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Simultaneous placement and sizing of DGs and shunt capacitors in distribution systems by using IMDE algorithm

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ABSTRACT

This paper presents a new optimization algorithm, named intersect mutation differential evolution (IMDE) to optimally locate and to determine the size of DGs and capacitors in distribution networks simultaneously. The objective function is taken to minimize the power loss and loss expenses providing that the bus voltage and line current remain in their limits. Simulation results on IEEE 33-bus and 69-bus standard distribution systems show the efficiency and the superior performance of the proposed method when it is compared with other algorithms.

Introduction

The increasing number of consumers and how to supply the loads are the most important challenges in the power system. Since the cost of construction or upgrading transmission lines and distribution networks is very high, the proper utilization of the low cost DGs has been a solution to eliminate or to delay such investments [1].

Moreover, among different sections of the power system, distribution network has the largest portion of the power loss because of its low level voltage with having a high current [1]. In this regard, it has been shown that one of the most cost-effective and an economical solution to solve this problem is to use DG resources [2]. In this regard, the optimal operation and planning of distribution networks, considering power system uncertainties, especially in the modern smart distribution networks are also very important. Refs. [3–6] highlight the importance of energy storage in combination with distributed generation for these purposes. More information about the application of DGs in implementing smart distribution network functions such as self-healing ability can be found in [7].

In addition to economic concerns, the power quality, reliability, energy saving and stability will be greatly improved by using DGs if they are installed in appropriate places [2]. Thus, determining the capacities and locations of DGs have been the subjects of several papers in which different optimization techniques such as genetic algorithms, continuous power flow, ant colony, particle swarm optimization have been used [8–11]. Analytical methods for finding the optimal size of different types of DGs are also suggested in [12]. In [13] an analytical method and in [14–17] numerical techniques are applied to find the optimal locations and sizes of multiple DGs. A fuzzy GA is employed to solve a weighted multi-objective optimal DG placement model [18–19].

Furthermore, it is very common to use reactive power sources such as parallel capacitors to improve the voltage profile as well as reducing the power losses in the lines. Refs. [20–23] determine the locations and sizes of shunt capacitors with different goals and algorithms.

Considering the advantages of using both DGs and capacitors in distribution networks many researchers have recently proposed different techniques to simultaneously determine the locations and sizes of both to improve the voltage stabilization, system capacity release, energy loss minimization and reliability enhancement. Ref. [24] uses the PSO algorithm to find the optimal location and size of shunt capacitor and DG in 12, 30, 33 and 69-bus IEEE standard networks in order to minimize losses. The IEEE 33-bus network is employed as a test system in [25] to show the advantage of using an improved genetic algorithm for locating DG and capacitor. The same purpose was followed in [26] by using BFOA in the 33-bus network, and results are compared for three different cases of when; 1- only DG, 2- both DG and capacitor, and 3- none of them, are used in the test system. In [27] the problem of locating both DG and capacitor is solved by using BPSO algorithm, where in addition to the main objectives of loss reduction and voltage

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Nomenclature

Symbol	Description
AP_{i+1}	amplitude of injected active power at bus $i+1$
CR	crossover parameter
CT_1	active power base load electricity prices
CT_2	reactive power base load electricity prices
D	number of variables
F	mutation parameter
$F(\cdot)$	fitness function
f	cost of the loss in the period of T year
G	number of generations
I_{ij}	current flowing from bus i to bus j
NP	number of population
n_j	a randomly generated dimension
P	population
P_{DG}	active power of each DG
P_i	net active power of bus i
P_L	active power loss in the line
P_{Li}	active load power at bus i
P_{loss}	system active loss after DG and capacitor installation
P_{loss0}	system active loss before DG and capacitor installation
Q_C	reactive power of capacitor source
Q_i	net reactive power of bus i
Q_L	reactive power loss in the line
Q_{li}	reactive load power at bus i
Q_{loss}	system reactive loss after DG and capacitor installation
Q_{loss0}	system reactive loss before DG and capacitor installation
$r(j)$	a random number between [0,1]
$R_{i,i+1}$	resistance of the line between buses i and $i+1$
RP_{i+1}	amplitude of injected reactive power at bus $i+1$
T	useful life of the equipment
TP_{loss}	total active loss
TQ_{loss}	and total reactive loss
U	trial vector
$u_{i,j}$	jth member of ith trial vector
$u^j_{i,G+1}$	jth member of ith trial vector in the previous generation
V	mutant vector
V_i	voltage of bus i
$v_{i,j}$	jth member of ith mutant vector
$v^j_{i,G+1}$	jth member of ith mutant vector in the previous generation
X_{br}	individual chosen from the better part
$X_i^{(G)}$	target vector in the previous generation
$Xi^{(G+1)}$	ith vector in the next generation
$X_{i,i+1}$	reactance of the line between buses i and $i+1$
$x_{i,j}$	jth member of ith target vector
$x^j_{i,G}$	jth member of ith target vector in the previous generation
X_{wr}	individual chosen from the worse part
$x_{i,j}$	jth member of ith target vector
α	conversion ratio of operating expense
β	inflation rate
μ	annual interest rate
μ_P	active power coefficient
μ_q	reactive power coefficient

List of abbreviations

ABC	Artificial Bee Colony
BFOA	Bacterial Foraging Optimization Algorithm
BGSA	Binary Gravitational Search Algorithm
BPSO	Binary Particle Swarm Optimization
BSO	Bee Swarm Optimization
DE	Differential Evolution
DG	Distributed Generation
DPSO	Discrete Particle Swarm Optimization
FGA	Fuzzy Genetic Algorithm
GA	Genetic Algorithm
ICA	Imperialist Competitive Algorithm
IMDE	Intersect Mutation Differential Evolution Algorithm
IPSO	Improved Particle Swarm Optimization
PSO	Particle Swarm Optimization
TLBO	Teaching–Learning-Based Optimization

improvement, the network reliability indices are used. In [28] both artificial bee colony and artificial immune system algorithms are combined to locate and to determine the size of capacitors and DGs in distribution networks. The proposed method was tested on IEEE 33-bus test system for several cases. The simulation results show that the proposed approach provides better power loss reduction and voltage profile enhancement when compared with different methods. DGs and capacitors are optimally located and sized in [29] by using DPSO algorithm. Ref. [30] employs TLBO technique to maximize the ratio of the profit to cost when both capacitor and DG are used. Other algorithms such as BGSA [31], simple genetic algorithm [32,33], genetic and ICA techniques [34] have been also used in this field.

This paper presents a new algorithm, named IMDE [35] to optimally locate DGs and shunt capacitors as well as determining their sizes in radial distribution networks. This algorithm not only has a higher convergence speed, but also gives a better performance compared to earlier works in this field. The results clearly show the highest level of loss reduction as well as keeping the voltages of buses within their limits.

Differential evolutionary algorithm

Differential evolution (DE) is one of the meta-heuristic algorithms, which is widely used because of its nature and special features, especially for having a fast convergence. DE differs from other evolutionary algorithms in the mutation and recombination phases. It uses weighted differences between solution vectors to change the population, whereas in other stochastic techniques such as GA and expert systems, perturbation occurs in accordance with a random quantity. This algorithm also provides a simple and efficient way to calculate the global optimal solutions in both continuous and discrete spaces [36].

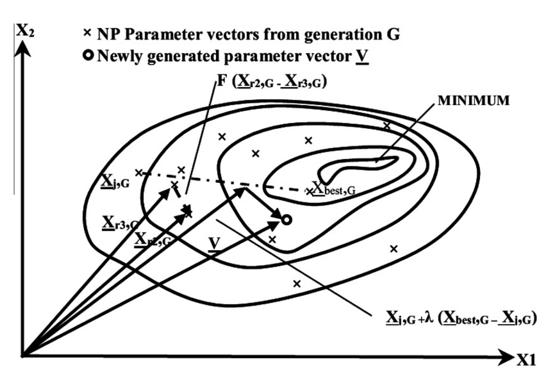

Fig. 1. Overview of behavior of the algorithm [36].

Fig. 1 shows an overview of the behavior of this algorithm. Like most meta-heuristic algorithms, DE has three operations: mutation, crossover and selection as well as three important parameters of *NP* (number of population), *F* (mutation parameter) and *CR* (crossover parameter).

A population consists of *NP* individual;

$$X_{i,G}, i = (1, 2, 3, \ldots, NP) \tag{1}$$

where *G* represents one generation. One individual $X_{i,G}$ consists of *D* variables. The initial population individuals are randomly determined. Then, mutation and crossover are used to generate new individuals. Finally, the selection operation is applied to determine that either the new individuals or the original ones are chosen for the next generation. The main advantage of this strategy is that it prevents the loss of population diversity by preventing concurrently transmission of target and trial vectors to the next generation.

In the next section a new method, called IMDE which has been presented by Zhou et al. [35] to improve the global search ability of DE is introduced. The main advantage of this method is that it has a better performance in convergence speed and finding optimal solution. The probability of getting stuck in a local optimum solution has been reduced and a more optimal solution is gained when compared to the traditional DE. This paper uses this algorithm for the first time for simultaneous design of DGs and shunt capacitors locating and sizing in distribution systems and shows its superior performance with other algorithms in this field.

Intersect Mutation Differential Evolution (IMDE)

In IMDE, first the individuals are sorted from worse to better according to their fitness values. Then, they are divided into better and worse parts. At last, novel mutation, crossover and selection operations, which will be explained, are used to create the next generation. In order to obtain the next generation two different processes should be carried out. There are only a few modifications in mutation operation between these two processes.

First process

Since mutation and crossover operations for worse and better parts are different, this part of process is separated into two portions. For the better part, the vectors are mutated with one individual (X_{wr1}) chosen from the worse part and two individuals (X_{br1} and X_{br2}) selected from the better part, as Eq. (2) shows.

$$v_{i,G+1} = x_{wr1,G} + F(x_{br1,G} - x_{br2,G}), \quad br1 \neq br2 \neq wr1 \neq j \tag{2}$$

As explained above the goal is to improve the searching ability. Therefore, some changes are made for the crossover operation. It is checked whether the fitness of $v_{i,G}$ is better than the fitness of $x_{i,G}$ or not. If $v_{i,G}$ wins, $v^j_{i,G+1}$ is assigned to $u^j_{i,G+1}$, else the crossover operation is used as the traditional DE algorithm does. Thus, this operator can be expressed as follows:

$$u^j_{i,G+1} = \begin{cases} v^j_{i,G+1} & \text{if } f(v_{i,G+1}) \leqslant f(x_{i,G}) \text{ or } r(j) \geqslant CR \text{ or } j = n_j \\ x^j_{i,G} & \text{otherwise} \end{cases} \tag{3}$$

In Eq. (3) the $u^j_{i,G+1}$ will be the *j*th member of *i*th trial vector, $v^j_{i,G+1}$ is the *j*th member of *i*th mutant vector, and x^j_{iG} is the *j*th member of *i*th target vector. The constant parameter of binomial crossover has been shown by CR.

In worse part, vectors are mutated with one individual (X_{br1}) chosen from the better part and two individuals (X_{wr1} and X_{wr2}) taken from the worse part, as Eq. (4) shows.

$$v_{i,G+1} = x_{br1,G} + F(x_{wr1,G} - x_{wr2,G}), \quad br1 \neq wr1 \neq wr2 \neq j \tag{4}$$

Since the crossover operation for IMDE and traditional DE algorithm is the same, $u^j_{i,G+1}$ is calculated as follows;

$$u^j_{i,G+1} = \begin{cases} v^j_{i,G+1} & \text{if } r(j) \leqslant CR \text{ or } j = n_j \\ x^j_{i,G} & \text{otherwise} \end{cases} \tag{5}$$

There are no changes to the selection operation. The selection operation for IMDE is also the same as the one for DE. According to Eq. (6), the fitness function of each member of the population is calculated and if the fitness function of trial vectors is more favorable, it will be selected instead of the previous generation, otherwise the previous individuals will also be in the next generated individuals.

$$X_i^{(G+1)} = \begin{cases} U_i & \text{if } F(U_i) \leqslant F(X_i^{(G)}) \\ X_i^{(G)} & \text{otherwise} \end{cases} \tag{6}$$

In Eq. (6) $X_i^{(G+1)}$ is the *i*th vector in the next generation, U_i is the trial vector and $X_i^{(G)}$ is the target vector in the previous generation.

Second process

The first process used the individuals in the worse part to search for wider regions with the goal to improve global search ability. However, this does not mean that the weak point of strategy, which is the problem of finding new ways for getting close to a better solution, is solved. Thus, in the second process, another new mutation operation is used to solve this drawback. The operation is similar to the previous strategy. However, this trend may reduce the ability of global search for multi-objective problems. For the second process, the formula changes to:

The better part:

$$v_{i,G+1} = x_{wr1,G} + F(x_{wr1,G} - x_{br2,G}), \quad br1 \neq wr1 \neq wr2 \neq j \tag{7}$$

$$u^j_{i,G+1} = \begin{cases} v^j_{i,G+1} & \text{if } f(v_{i,G+1}) \leqslant f(x_{i,G}) \text{ or } r(j) \geqslant CR \text{ or } j = n_j \\ x^j_{i,G} & \text{otherwise} \end{cases} \tag{8}$$

and for the worse part:

$$v_{i,G+1} = x_{br1,G} + F(x_{wr1,G} - x_{wr2,G}), \quad br1 \neq wr1 \neq wr2 \neq j \tag{9}$$

$$u^j_{i,G+1} = \begin{cases} v^j_{i,G+1} & \text{if } r(j) \leqslant CR \text{ or } j = n_j \\ x^j_{i,G} & \text{otherwise} \end{cases} \tag{10}$$

The flowchart of IMDE algorithm is implemented in Fig. 2. By implementing the steps given in this figure it is possible to obtain the best result for the optimization process based on the objective functions and constraints.

Problem formulation

As mentioned before, determining the locations and sizes of DGs and capacitors for distribution network is a complex discrete optimization problem which requires an efficient method. This paper will solve this problem by using IMDE algorithm as will be explained in the next subsections.

Load flow formulation

Load flow problem is solved by using the following recursive equations which are obtained from single line diagram shown in Fig. 3 [37].

$$P_{i+1} = P_i - P_{Li+1} - R_{j,i+1}.\frac{P_j^2 + Q_i^2}{|V_i|^2} \tag{11}$$

$$Q_{i+1} = Q_i - Q_{Li+1} - X_{j,i+1}.\frac{P_j^2 + Q_i^2}{|V_i|^2}$$

$$V_{i+1}^2 = V_i^2 - 2(R_{j,i+1}.P_i + X_{j,i+1}.Q_i) + (R_{i,i+1}^2 + X_{i,i+1}^2).\frac{P_j^2 + Q_i^2}{|V_i|^2}$$

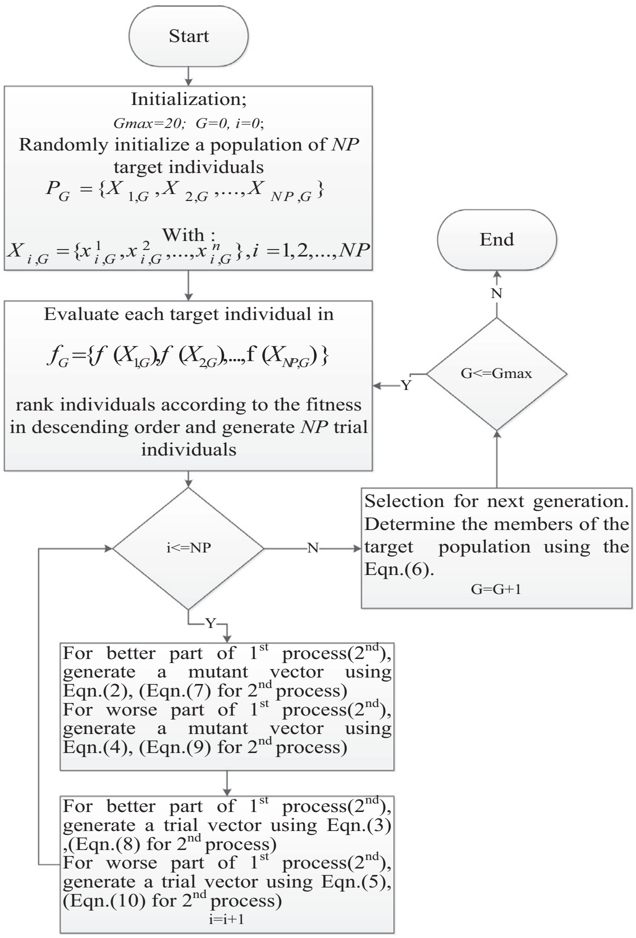

Fig. 2. Flowchart of IMDE algorithm.

In Eq. (11) P_i and Q_i are the net active and reactive powers of bus i respectively. P_{Li} and Q_{li} are also active and reactive load powers at bus i respectively. The resistance and reactance of the line between buses i and $i+1$ are represented by $R_{i,i+1}$ and $X_{i,i+1}$ respectively. The power losses in this line can be calculated by using the following equations.

$$P_L = R_{i,i+1} \cdot \frac{P_i^2 + Q_i^2}{|V_i|^2} \qquad (12)$$

$$Q_L = X_{i,i+1} \cdot \frac{P_i^2 + Q_i^2}{|V_i|^2}$$

Total power losses P_{TL} in the feeder can be obtained by adding the power losses in the lines as follows:

$$TP_{loss} = \sum_{i=0}^{n-1} P_L(i, i+1) \qquad (13)$$

$$TQ_{loss} = \sum_{i=0}^{n-1} Q_L(i, i+1)$$

where TP_{loss} and TQ_{loss} are total active and reactive losses in the system respectively.

To use the IMDE method the recursive equations given in Eq. (11) shall be modified as follows:

$$P_{i+1} = P_i - P_{Li+1} - R_{j,i+1} \cdot \frac{P_i^2 + Q_i^2}{|V_i|^2} + \mu_p . AP_{i+1} \qquad (14)$$

$$Q_{i+1} = Q_i - Q_{Li+1} - X_{j,i+1} \cdot \frac{P_i^2 + Q_i^2}{|V_i|^2} + \mu_q . RP_{i+1}$$

In Eq. (14) μ_P is the active power coefficient. When there is an active power source, μ_P is equal to one, otherwise it will be zero. Similarly, for μ_q which is the reactive power coefficient, when there is a reactive power source it is equal to one, otherwise it will be zero. Also, AP_{i+1} is the amplitude of injected active power at bus $i+1$ and RP_{i+1} is the amplitude of injected reactive power at bus $i+1$.

Objective function

The total cost of losses in the design process can be calculated as follows:

$$f = 8760 \times \sum_{t=1}^{T} \frac{1}{3\alpha^t} (\Delta P_{loss} \times CT_1 + \Delta Q_{loss} \times CT_2) \qquad (15)$$

$$\alpha = \frac{1+\beta}{1+\mu}$$

$$\Delta P_{loss} = P_{loss0} - P_{loss}$$

$$\Delta Q_{loss} = Q_{loss0} - Q_{loss}$$

where f is the cost of the loss in the period of T year in \$, T is the useful life of the equipment in years, β is the inflation rate, μ is the annual interest rate, α is the conversion ratio of operating expense, P_{loss} is the system active loss after DG and capacitor installation, P_{loss0} is the system active loss before DG and capacitor installation, Q_{loss} is the system reactive loss after DG and capacitor installation, Q_{loss0} is the system reactive loss before DG and capacitor installation, CT_1 is the active power base load electricity prices (\$/MW h), and CT_2 is the reactive power base load electricity prices (\$/MW h). The factor of 1/3 is considered for the increment of the peak energy price.

Problem constraints

Constraints which are included in this optimization problem are the voltage limits of buses, the power flow through the lines and the minimum and the maximum capacity available for the installation of capacitor banks and DGs. These constraints are shown as follows;

$$V_i^{min} \leqslant V_i \leqslant V_i^{max} \qquad (16)$$

$$I_{ij} \leqslant I_{ij}^{max}$$

$$P_{DG}^{min} \leqslant P_{DG} \leqslant P_{DG}^{max}$$

$$Q_C^{min} \leqslant Q_C \leqslant Q_C^{max}$$

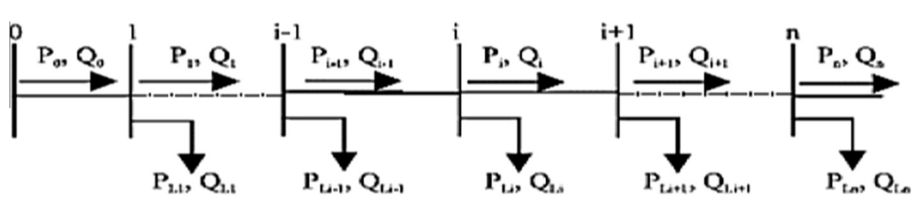

Fig. 3. Single line diagram of a main feeder [37].

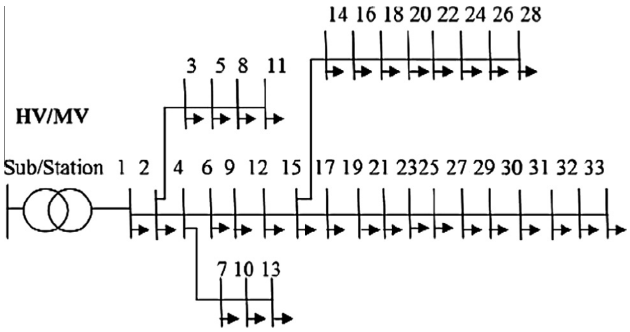

Fig. 4. IEEE 33-bus distribution system.

Table 2
Simulation results on 69-bus network.

		IMDE
Original system (Case 1)	PT,Loss (kW)	224.5935
	Vworst in p.u. (Bus No)	0.9102 (65)
Only capacitor installation (Case 2)	Capacitor size in MVAr (Bus)	1.2637(61)
		0.3752(21)
	PT,Loss (kW)	145.5310
	VWorst in p.u. (Bus No)	0.9330(65)
	% Loss reduction	35.2
Only DG installation (Case 3)	DG size in MW (Bus)	1.730(61)
		0.473(20)
	PT,Loss (kW)	70.926
	Vworst in p.u. (Bus No)	0.9808(65)
	% Loss reduction	68.42

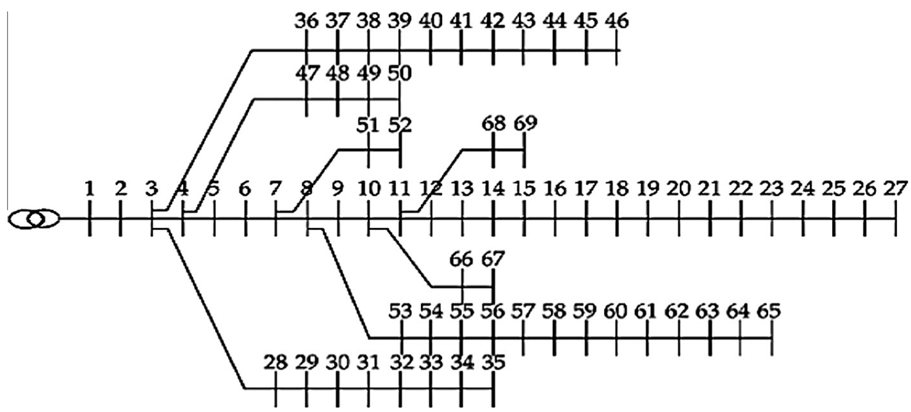

Fig. 5. IEEE 69-bus distribution system.

Table 1
Simulation results on 33-bus network.

		IMDE	Analytical [38]	PSO [24]	FGA [39]	BPSO [27]	BFOA [26]
Original system (Case 1)	PT,Loss (kW)	211	211	211	211	211	211
	Vworst in p.u. (Bus No)	0.904 (18)	0.904 (18)	0.904 (18)	0.904 (18)	0. 904 (18)	0.904 (18)
Only capacitor installation (Case 2)	Capacitor size in MVAr (Bus)	0.475 (14) 1.037 (30)	1 (33)	–	0.95 (18) 0.7 (30)	0.92 (33) 0.61 (14)	0.35(18) 0.820 (30) 0.277 (33)
	PT,Loss (kW)	139.7	164.6	–	141.3	151.7	144.04
	Vworst in p.u. (Bus No)	0.942 (18)	0.916 (18)	–	0.929(18)	0.935 (18)	0.9361
	% Loss reduction	33.79	22.83	–	33.03	28.1	31.72
Only DG installation (Case 3)	DG size in MW (Bus)	0.84 (14) 1.13 (30)	1 (18)	–	0.6 (7) 1.1 (32)	1.3 (33) 0.52 (8)	0.633(7) 0.090(18) 0.947(33)
	PT,Loss (kW)	84.28	142.34	–	119.7	111.5	98.3
	Vworst in p.u. (Bus No)	0.971 (33)	0.931 (33)	–	0.935 (18)	0.919 (18)	0.9645
	% Loss reduction	60.06	33.29	–	43.27	47.15	53.41
Simultaneous DG and capacitor allocation (Case 4)	Capacitor size in MVAr (Bus)	0.2548 (16) 0.9323 (30)	0.4 (33) 0.5 (32)	1.457 (30)	0.8 (33) 0.65 (16)	1.5 (30)	0.163(18) 0.541(30) 0.338(33)
	DG size in MW (Bus)	1.08 (10) 0.8964 (31)	0.447 (18) 0.559 (17)	2.511 (6)	0.6 (7) 1.1 (32)	2.5 (6)	0.542(17) 0.160(18) 0.895(33)
	PT,Loss (kW)	32.08	84.28	59.7	59.5	57.3	41.41
	Vworst in p.u. (Bus No)	0.979 (25)	0.961 (30)	0.955 (18)	0.96 (18)	0.959 (18)	0.9783
	% Loss reduction	84.79	60.05	71.7	71.8	72.84	80.37

Table 3
Simulation results on 69-bus network and comparison.

		IMDE	PSO [24]
Simultaneous DG and capacitor allocation (Case 4)	Capacitor size in MVAr (Bus)	0.1090(63) 1.1920(61)	1.4013(61)
	DG size in MW (Bus)	1.7380(62) 0.4790(24)	1.566(61)
	PT,Loss (kW)	13.833	25.9
	Vworst in p.u. (Bus No)	0.9915(68)	0.97(27)
	% Loss reduction	93.84	88.4

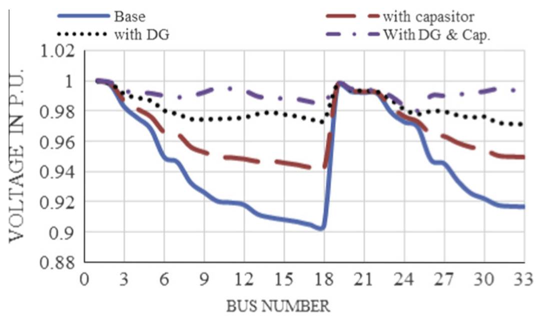

Fig. 6. 33-bus network voltage profile in the different scenarios.

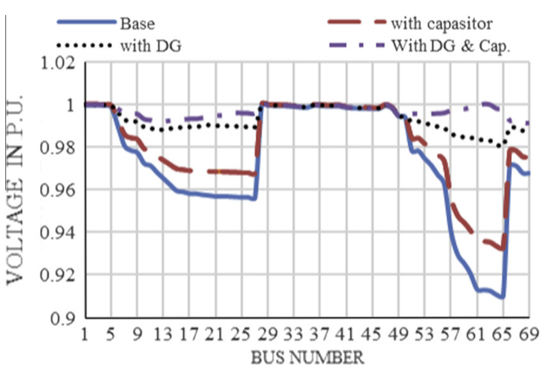

Fig. 7. 69-bus network voltage profile in the different scenarios.

where I_{ij} is the current flowing from bus i to bus j, P_{DG} and Q_C are active and reactive power of each DG and capacitor source which are between their maximum and minimum limits.

Implementing IMDE to the optimization problem

The locations and sizes of DGs and capacitors are chosen as decision variables. The step-by-step implementation of IMDE algorithm to solve the optimization problem can be given as follows:

1. Reading feeder information; the maximum number of DGs are set to N_c^{max}, and the maximum number of capacitors are set to N_{DG}^{max}.
2. Tuning and determining the control parameters of IMDE as; the number of generations ($NP = 20$), number of decision variables (D), mutation factor ($F = 0.7$), crossover parameter ($CR = 0.8$) and maximum number of generations (G^{max}).
3. Initializing the first population (NP individuals) for decision variables.
4. Running load flow in the presence of DGs and capacitors which are determined by using Eq. (14).
5. Calculating active power, reactive power and voltage profile using Eqs. (11), (12), and (14).
6. Calculating total active power, total reactive power and loss cost function using Eqs. (13) and (15).
7. Rank individuals according to their fitness function (Eq. (15)) in descending order.
8. Dividing individuals into two better and worse groups.
9. Applying mutation and recombination operators for the better part of the first process using Eqs. (2) and (3) (Eqs. (7) and (8) for the second process).
10. Repeating steps 4 to 6.
11. Applying mutation and recombination operators for the worse part of the first process using Eqs. (4) and (5) (Eqs. (9) and (10) for the second process).
12. Repeating steps 7 to 11 for the second process.
13. Repeat steps 9 to 12 for each NP target individuals.
14. Applying the selection operation using Eq. (6).
15. Add the number of generations and repeat steps from 4 to 14 until the number of generations does not exceed G^{max}.
16. Check constraints in Eq. (16) and if they are satisfied, stop, else go back to step 3.

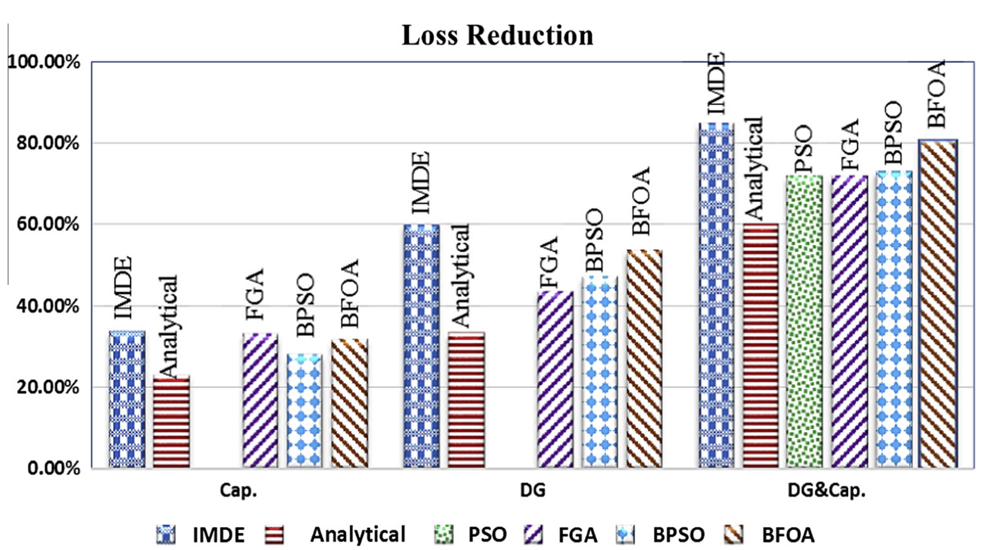

Fig. 8. The decrease in loss of 33 bus network in different scenarios.

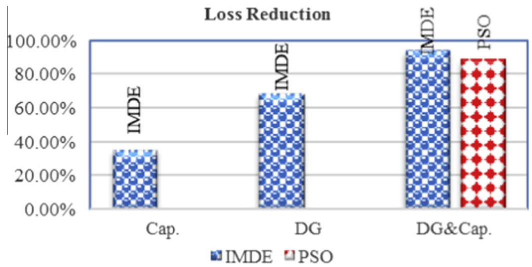

Fig. 9. The loss reduction of 69-bus network for different scenarios.

Table A
System data for 33-bus radial distribution network.

Branch number	Sending bus	Receiving bus	Resistance Ω	Reactance Ω	Nominal load at receiving bus	
					P (kW)	Q (kVAr)
1	1	2	0.0922	0.047	100	60
2	2	3	0.493	0.2511	90	40
3	3	4	0.366	0.1864	120	80
4	4	5	0.3811	0.1941	60	30
5	5	6	0.819	0.707	60	20
6	6	7	0.1872	0.6188	200	100
7	7	8	0.7114	0.2351	200	100
8	8	9	1.03	0.74	60	20
9	9	10	1.044	0.74	60	20
10	10	11	0.1966	0.065	45	30
11	11	12	0.3744	0.1298	60	35
12	12	13	1.468	1.155	60	35
13	13	14	0.5416	0.7129	120	80
14	14	15	0.591	0.526	60	10
15	15	16	0.7463	0.545	60	20
16	16	17	1.289	1.721	60	20
17	17	18	0.732	0.574	90	40
18	2	19	0.164	0.1565	90	40
19	19	20	1.5042	1.3554	90	40
20	20	21	0.4095	0.4784	90	40
21	21	22	0.7089	0.9373	90	40
22	3	23	0.4512	0.3083	90	50
23	23	24	0.898	0.7091	420	200
24	24	25	0.896	0.7011	420	200
25	6	26	0.203	0.1034	60	25
26	26	27	0.2842	0.1447	60	25
27	27	28	1.059	0.9337	60	20
28	28	29	0.8042	0.7006	120	70
29	29	30	0.5075	0.2585	200	600
30	30	31	0.9744	0.963	150	70
31	31	32	0.3105	0.3619	210	100
32	32	33	0.341	0.5302	60	40

Simulation and numeral results

To evaluate the effectiveness of the proposed algorithm for simultaneous placement and sizing of DG and shunt capacitor, IEEE 33 and 69-bus test systems shown in Figs. 4 and 5 are used. The first system has 3.7 MW active and 2.3 MVAr reactive load power. The 69-bus system has 3.8 MW active and 2.69 MVAr reactive load powers. The details of both systems are given in Appendix.

In this study, several scenarios are investigated. In the first scenario there are no capacitors and DGs in the test systems. For the second scenario only capacitors and in the third scenario, only DGs are used in order to see the impact of each scenario separately and to compare with the last scenario that simultaneously uses two active and two reactive sources. It should be noted that due to the high investment costs of distributed generation sources, and particularly shunt capacitors, it is not possible to install any number of capacitors and DGs in the network.

The simulation results of 33-bus system for different scenarios, and also different methods reported in the literature are shown in Table 1. The simulation results for 69-bus distribution system are also obtained and depicted in Tables 2 and 3.

It should be noted that the objective function and constraints used in this paper are the same as what have been used in [24,26,38] except a minor difference in which, in this paper, the minimization of the cost of real and reactive power losses is considered instead of loss minimization used in these references. Also, the results reported in Table 1 for Refs. [27,39] are obtained by using their algorithm to optimize the objective function given in Eq. (15).

As it can be seen from Tables 1–3, IMDE algorithm has better performance for improving minimum bus voltage and system losses than other methods. The total values of active and reactive power installed in most cases are also less than other algorithms. For example, in 33-bus network for case 2 as shown in Table 1; when only capacitor banks are located by employing IMDE algorithm, the total loss reduction of 33.79% is obtained by using two capacitors of 0.475 MVAr at bus 14 and 1.037 MVAr at bus 30 (totally, 1.512 MVAr). The worst bus voltage appears at bus 18 with the value of 0.942 pu. However, for FGA method not only the total amount of installed capacitors is more (1.65 MVAr), but also it gives a worse voltage magnitude (0.929 p.u) and a less loss reduction (33.03%). For BFOA method given in [26] the amount of installed capacitors is almost the same (1.447 MVAr), but for the worst voltage (0.9361 p.u) and loss reduction (31.72%) IMDE technique gives better results.

For case 3; when only DGs are located (two DGs of 0.84 MW at bus 14 and 1.13 MW at bus 30), a 60.06% loss reduction and the worst voltage of 0.971 pu at bus 33 are obtained by using IMDE. As can be also seen in Table 1 the best result for the case 3 among other methods is BFOA [26] in which the results are still inferior to the proposed method of this paper. Although FGA algorithm applied in [39] uses 1.7 MW amount of DG, the loss reduction is 43.27% and the worst voltage is 0.935 pu at bus 18. This clearly shows that IMDE algorithm gives much better performance.

For the case of simultaneous DG and capacitor locating and sizing, IMDE shows a loss reduction of 84.79%, and its worst bus voltage is 0.979 pu. It is evident from both of these results that a notable improvement has been achieved. Although the best results obtained for other techniques, in this case, belong to BFOA given by Kowsalya [26] in which a loss reduction of 80.37% has been obtained and its worst voltage is 0.978 pu, its performance is still worse than IMDE method.

IMDE algorithm also has better performance in 69-bus test system where it shows a loss reduction of 93.84%, and the worst voltage of 0.9915 pu when DG and capacitor locating and sizing is done simultaneously. For this case PSO algorithm used in [24] has reached to a loss reduction of 88.4%, and its worst voltage is 0.97 pu, which shows that the proposed method given in this paper has better results.

Figs. 6 and 7 also show the bus voltage profiles of different scenarios for 33 and 69-bus systems, respectively for the IMDE algorithm. It can be seen that the bus voltage has been considerably improved by using both DGs and capacitors when their locations and sizes are determined by using the proposed optimization method.

Figs. 8 and 9 also show the loss reduction obtained by different methods for 33 and 69-bus systems respectively. These figures clearly imply that the IMDE method gives a better performance than other algorithms.

Table B
System data for 69-bus radial distribution network.

Branch number	Sending bus	Receiving bus	Resistance Ω	Reactance Ω	Nominal load at receiving bus		Maximum line capacity (kVA)
					P (kW)	Q (kVAr)	
1	1	2	0.0005	0.0012	0.0	0.0	10761
2	2	3	0.0005	0.0012	0.0	0.0	10761
3	3	4	0.0015	0.0036	0.0	0.0	10761
4	4	5	0.0251	0.0294	0.0	0.0	5823
5	5	6	0.3660	0.1864	2.60	2.20	1899
6	6	7	0.3811	0.1941	40.40	30.00	1899
7	7	8	0.0922	0.0470	75.00	54.00	1899
8	8	9	0.0493	0.0251	30.00	22.00	1899
9	9	10	0.8190	0.2707	28.00	19.00	1455
10	10	11	0.1872	0.0619	145.00	104.00	1455
11	11	12	0.7114	0.2351	145.00	104.00	1455
12	12	13	1.0300	0.3400	8.00	5.00	1455
13	13	14	1.0440	0.3450	8.00	5.50	1455
14	14	15	1.0580	0.3496	0.0	0.0	1455
15	15	16	0.1966	0.0650	45.50	30.00	1455
16	16	17	0.3744	0.1238	60.00	35.00	1455
17	17	18	0.0047	0.0016	60.00	35.00	2200
18	18	19	0.3276	0.1083	0.0	0.0	1455
19	19	20	0.2106	0.0690	1.00	0.60	1455
20	20	21	0.3416	0.1129	114.00	81.00	1455
21	21	22	0.0140	0.0046	5.00	3.50	1455
22	22	23	0.1591	0.0526	0.0	0.0	1455
23	23	24	0.3463	0.1145	28.00	20.0	1455
24	24	25	0.7488	0.2475	0.0	0.0	1455
25	25	26	0.3089	0.1021	14.0	10.0	1455
26	26	27	0.1732	0.0572	14.0	10.0	1455
27	3	28	0.0044	0.0108	26.0	18.6	10761
28	28	29	0.0640	0.1565	26.0	18.6	10761
29	29	30	0.3978	0.1315	0.0	0.0	1455
30	30	31	0.0702	0.0232	0.0	0.0	1455
31	31	32	0.3510	0.1160	0.0	0.0	1455
32	32	33	0.8390	0.2816	14.0	10.0	2200
33	33	34	1.7080	0.5646	9.5	14.00	1455
34	34	35	1.4740	0.4873	6.00	4.00	1455
35	3	36	0.0044	0.0108	26.0	18.55	10761
36	36	37	0.0640	0.1565	26.0	18.55	10761
37	37	38	0.1053	0.1230	0.0	0.0	5823
38	38	39	0.0304	0.0355	24.0	17.00	5823
39	39	40	0.0018	0.0021	24.0	17.00	5823
40	40	41	0.7283	0.8509	1.20	1.0	5823
41	41	42	0.3100	0.3623	0.0	0.0	5823
42	42	43	0.0410	0.0478	6.0	4.30	5823
43	43	44	0.0092	0.0116	0.0	0.0	5823
44	44	45	0.1089	0.1373	39.22	26.30	5823
45	45	46	0.0009	0.0012	39.22	26.30	6709
46	4	47	0.0034	0.0084	0.00	0.0	10761
47	47	48	0.0851	0.2083	79.00	56.40	10761
48	48	49	0.2898	0.7091	384.70	274.50	10761
49	49	50	0.0822	0.2011	384.70	274.50	10761
50	8	51	0.0928	0.0473	40.50	28.30	1899
51	51	52	0.3319	0.1114	3.60	2.70	2200
52	52	53	0.1740	0.0886	4.35	3.50	1899
53	53	54	0.2030	0.1034	26.40	19.00	1899
54	54	55	0.2842	0.1447	24.00	17.20	1899
55	55	56	0.2813	0.1433	0.0	0.0	1899
56	56	57	1.5900	0.5337	0.0	0.0	2200
57	57	58	0.7837	0.2630	0.0	0.0	2200
58	58	59	0.3042	0.1006	100.0	72.0	1455
59	59	60	0.3861	0.1172	0.0	0.0	1455
60	60	61	0.5075	0.2585	1244.0	888.00	1899
61	61	62	0.0974	0.0496	32.0	23.00	1899
62	62	63	0.1450	0.0738	0.0	0.0	1899
63	63	64	0.7105	0.3619	227.0	162.00	1899
64	64	65	1.0410	0.5302	59.0	42.0	1899
65	11	66	0.2012	0.0611	18.0	13.0	1455
66	66	67	0.0047	0.0014	18.0	13.0	1455
67	12	68	0.7394	0.2444	28.0	20.0	1455
68	68	69	0.0047	0.0016	28.0	20.0	1455
69*	11	43	0.5000	0.5000			566
70*	13	21	0.5	0.5			566
71*	15	46	1.0	1.0			400
72*	50	59	2.0	2.0			283
73*	27	65	1.0	1.0			400

Conclusions

This paper presented an efficient technique for the simultaneous placement and sizing of DG and parallel capacitors in distribution networks. The simulation results for two typical IEEE distribution systems showed that the power losses were reduced as well as keeping the voltages of buses within the limited ranges.

Appendix A

See Tables A and B.

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