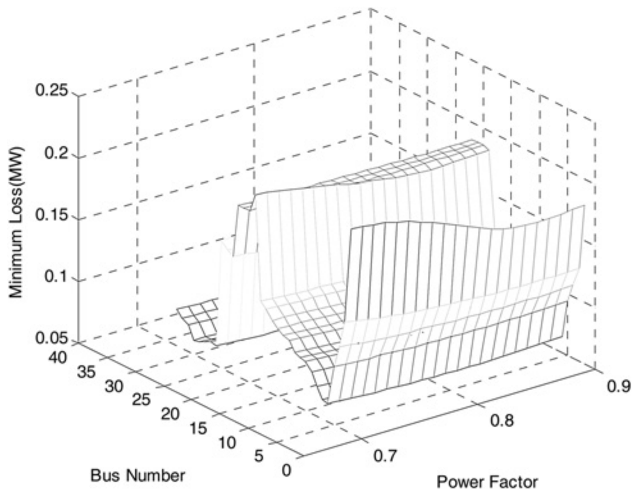

Fig. 6 *System losses versus location of DG and its power factor*

Table 3 Minimum and maximum voltages for 33-bus test distribution system after DG installation

DG power factor at	Cases	Minimum voltage at bus	Maximum voltage at bus
unity power factor	1 DG	0.953 at 18	1.0 at 1
	2 DG	0.974 at 33	1.0 at 1
	3 DG	0.973 at 33	1.0 at 1
	4 DG	0.973 at 18	1.0 at 1
non-unity power factor	1 DG	0.95 at 18	1.005 at 30
	2 DG	0.981 at 25	1.006 at 30
	3 DG	0.994 at 22	1.005 at 30
	4 DG	0.994 at 22	1.007 at 30
	5 DG	0.998 at 25	1.007 at 30

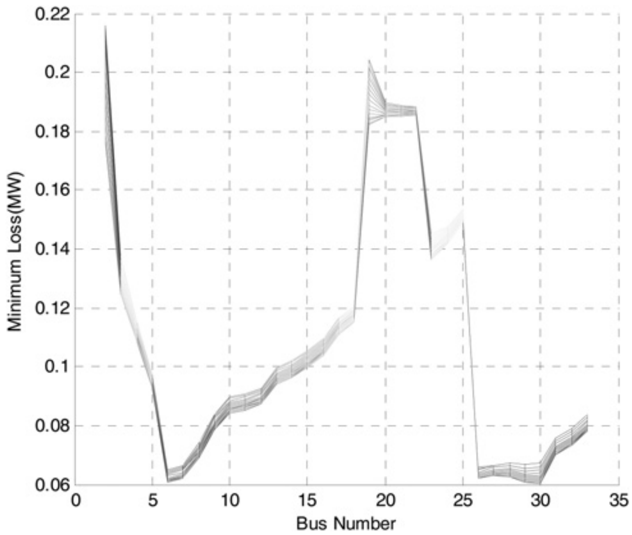

Fig. 7 *Minimum value of network losses by installing one DG at bus 30*

Table 4 Simulation results for the first scenario (69-bus test distribution system)

Number of DG	Method	Location bus	Power, kW	Power factor	Loss, kW
1	LSF [33]	65	1520	1	109.77
	IA [33]	61	1900	1	81.33
	ELF [33]	61	1900	1	81.33
	proposed method	61	2027	1	80.02
2	LSF [33]	65	1440	1	98.74
		27	540	1	
	IA [33]	61	1700	1	70.30
		17	510	1	
	ELF [33]	61	1700	1	70.30
		17	510	1	
	proposed method	17	636.8	1	70.05
		61	1872	1	
3	LSF [33]	65	1360	1	90.84
		27	510	1	
		61	510	1	
	IA [33]	61	1700	1	68.38
		17	510	1	
		11	340	1	
	ELF [33]	61	1700	1	68.38
		17	510	1	
		11	340	1	
	proposed method	61	1739	1	68.12
		11	800	1	
		18	372	1	
4	proposed method	11	558.4	1	67.07
		49	1074	1	
		61	1685.19	1	
		19	357	1	

Table 5 Simulation results for the second scenario (69-bus test distribution system)

Number of DG	Method	Location bus	Power, kW	Power factor	Loss, kW
1	IA [33]	61	2243	0.82	22.62
	proposed method	61	2208.13	0.812	22.13
2	IA [33]	61	2195	0.82	7.25
		17	659	0.82	
	proposed method	61	2115.39	0.812	7.21
		17	621.13	0.825	
3	IA [33]	61	2073	0.82	4.95
		17	622	0.82	
		50	829	0.82	
	proposed method	11	602.35	0.806	4.27
		18	452.64	0.834	
		61	2050.43	0.813	
4	proposed method	66	527.27	0.812	2.33
		50	877.94	0.807	
		61	2064.02	0.814	
		18	475.22	0.833	
5	proposed method	11	643.95	0.772	1.33
		21	415.48	0.8	
		61	1713.36	0.807	
		50	887.83	0.831	
		64	354.72	0.844	

Table 6 Minimum and maximum voltages for 69-bus test distribution system after DG installation

DG power factor at	Cases	Minimum voltage at bus	Maximum voltage at bus
unity power factor	1 DG	0.969 at 27	1.0 at 1
	2 DG	0.983 at 65	1.0 at 1
	3 DG	0.981 at 65	1.0 at 1
	4 DG	0.978 at 65	1.0 at 1
non-unity power factor	1 DG	0.973 at 27	1.002 at 61
	2 DG	0.994 at 50	1.003 at 61
	3 DG	0.994 at 50	1.004 at 61
	4 DG	0.998 at 41	1.004 at 61
	5 DG	0.998 at 41	1.005 at 64

lists the minimum and maximum voltages for 33-bus systems after DG units are installed.

3.2 Simulation of 69-bus test distribution system

In this section, the 69-bus test distribution system is simulated. Two different modes of the DG operation are considered in the following two scenarios.

3.2.1 Scenario 1: unity power factor mode of DG operation: In this case, it is assumed that DGs are working in the unity power factor mode and they can only generate active power. The results of the DG allocation are listed in Table 4. As listed in this table, the proposed method leads to lower network losses compared with the other methods.

3.2.2 Scenario 2: non-unity power factor mode of DGs operation: In this case, the DGs can generate active and reactive powers and their power factors are not necessarily equal to 1. The results of the optimal allocation of DGs in the 69-bus test distribution system are given in Table 5. Table 6 lists the minimum and maximum voltages for 69-bus systems after DG units are installed.

4 Conclusion

A combination of analytical and GA methods has been proposed in this paper for multiple DG units allocation in the distribution system to minimise system losses. The proposed method has used the GA to find the optimal location for DGs installation and an analytical novel formulation has been used to determine the DG capacities. The proposed method has been compared with IA, LSF, and ELF methods in terms of loss reduction. The results illustrate that the proposed method reaches the lowest losses compared with other methods.

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