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Optimal multi objective placement and sizing of multiple DGs and shunt capacitor banks simultaneously considering load uncertainty via MOPSO approach

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ABSTRACT

This study proposes a new application of multi objective particle swarm optimization (MOPSO) with the aim of determining optimal location and size of distributed generations (DGs) and shunt capacitor banks (SCBs) simultaneously with considering load uncertainty in distribution systems. The multi objective optimization includes three objective functions: decreasing active power losses, improving voltage stability for buses and balancing current in system sections. The uncertainty of loads is modeled by using fuzzy data theory. This method uses Pareto optimal solutions to solve the problem with objective functions and constraints. In addition, a fuzzy-based mechanism is employed to extract the best compromised solution among three different objective functions. The proposed method is implemented on IEEE 33 bus radial distribution system (RDS) and an actual realistic 94 bus Portuguese RDS and the results are compared with methods of Strength Pareto Evolutionary Algorithm (SPEA), Non-dominated Sorting Genetic Algorithm (NSGA), Multi-Objective Differential Evolution (MODE) and combination of Imperialist Competitive Algorithm and Genetic Algorithm (ICA/GA). Test results demonstrate that the proposed method is more effective and has higher capability in finding optimum solutions in cases where DG and SCB are located and sized simultaneously in a multi objective optimization.

Introduction

Problem description

Distribution systems usually consist of feeders configured radially. Nowadays the increasing demand and load have led to the development of distributed systems. This factor causes further voltage drop, increased losses, as a result reduction of the bus voltage stability and load imbalance. Therefore, the usage of distributed generations (DGs) has been increased. The installation of such sources in distribution systems can prevent from the establishment of new transmission and distribution lines to supply power and makes economical saving. The proper installation of DGs decreases network losses, improves network performance, delays investment, and increases the reliability. In addition, in distribution systems, shunt capacitor banks (SCBs) can improve power quality parameters and compensate portion of reactive power losses with injecting reactive power. They are cheaper than DGs and do not have any limits for installation. Using DGs and SCBs simultaneously has additional advantages and capabilities for the distribution system. The mentioned is related to the location and size of DGs and SCBs. On the other hand, the network operators need to access load data for planning and operation of distribution systems. Load on distribution networks can be stochastic. They need to find a suitable technique for evaluating distribution systems which consider uncertainty loads. The load of distribution systems is very important for solving sitting and sizing problem of DGs and SCBs, therefore load must be considered as uncertain. The technique of solution for the optimization problem can be single or multi objective.

Literature review

Table 1 has summarized a total list of previous works on different techniques for solving the problem of choosing proper location and capacity of installing DGs and SCBs in RDS. It is shown in this table that there is a wide range of methods and techniques for placement and sizing of DGs and SCBs separately [1–14] and simultaneously

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Nomenclature

RDS	radial distribution system
DGs	distributed generations
SCBs	shunt capacitor banks
SCI	section current index
VSI	voltage stability index
Is_m	mean of Line section current after placement DGs and SCBs
Isa	line section current after placement DGs and SCBs
s	line section
L	total number of line section
n_n	total number of buses in the given RDS
n_i	receiving bus number (n_i = 2, 3, ..., n)
m_i	bus number that sending power to bus n_i ($m_2 = n_1 = 1$)
i	branch number that fed bus n_i
$N = n_n - 1$	total number of branches in the given RDS
N_{DG}	total number of DG
C_{DGni}	selected capacity of DG for installation in node i (MW): 2 MW
n_{DG}	bus number of DG installation
P_{gni}	active power output of the DG at bus n_i (MW)
Q_{gni}	reactive power output of the DG at bus n_i (Mvar)
P_{cni}	active power output of the capacitor bank at bus n_i (kW)
Q_{cni}	reactive power output of the capacitor bank at bus n_i (kvar)
P_{dni}	active power demand at bus n_i
Q_{dni}	reactive power demand at bus n_i
$P_{ni}(n_i)$	total real power load fed through bus n_i
$Q_{ni}(n_i)$	total reactive power load through bus n_i
P_{gni}^{min}	minimum active power of DG at bus n_i
P_{gni}^{max}	maximum active power of DG at bus n_i
P_{RPL}	real power losses of n_n-bus distribution system
Q_t	maximum allowable capacitance at buses
Q_D	total reactive power demand
Q_0	minimum capacity of SCB
V_{ni}	voltage of bus n_i
V_{mi}	voltage of bus m_i
V_{ni}^{min}	minimum voltage at bus n_i
V_{ni}^{max}	maximum voltage at bus n_i
V_{rated}	rated voltage (1 pu)
$\lvert s_{ni}^{max}\rvert$	maximum apparent power at bus n_i
Y_{ni}	admittance between bus n_i and bus m_i
θ_{ni}	phase angle of $Y_i = Y_{ni}\angle\theta_{ni}$
δ_{ni}	Phase angle of voltage at bus n_i ($V_{ni} = V_{ni}\angle\delta_{ni}$)
δ_{mi}	phase angle of voltage at bus m_i
I_{ni}	current of branch i
R_{ni}	resistance of branch i
X_{ni}	reactance of branch i
SI (n_i)	voltage stability index of bus n_i (n_i = 2, 3, ..., n)
pf_{ni}^{DG}	power factor DG_i at bus n_i
S_{ni}^{DG}	apparent power DG_i at bus n_i
Qc_n	the reactive power of capacitor banks on bus-n
y_n	the shunt admittance in section-s
$S_{l\ n}$	the complex power at the n-th bus
R_s	the resistance of section-s
X_s	the reactance of section-s
V_n^k	the voltage of bus-n in iteration-k
I_n^k	the current of bus-n in iteration-k
Is_s^k	the current in section-s in iteration-k
N_j	the set of branches connected to bus-n
w	the inertia weight
c_1, c_2	acceleration constants
r_1, r_2	two random numbers in the range of [0, 1]
$pbest_i[t]$	the best position ever visited by the particle i at the t-th iteration
$gbest_i[t]$	the global best position in the entire swarm.
f_i^{min}	the minimum value of the i-th objective function among all Pareto front solutions
f_i^{max}	the maximum value of the i-th objective function among all Pareto front solutions
N_{nd}	is the number of Pareto front solutions
m	total number of line
n_c	the allowable number of SCBs based on Q_0
U	integer multiples (1, 2, ..., n_c)
n_{sc}	the total number of SCBs to be installed
K_{cni}	the annual cost of the reactive power injection at bus i ($/kvar/year)
k_{dni}	fixed cost of capacitor ($) = 1000
k_{IDG}	investment cost of DG sources ($/MW) = 318,000
K_{EDG}	operation cost of DG sources including maintenance cost ($/MW h) = 36
nyr	planning period (year) = 10
T	one year period (h) = 8760 h
IntR	the interest rate = 9%
InfR	the inflation rate = 12.5%
$I_{inj.}$	current injected from substation to RDS
V_{ss}	nominal voltage of substation (pu) = 1 pu
K_{ss}	energy market price ($/MW h) = 49

[15–19]. Some references used analytical practice to obtain the optimal location for DGs and SCBs in a RDS [1,2,4,8]. Refs. [5–7,9,10,12–15,17–19] have proposed heuristic algorithms to determine the optimum location and size of the DGs and SCBs. In this classification, the models are single objective [10–13] or multi objective [17–19] that the used model of multi objective optimization is penalty coefficient method. Multi objective studies have considered a variety of objective functions and technical issues including voltage profile, loss minimization, reliability [2,7], network global cost, voltage stability [9,18,19] and load modeling [7,18].

Contributions

The placement and sizing of DGs and SCBs should be modeled simultaneously in the form of an optimization problem; otherwise the operation of the power distribution system would not be optimal properly. In present work, unlike the previous works in Table 1, a multi objective (no single objective) placement and sizing of DGs and SCBs simultaneously (no separately) is formulated and fuzzy multi objective particle swarm optimization (MOPSO) with Pareto solutions is proposed to solve the problem. First the mentioned algorithm obtains Pareto front optimal solutions, and then fuzzy selection method chooses the best solution among the Pareto front optimal solutions.

Access to load data is one of the most important processes in planning and operation of distribution systems. Load in distribution networks can be stochastic in nature. For historical or online data gathering, a limited number of data recorders are used for load monitoring of feeders. Because the results of load estimation and forecasting techniques are not exact, it is desirable to find a suitable approach for consideration of load uncertainty to obtain accurate and correct results for optimum size and location of DGs and SCBs.

The proposed model gets the optimal location and size of DGs and SCBs with satisfying objective functions. In this paper, objective functions are considered to increase performance and

Table 1
Literature review on specifying location and capacity of DGs and SCBs in RDS.

Ref.	SCBs separately	DGs separately	DGs and SCBs simultaneously	Load modeling	Objective	Solution method	Published
Caisheng et al. [1]	×	✓	×	Cons.	Single	Analytical	2004
Borges et al. [2]	×	✓	×	Cons.	Multi	Analytical-power flow	2003
Chiradeja et al. [3]	×	✓	×	Cons.	Multi	General-penalty coef.	2004
Ochoa el al. [4]	×	✓	×	Cons.	Multi	General-penalty coef.	2006
Gandomkar et al. [5]	×	✓	×	Cons.	Single	GA[a]/TS[b]	2005
Falaghi and Haghifam [6]	×	✓	×	Cons.	Multi	ACO[c]-penalty coef.	2007
Khalesi et al. [7]	×	✓	×	Time var.	Single	Dynamic programming-penalty coef.	2011
Acharyaet al. [8]	×	✓	×	Cons.	Single	Analytical	2006
Moradi and Abedini [9]	×	✓	×	Cons.	Multi	GA/PSO-penalty coef.	2012
Masoum et al. [10]	✓	×	×	Cons.	Single	GA	2004
Da Silva IC et al. [11]	✓	×	×	Cons.	Single	Heuristic constructive algorithm	2008
Eajal et al. [12]	✓	×	×	Cons.	Single	PSO	2010
Ladjavardi and Masoum [13]	✓	×	×	Cons.	Single	GA/fuzzy	2008
Chung-Fu Chang [14]	✓	×	×	Cons.	Multi	ACO-penalty coef.	2008
Abu-Mouti and El-Hawary [15]	×	×	✓	Cons.	Single	ABC[d]	2011
Wang and Zhong [16]	×	×	✓	Cons.	Single	Power flow	2011
Esmaeilian et al. [17]	×	×	✓	Cons.	Multi	GA	2013
Sajjadi et al. [18]	×	×	✓	Time var.	Multi	Memetic	2013
Moradi et al. [19]	×	×	✓	Cons.	Multi	ICA[e]/GA-penalty coef.	2014

[a] Genetic Algorithm.
[b] Tabu Search.
[c] Ant Colony Optimization.
[d] Artificial Bee Colony.
[e] Imperialist Competitive Algorithm.

technical benefits of distribution systems. The contributions of this paper are as follows:

1. Multi objective approach with Pareto optimal solutions is applied to solve the problem instead of other methods (i.e. Penalty Function Method such as Ref. [9]). This procedure satisfies all objectives correctly and accurately.
2. The load uncertainty is considered in the proposed model (no constant load or time varying load).
3. Optimal placement and sizing of DGs and SCBs are simultaneous (no separately).
4. A fuzzy decision making is applied to the non-dominated solutions (no several decisions).
5. The proposed MOPSO method is performed on the standard and real case studies.

Problem formulation

The problem regarded in this paper is to find out the locations, number and sizes of DGs and SCBs to be installed in distribution systems with consideration of load uncertainty. The objective functions adopted in this study are Reduction of active power losses, improving voltage stability and balancing of sections current of distribution systems. Objective functions are bounded by equality and inequality constraints.

Objective function

The objective functions in this paper include three terms: active power loss reduction, improvement of voltage stability and balancing of sections current.

Active power loss reduction

In the power distribution network, loss depends on two factors: line resistance and current. Variations of the line resistance are low and negligible. Overall line loss is related to the current and the line current depends on system topology and loads. It is usually impossible to reduce the value of the load, but line currents can be reduced with DGs and SCBs proper placement. The objective function to give network real power losses is:

$$f_1 = \min\left\{P_{RPL} = \sum_{i=2}^{n_n}(P_{gni} - P_{dni} - V_{mi}V_{ni}Y_{ni}\cos(\delta_{mi} - \delta_{ni} + \theta_{ni}))\right\} \quad (1)$$

Voltage stability index

When DG or capacitor is connected to distribution network, the index of voltage stability of the network will be changed. This index, which can be evaluated at all buses, was presented in [20]. Fig. 1 shows a representative branch of RDS. The equations used to formulate this index are given in [21] to solve the load flow for RDSs. Eq. (2) represents the voltage stability index.

$$SI(n_2) = |V_{mi}|^4 - 4[P_{ni}(ni)R_{ni} + Q_{ni}(ni)X_{ni}]|V_{mi}|^2 - 4[P_{ni}(ni)R_{ni} + Q_{ni}(ni)X_{ni}]^2 \quad (2)$$

$$f'_2 = \max(SI(n_i)) \quad i = 2, 3, \ldots, N_n \quad (3)$$

To improve the voltage stability index, the objective function is presented as below:

$$f_2 = \left(\frac{1}{f'_2}\right) \quad (4)$$

The voltage stability index (VSI) is calculated for all of the buses, buses with minimum voltage stability index are prone to voltage instability, and it is very important to distinguish weak buses. $SI(n_i)$ must be maximized for improving voltage stability as its consequence the presented objective function will be minimized.

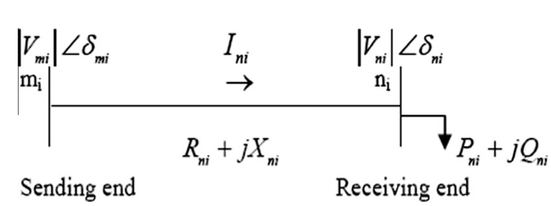

Fig. 1. A representative branch of a RDS.

Index of balancing current of sections

Providing active and reactive power near loads may increase or decrease current flow in some sections of the network, thus releasing more capacity or also placed out of distribution line limits. The sections current index gives important information about the level of currents through the network. The index of balancing current of sections or load balancing index makes reserve capacity for demand growth. The current index can be calculated when performing the power flow analysis before and after installation of DGs and SCBs as follows:

$$SCI = \frac{\sum_{s=1}^{L} \left| \frac{Is_m - Isa_s}{\max(Is_m, Isa_s)} \right|}{L} \tag{5}$$

$$f_3 = \min(SCI) \tag{6}$$

Assumptions

The assumptions used in problem formulation are as follows:

(1) The type of used DGs is capable to inject both real and reactive power.
(2) Maximum power limitation of DGs for different systems is assumed to be 2 MW.
(3) The smallest capacitor size available is 150 kvar.
(4) The maximum allowable number of the parallel capacitors is 15, in each bus.
(5) The load model which is used in the simulations is fuzzy with uncertainty.
(6) A fuzzy decision making method is applied to guide the decision-maker to the compromise trade-off solutions among three different objective functions.

Constraints

Load balancing constraint

The constraints for each bus can be expressed as follows:

$$P_{gni} - P_{dni} - V_{ni} \sum_{j=1}^{N} V_{nj} Y_{nj} \cos(\delta_{ni} - \delta_{nj} - \theta_{nj}) = 0 \tag{7}$$

$$Q_{gni} - Q_{dni} - V_{ni} \sum_{j=1}^{N} V_{nj} Y_{nj} \sin(\delta_{ni} - \delta_{nj} - \theta_{nj}) = 0 \tag{8}$$

The voltage magnitude at the sending end V_{ni+1} can be expressed by the following recursive set of equations [15]

$$V_{ni+1}^2 = V_{ni}^2 - 2(r_{ni+1} P_{ni} + x_{ni+1} Q_{ni}) + \left(\frac{(r_{ni+1}^2 + x_{ni+1}^2)(P_{ni}^2 + Q_{ni}^2)}{V_{ni}^2} \right) \tag{9}$$

Voltage constraint

The voltage of all buses is only allowed in the range of

$$V_{\min} \leqslant V_{ni} \leqslant V_{\max} \tag{10}$$

DG constraints

The DG source used must be allowable in the range of size and power factor

$$S_{\min}^{DG} \leqslant S_{ni}^{DG} \leqslant S_{\max}^{DG} \tag{11}$$

$$pf_{\min}^{DG} \leqslant pf_{ni}^{DG} \leqslant pf_{\max}^{DG} \tag{12}$$

Parallel capacitor constraints

Capacitors that are commercially available come in discrete sizes. That is the shunt capacitors to be dealt with are multiple integers of the smallest capacitor size available.

$$Q_{cni} = U \cdot Q_0 \tag{13}$$

Moreover, due to economic problems and limited installation space, maximum allowable capacitance at the buses should not be beyond the allowed constraint.

$$\sum_{i=1}^{nc} Q_{cni} \leqslant Q_t \tag{14}$$

Constraints of reactive power of DG and SCB

Total reactive power injection of SCBs and DGs at each bus should not be more than reactive power consumption of studied system.

$$Q_{cni} + Q_{gni} \leqslant Q_D \tag{15}$$

Thermal limit

Final thermal limitation of distribution lines of the network must not be exceeded from following range.

$$|S_{ni}| \quad \leqslant \quad |S_{ni}^{\max}| \quad ni = 1, \ldots, N \tag{16}$$

2.4 Backward–forward sweep power flow based on fuzzy

The method to carry out the power flow for distribution system under balanced operating conditions employing an uncertainty load model can be understood through the following points:

Current injection

The method is based on the equivalent current injection. At bus n, the complex power S_l is specified and the corresponding equivalent current injection at the k-th iteration of the solution is computed as

$$I_n^k = \left(\frac{y_n}{2} . V_n^k \right) + \left[\left(\frac{S_{l\,n}}{V_n^k} \right)^* \right] \tag{17}$$

Nodal current injection with SCB:

$$I_n^k = \left(\frac{y_n}{2} V_n^k \right) + \left[\left(\frac{S_{l\,n}}{V_n^k} \right)^* - \left(\frac{Qc_n}{V_n^k} \right)^* \right] \tag{18}$$

Nodal current injection with DG:

$$I_n^k = \left(\frac{y_n}{2} V_n^k \right) + \left[\left(\frac{S_{l\,n}}{V_n^k} \right)^* - \left(\frac{S_{DG\,n}}{V_n^k} \right)^* \right] \tag{19}$$

Section current

The branch currents can be formed as a function of the equivalent current injections

$$Is_s^k = I_n^k + \sum_{j=1}^{Nj} Is_j^k \tag{20}$$

Bus voltage calculation

$$V_n^{k+1} = V_m^{k+1} - (R_s + jX_s) Is_s^k \tag{21}$$

The power injections at each bus can be converted into the equivalent current injections using Eqs. (17)–(19) and a set of equations can be written by applying Kirchhoff's Current Law (KCL) at each bus. Then, the current of sections can be formed as a function of the equivalent current injections (Eq. (20)). (Using section current can be calculated by summing the injection currents (backward sweep). The relations between the branch currents and bus voltages can be expressed as a function of the

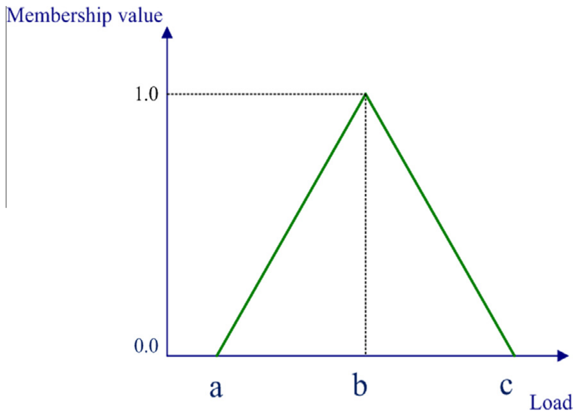

Fig. 2. A triangular fuzzy membership function.

branch currents, line parameters and substation voltage. Forward sweep is used from the sending bus toward the receiving bus of the feeder (Forward Voltage Sweep) [22].

The load uncertainty model

In this paper, the uncertainties in the input parameters are modeled with the help of triangular fuzzy number, a triangular fuzzy membership function is shown in Fig. 2. In this fig. three points a, b, c, are specified and points x: [a, b] have membership values ($0 \leqslant \mu x \leqslant 1$). "$x$" on real axis can be considered as the PL and QL. Finally, a defuzzification criterion based on operator and planner intuition is performed to obtain the results for use in the objective function [23].

Proposed solution algorithm

In this section, first PSO is briefly described which fulfills our proposed method i.e. MOPSO in finding site and size of DGs and SCBs simultaneously. Population-based optimization is developed by Eberhart and Kennedy in 1995 [24,25]. It employs a population of individuals, called particles. Each particle in the swarm represents a potential solution of the problem considered. Each particle looks for the best solution in the D-dimensional search space at a random velocity. Each particle updates its velocity and position according to the following equations:

$$v_i[t+1] = wv_i[t] + c_1r_1(pbest_i[t] - x_i[t]) + c_2r_2(gbest_i[t] - x_i[t]) \tag{22}$$

$$x_i[t+1] = x_i[t] + v_i[t+1] \tag{23}$$

The position and velocity of the swarm particles are dynamically modified according to the combined communication among all the particles and each individual's own experience simultaneously Each particle modifies its velocity and position according to its own past flying experience and that of the rest of the swarm. If any particle, say particle i, is randomly placed in two dimensional search space at the point ($x_i[t]$), this particle flies through the problem search space with a random velocity ($v_i[t]$). The particle remembers the best position achieved so far and stores it as ($pbest_i[t]$), each particle compares its best position with those attained by other particles. Finally, each particle stores the best position achieved in the entire swarm as $gbest_i[t]$.

Multi objective particle swarm optimization (MOPSO)

The multi objective format of PSO named MOPSO is suitable in case of minimizing multiple objective functions simultaneously. MOPSO was presented in 2004 by Coello et al. [26]

$$\begin{aligned} &\min\ F(X) = [f_1(X), \ldots, f_N(X)] \\ &X = [x_1, \ldots, x_m] \end{aligned} \tag{24}$$

Multi-objective optimization technique results arrange optimal solutions, instead of one solution. One of the solutions cannot be considered to be better than any other with regard to all objective functions. Consequently, in MOPSO method, there is not generally one global optimum, but a bunch of so called Pareto-optimal solutions. Non-dominated solution can be located in Pareto front solution. (Non-dominated solution is not dominated by any other solution.) A decision vector x_1 dominates vector x_2 if.

$$\begin{aligned} &\forall i \in \{1, 2, \ldots, N_{obj}\} : f_i(x_1) \leqslant f_i(x_2) \\ &\exists j \in \{1, 2, \ldots, N_{obj}\} : f_j(x_1) \leqslant f_j(x_2) \end{aligned} \tag{25}$$

MOPSO procedure for problem of placement and size of DGs and SCBs is described as follows:

Step 1. Creating initial population.

Procedure of creating initial population: The DGs size variables are continuous, while the variables that represent the SCBs size are discrete and multiple integers of the smallest capacitor size available. The DGs and SCBs placement buses are positive integers. The DGs optimized variables are its real power output, P_{DG} with the power factor pf_{DG} and they are described as:

$$P_{DG} = \left[0, P_{DG}^{\max}\right] \tag{26}$$

$$pf_{DG} = \left[pf_{DG}^{\min}, pf_{DG}^{\max}\right] \tag{27}$$

The corresponding reactive power generated by the DG is calculated as follows:

$$Q_{DG} = P_{DG} \cdot \tan(\cos^{-1}(pf_{DG})) \tag{28}$$

The size of SCBs is discrete. First the method produces a continuous number randomly between ([0,1]) then uses Eq. (30) to convert it to a discrete number.

$$b_{cap} = [0, 1] \tag{29}$$

$$Q_{cap} = round(n_c \cdot b_{cap}) \cdot Q_0 \tag{30}$$

As a result, initial population can be produced for each particle as follows:

$$X_i = [\overbrace{(P_{DG}, pf_{DG}, n_{DG})}^{DG1}, \ldots \overbrace{(P_{DG}, pf_{DG}, n_{DG})}^{DG_n}, \overbrace{(Q_{cap}, n_{cap})}^{Cap1}, \ldots \overbrace{(Q_{cap}, n_{cap})}^{Cap_n}]$$

Step 2. Run power flow and calculate objective functions.
Step 3. Determining non-dominated solutions.

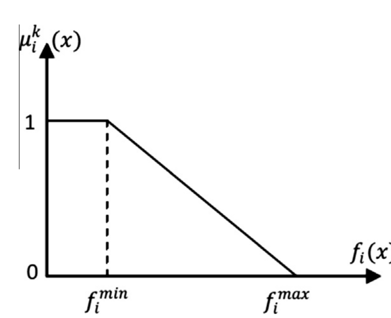

Fig. 3. Linear type membership function.

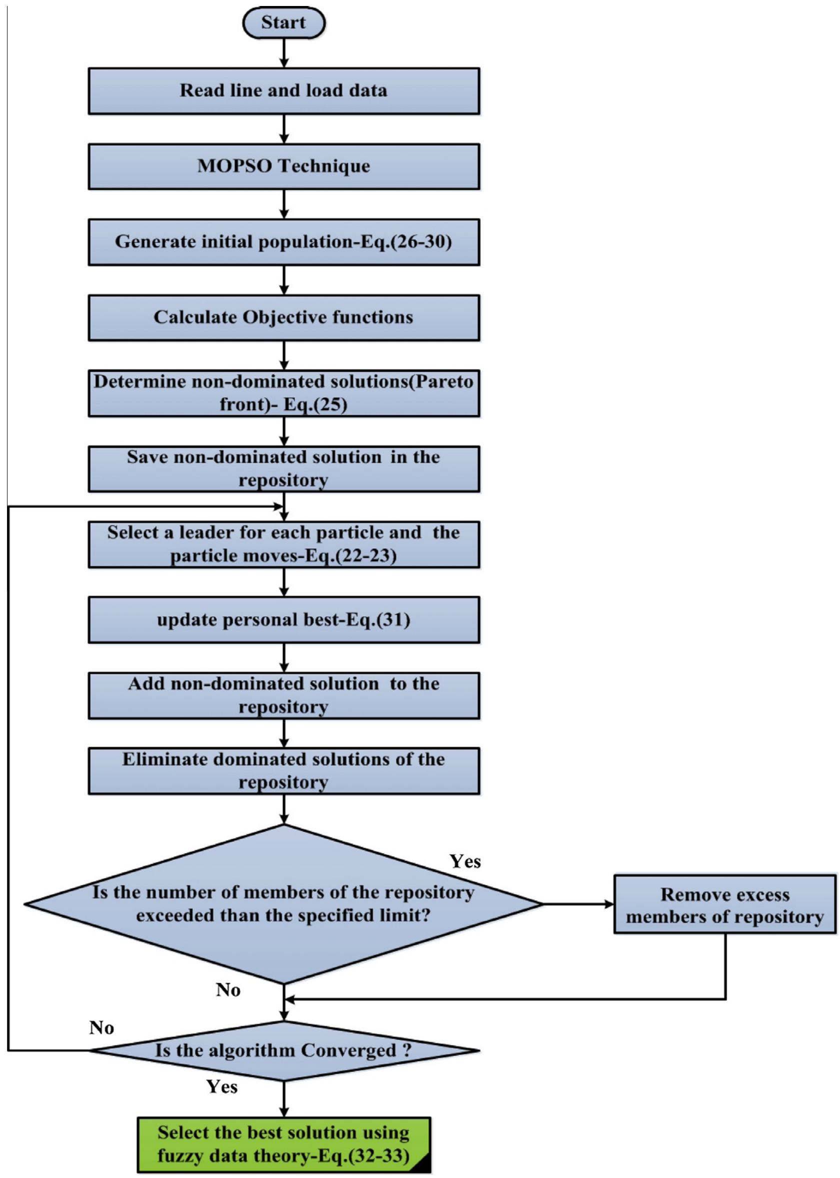

Fig. 4. Flowchart of MOPSO method for optimal multi objective sitting and sizing of DGs and SCBs simultaneously with fuzzy selection and considering load uncertainty.

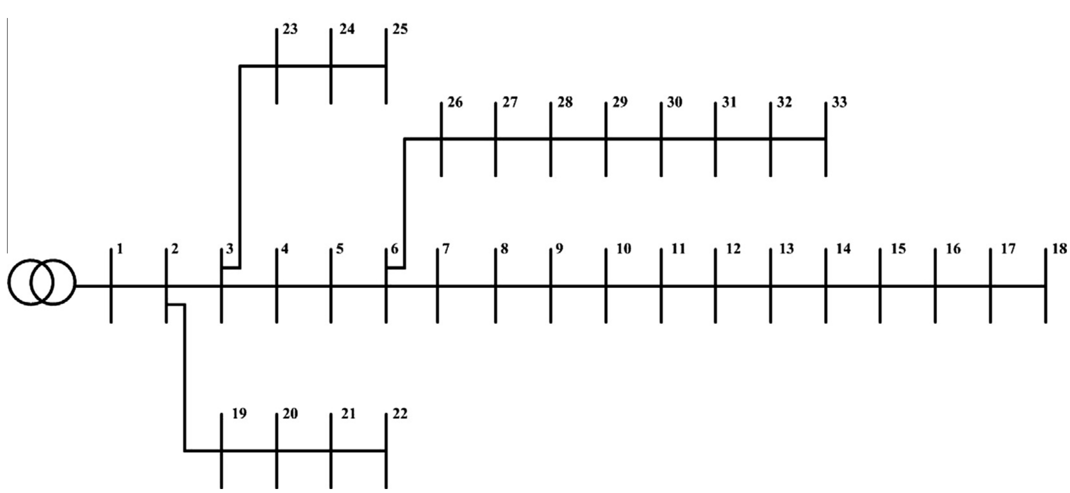

Fig. 5. Single line diagram of the 33 bus distribution test system.

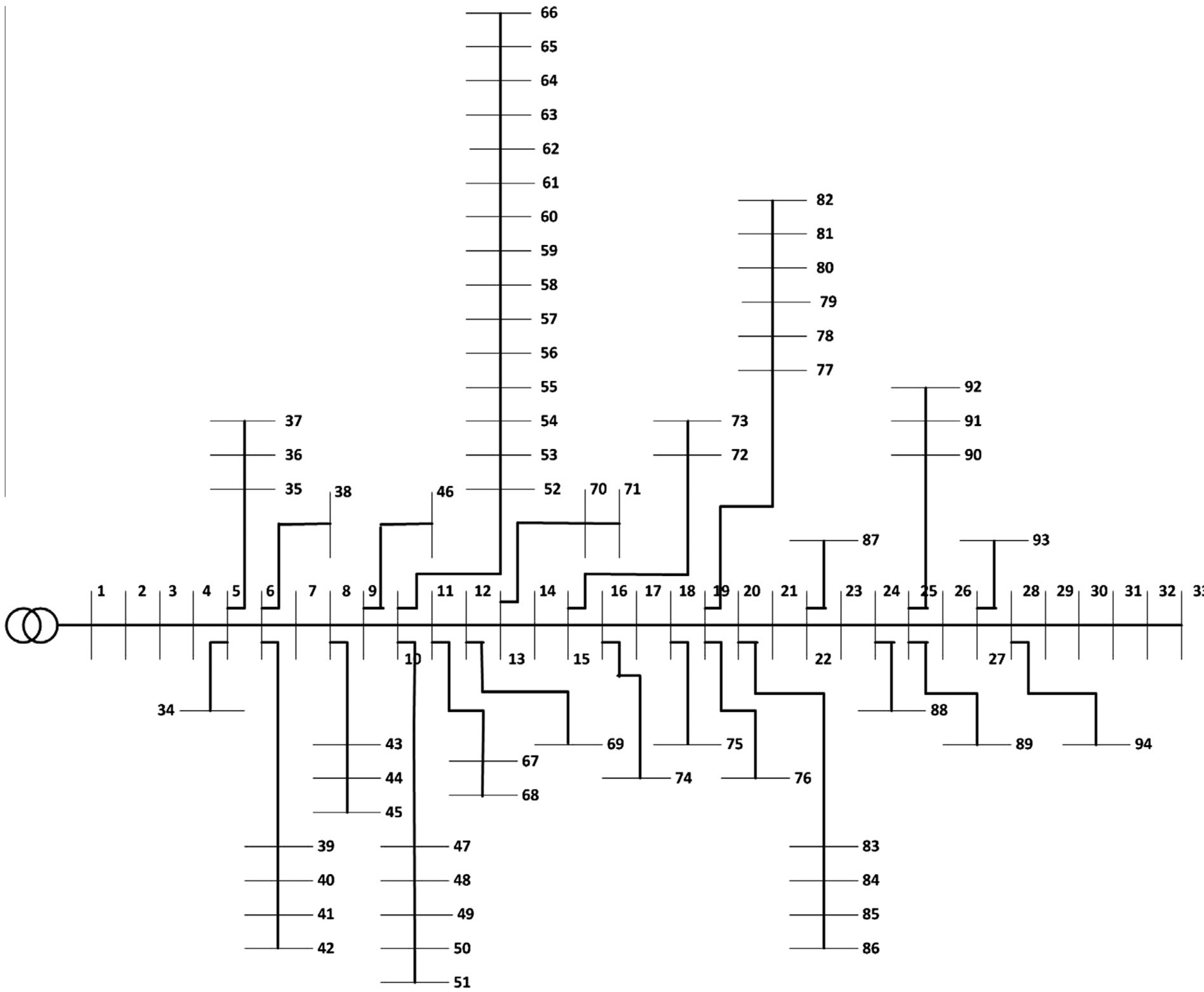

Fig. 6. Single line diagram of the 94 bus actual Portuguese distribution test system.

Step 4. Separating non-dominated solution and saving those in the repository (the repository is an archive of non-dominated solution).

Step 5. Select a leader from repository for each particle as global best and the particle moves by using Eqs. (22) and (23).

Procedure for selecting leader: each particle needs to be updated by using Eqs. (22) and (23). There are non-dominated solutions instead of one solution as global best, for this reason, they should select a leader as a global best to update their position, this mechanism need to insure the diversity among the solutions, in the first stage, search space should be divided into equal parts. Each part of the search space that has fewer members of the repository. It has more probability to be selected, in the second stage. One of the members of selected part is chosen randomly as a leader for each particle.

Step 6. Update best position of each particle (personal best).

Procedure of updating best position: each particle needs to be updated its best position. Comparing new position and former best position, according to the following equation

$$pbest[t+1] = \begin{cases} pbest[t] & pbest[t] \text{ dominate } x_i[t+1] \\ x_i[t+1] & x_i[t+1] \text{ dominate } pbest[t] \\ \text{select randomly among} & \text{otherwise} \\ x_i[t+1] \& pbest[t] & \end{cases} \tag{31}$$

Step 7. Add non-dominated solution of the current population to the repository.

Step 8. Eliminate dominated solutions of the repository.

Step 9. If the number of members of the repository was exceeded than the specified limit, remove excess members.

Step 10. If the algorithm is converged the operation will stop else go back to the step 5.

Step 11. The reminded members of the repository form Pareto front.

Table 2
Objective function values of the systems before installation of DGs and SCBs (default).

System	Ploss (kW)	*VSI* (pu)	*SCI*
33 bus-IEEE Standard	232.3	1.515	0.49
94 bus-Actual Portuguese	362.6	1.928	0.746

Fuzzy decision making

Pareto front is made from the number of solutions. The planners need an appliance base on their intuition to select the final solution among the solutions of Pareto front. Because of the uncertain nature of the planner's judgment, a fuzzy satisfying method is used for

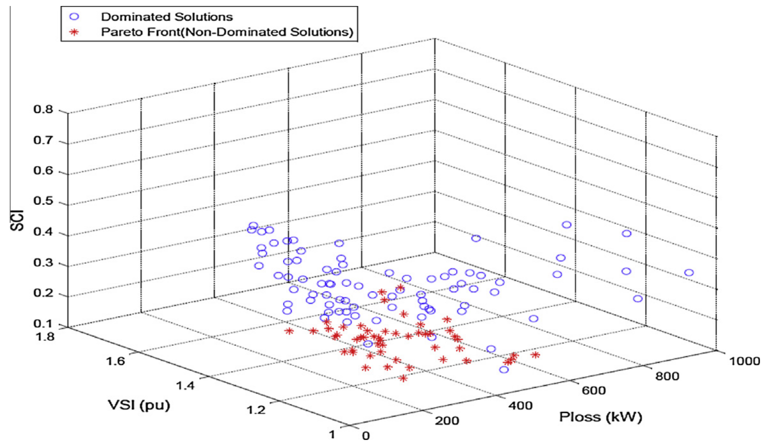

Fig. 7. The Pareto front solutions obtained for 3 objectives for a 33 bus RDS.

Table 3
The results of optimal DGs and SCBs simultaneously for a 33 bus RDS compared with other algorithms.

Method	SPEA[a]	NSGA[b]	MODE[c]	ICA/GA (penalty coefficient method) [19]	Proposed (MOPSO-Pareto optimal solution)
Optimal placement bus for DG	11	9	9	9	9
	23	24	21	25	23
	33	32	28	33	30
DG size (kW)	1603	1477	1193	1284	911
	1980	1960	1991	1970	669
	1960	1617	1308	1616	1423
Power factor	0.97	0.87	0.86	0.8	0.982
	0.84	0.917	0.99	0.91	0.808
	0.829	0.938	0.854	0.88	0.8
Optimal placement bus for capacitor	2	3	33	2	10
	20	19		4	21
		33		33	
Capacitor size (kvar)	1500	1950	1800	1200	1050
				300	1200
	2250	600		900	
		750			
Real power losses (kW)	178.05	113.8	89.1	88.2	80.8
VSI (pu)	1.01	1.02	1.14	1.01	1.002
SCI	0.404	0.39	0.34	0.35	0.33

[a] Strength Pareto Evolutionary Algorithm.
[b] Non-dominated Sorting Genetic Algorithm.
[c] Multi-Objective Differential Evolution.

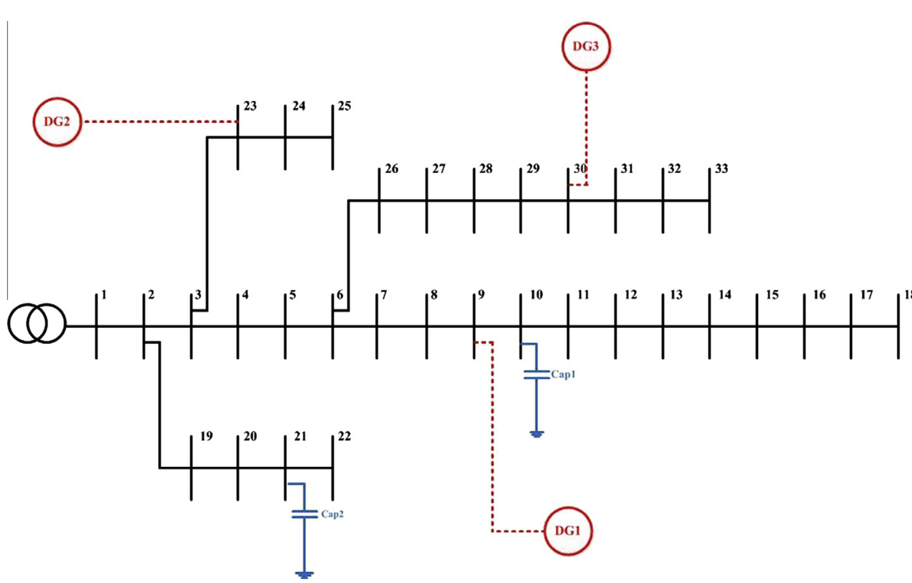

Fig. 8. A schematic of optimal placement of DGs and SCBs for a 33 bus RDS.

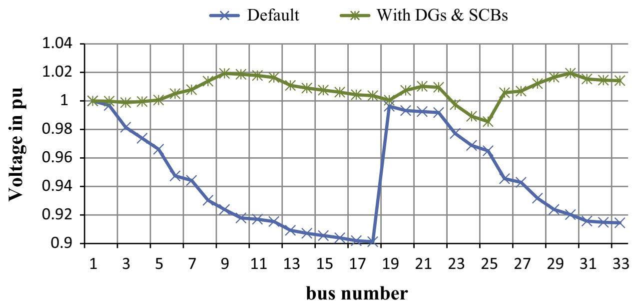

Fig. 9. Voltage levels for a 33 bus RDS with DGs and SCBs simultaneously.

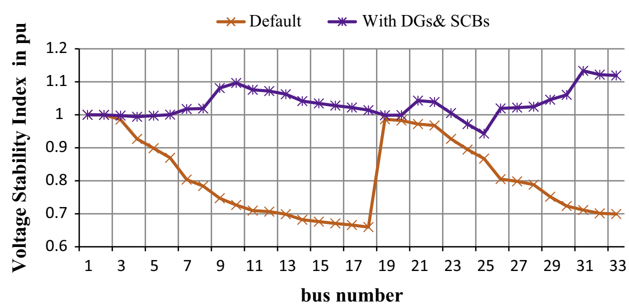

Fig. 10. Voltage stability index (VSI) for a 33 bus RDS with DGs and SCBs simultaneously.

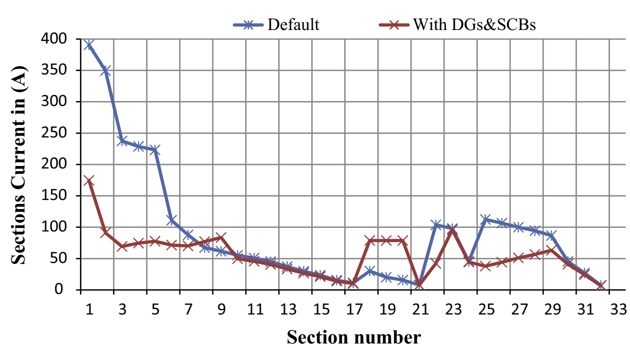

Fig. 11. Sections current for a 33 bus RDS with DGs and SCBs simultaneously.

this purpose; i-th objective function F_i of single k is represented by the membership function μ_i^k defined as follows:

$$\mu_i^k = \begin{cases} 1 & f_i \leqslant f_i^{\min} \\ \frac{f_i^{\max} - f_i}{f_i^{\max} - f_i^{\min}} & f_i^{\min} \prec f_i \prec f_i^{\max} \\ 0 & f_i \geqslant f_i^{\max} \end{cases} \tag{32}$$

μ_i^k ranges from 0 to 1, where $\mu_i^k = 0$ indicates incompatibility of the solution with the set, while $\mu_i^k = 1$ means full compatibility. Fig. 3 illustrates the graph of this membership function.

For each Pareto front solution k, the normalized membership function μ^k is calculated

$$\mu^k = \frac{\sum_{i=1}^{m} \mu_i^k}{\sum_{k=1}^{N_{nd}} \sum_{i=1}^{m} \mu_i^k} \tag{33}$$

The maximum value of μ^k is the best compromise solution. Fig. 4 shows flowchart of MOPSO method for optimal multi objective sitting and sizing of DGs and SCBs simultaneously with fuzzy selection that load uncertainty is considered, too.

Results

Test systems

Two test systems have been used to test and validate the proposed MO fuzzy method.

Case 1: The first system is a 33 bus IEEE standard test RDS with a total real and reactive load of 3.72 MW and 2.3 Mvar, respectively and the rated voltage is 12.66 kV and the system is demonstrated in Fig. 5 [25].
Case 2: The second system is an actual Portuguese RDS with 94 buses. The system scheme is shown in Fig. 6. The line data and load data of the network are given in Appendix. The voltage at the substation is 15 kV + 5%. The total demands of the system are 4.79719 MW and 2.323 Mvar
The proposed method has been implemented in the MATLAB and tested for the two test systems.

Simulation results

In this section, the technical results of proposed method for both test systems are presented and discussed. The following

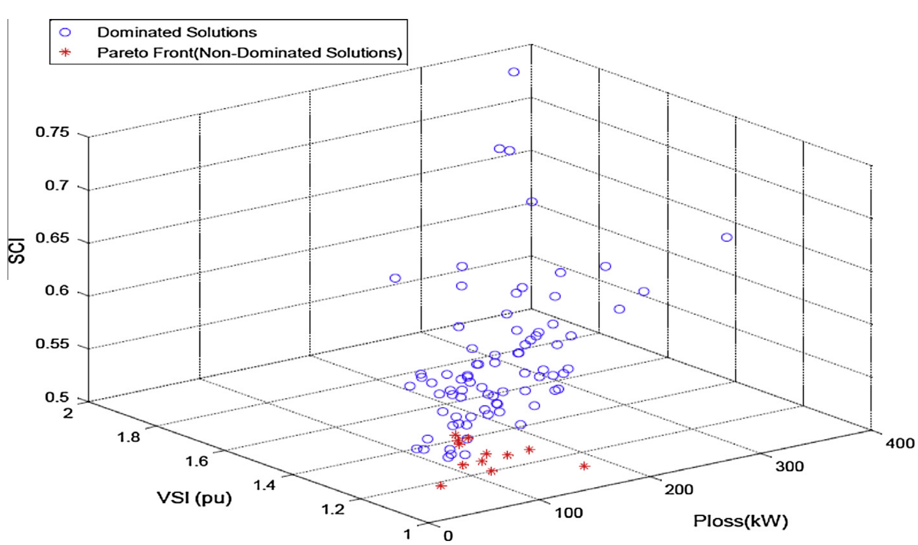

Fig. 12. The Pareto front solutions obtained for 3 objectives for 94 bus RDS.

Table 4
The results of optimal DGs and SCBs simultaneously for 94 bus RDS compared with other algorithms.

Method	SPEA[a]	NSGA[b]	MODE[c]	ICA/GA (penalty coefficient method)	Proposed
Optimal placement bus for DG	33	61	22	33	21
	66	87	55	59	56
	76	71	80	78	74
DG size (kW)	977	1158	950	834	557
	1665	1694	1990	1699	1823
	1542	1266	1330	1533	1693
Power factor	0.901	0.91	0.97	0.9	0.927
	0.844	0.856	0.83	0.83	0.816
	0.96	0.99	0.979	0.96	0.954
Optimal placement bus for capacitor	42	32	30	38	33
	54				
	86	64	45	42	
			65	77	42
Capacitor size (kvar)	600	300	300	150	300
			600	450	
	150		300	150	600
	300	300			
Real power losses (kW)	140.5	64.74	54.1	50.44	39.82
VSI (pu)	1.032	1.033	1.025	1.018	1.028
SCI	0.545	0.532	0.553	0.56	0.5432

[a] Strength Pareto Evolutionary Algorithm.
[b] Non-dominated Sorting Genetic Algorithm.
[c] Multi-Objective Differential Evolution.

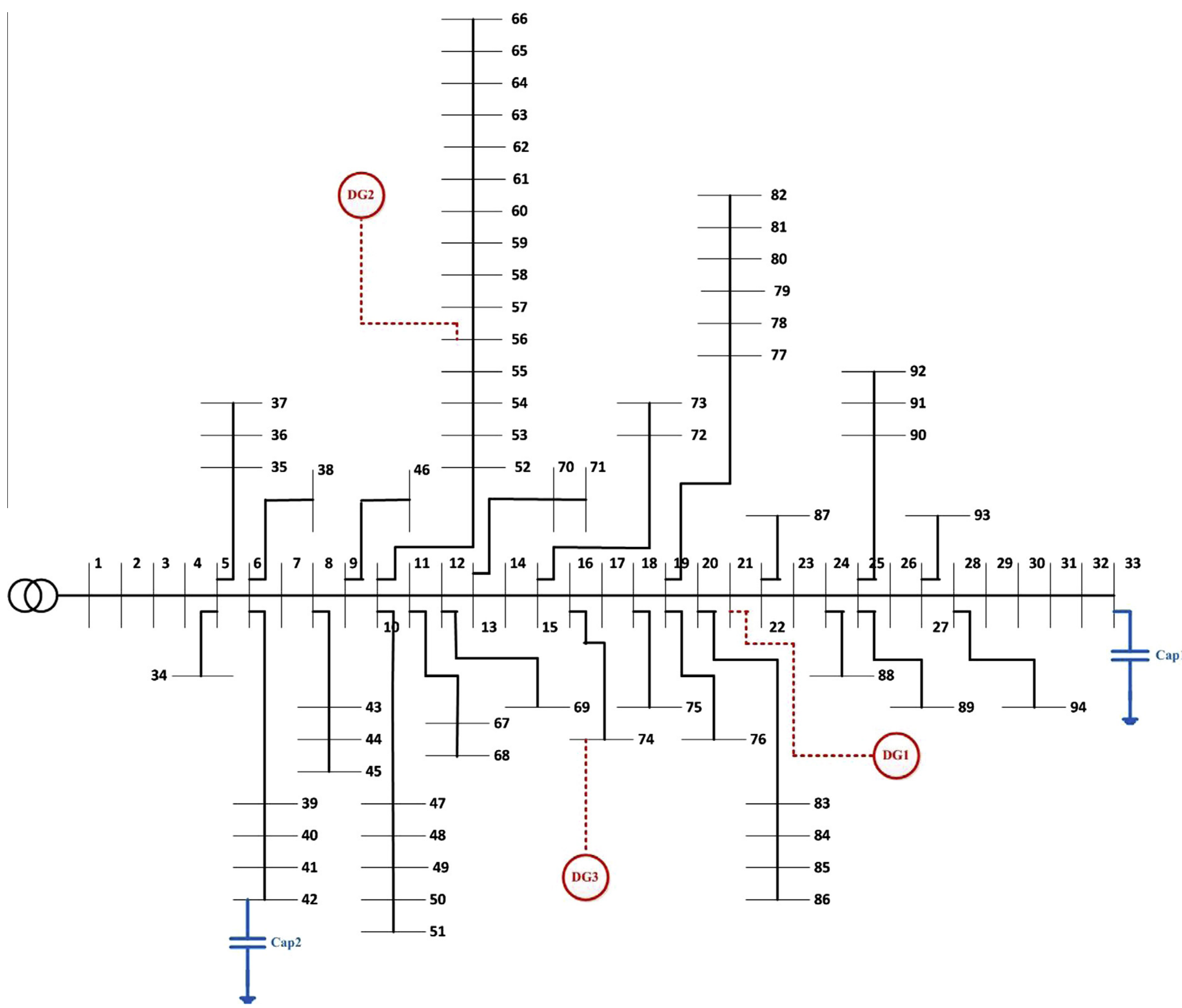

Fig. 13. A schematic of optimal placement of DGs and SCBs for 94 bus RDS.

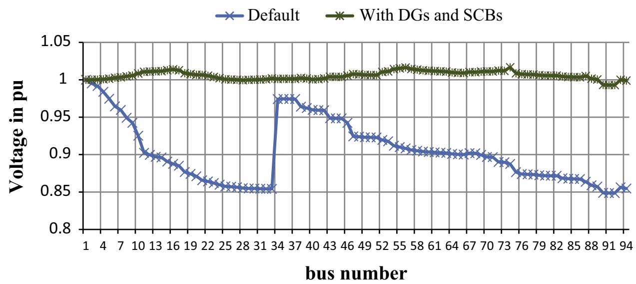

Fig. 14. Voltage levels for 94 bus RDS with DGs and SCBs simultaneously.

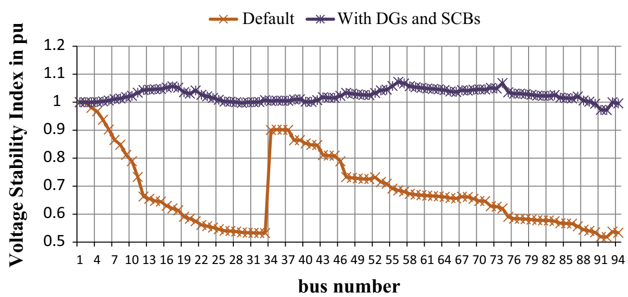

Fig. 15. Voltage stability index (VSI) for 94 bus RDS with DGs and SCBs simultaneously.

Table 5
Objective function values of the systems after installation of DGs and SCBs.

System	Ploss (kW)	VSI (pu)	SCI
33 bus-IEEE Standard	80.8	1.002	0.33
94 bus-actual Portuguese	39.82	1.028	0.5432

detailed case studies have been carried out for optimal capacity and location of DGs and SCBs. Table 2 shows the pre installation objective function values of DGs and SCBs for the systems using suggested power flow algorithm.

Case 1–33 bus standard RDS

In Fig. 7 Pareto front solutions obtained for 3 objectives are shown. Blue circles are dominated solutions and Red asterisks are non-dominated solutions. Table 3 describes the fuzzy selected non-dominated solutions from proposed method (MOPSO). Also shows results of the optimal size, location, power factor (for DG), VSI, SCI and real power losses of DGs and SCBs simultaneously in the 33 bus RDS, which these results are compared with SPEA, NSGA [27], MODE and ICA/GA [19]. It is seen from this table real power losses is less than other methods and the losses is 80.8 kW. The indices of VSI and SCI have allowable values in compare other methods; these values are 1.002 and 0.33 respectively. A schematic of optimal placement of DGs and SCBs from proposed method for the 33 bus RDS is shown in Fig. 8.

Fig. 9 describes the voltage profile of whole buses in the 33 bus RDS. It compares the voltage profile magnitudes before and after installation of DGs and SCBs. Prior to installation, the voltage magnitude of bus 18 was poor, which is improved with installation of DGs and SCBs. In addition, the voltage ranks at whole buses of the network have been improved. Fig. 10 shows the VSI. The VSI at the buses for the network were improved after installation of DGs and SCBs. Fig. 11 shows sections current for the 33 bus RDS that the current in almost all sections has decreased after installing DGs and SCBs.

Table 7
Overall economic results obtained from the proposed method.

System	33 bus	94 bus
Economical saving of reduction in purchased energy from the substation in life time period ($)	16,116,055	22,403,500
Final benefit including the total of costs in life time period ($)	2,943,269	5,217,130

Case 2–94 bus real RDS

In Fig. 12 a 3D plot of Pareto front solutions for 94 bus real RDS is shown. In Table 4 the fuzzy selected optimal results from proposed method compared with SPEA, NSGA, MODE and ICA/GA [19] are given. The improvement can be seen in solutions with proposed method. The values for Ploss, VSI and SCI are 39.82 kW, 1.028 pu and 0.5432, respectively. Optimal location buses for DGs are 21, 56, and 74 and for SCBs are 33 and 42 as shown in Fig. 13. The voltage profile and VSI pre and after placing of DGs and SCBs are shown in Figs. 14 and 15. The values are improved relative values before installing DGs and SCBs with proposed method. In Fig. 15 sections current for the 94 bus real is RDS illustrated that the current in almost all sections has decreased after installing DGs and SCBs.

Table 5, shows the objective function values after installation of DGs and SCBs.

Economic evaluation of applying DGs and SCBs simultaneously

Determining proper capacity and location of DGs and SCBs in RDS is important for obtaining their maximum potential benefits such as improving system stability and voltage profile reducing

Table 6
Comparison of final solution and initial condition along with commercial information of DG and SCB for proposed method-33 and 94 bus RDS.

Information	Unit	Value	33 bus		94 bus	
			Without DG and SCB ($)	With DG and SCB ($)	Without DG and SCB ($)	With DG and SCB ($)
Cost of purchased active power dispatched from substation including network losses	$/MW h	49	22,501,000	6,384,945	26,306,000	3,902,500
DG installation cost	$/MW	318,000	0	1,908,000	0	1,908,000
DG operation and maintenance cost	$/MW h	36	0	11,258,352	0	15,274,000
Fixed cost of capacitor	$	1000	0	2000	0	2000
Yearly capacitor cost	$/kvar	0.35	0	4434	0	2370
300 kvar		0.22				
600 kvar		0.228				
1050 kvar		0.170				
1200 kvar						
Planning period	Year	10				

Table 8
Improvement in the objective function values of the systems using proposed method with fuzzy selection and load uncertainty.

System	Improvement (%)		
	Ploss	VSI	SCI
33 bus-IEEE standard	65.2	34	32.65
94 bus-actual Portuguese	89	46.7	27

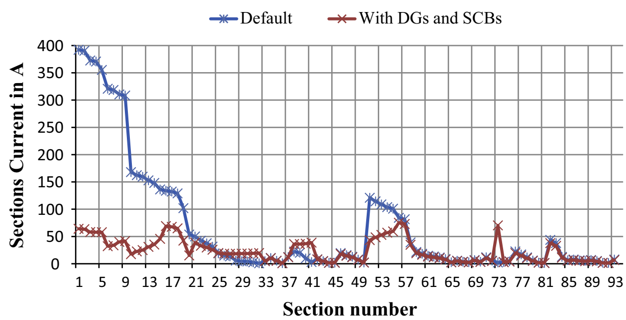

Fig. 16. Section current for 94 bus RDS with DGs and SCBs simultaneously.

power losses, and network reinforcement. The results show that proper placement not only improves mentioned power quality parameters but also makes economic saving or benefit for DG companies in planning period. Equations for calculating economic evaluation can be found in Appendix 1.

4.3.1 Simulation results relation to economical saving

In this section, the economical saving are presented and discussed. According to details in Appendix 1, energy saving and purchased benefit from substation and final benefit have been calculated for optimal capacity and location of DGs and SCBs in both test systems. Table 6 illustrates the commercial data of DGs [7] and SCBs [12] and comparison the costs of purchased active power dispatched from substation including RDS losses, DGs installation, operation and maintenance pre installation and after installation of DGs and capacitors for both systems. Saving or benefit of decrement in purchased energy getting from the substation and final benefit containing the total costs in a 10 years life time period can be noticed in Table 7. According to the table, final benefit of the 33 and 94 bus RDS are 2,943,269 $ and 5,217,130 $, respectively.

Discussion

This section provides a discussion of the performance of the proposed method outlined with regards to specific aspects.

Multi objective functions

MOPSO method is a Pareto solution method for solving multi objective problems. This method gains real optimum solution of a multi objective problem Based on non-dominated front (Pareto front). Most of the articles use the penalty coefficient method to obtain solution. In this method weight coefficient have high

Table 9
Line data of actual realistic 94 bus Portuguese RDS.

Sending node	Receiving node	*R* (Ω)	*X* (Ω)	Sending node	Receiving node	*R* (Ω)	*X* (Ω)	Sending node	Receiving node	*R* (Ω)	*X* (Ω)
1	2	0.112	0.1873	40	41	0.5177	0.2892	79	80	1.1738	0.6556
2	3	0.0763	0.1274	41	42	0.7148	0.3992	80	81	0.619	0.3457
3	4	0.1891	0.3161	8	43	1.0575	0.2785	81	82	0.5684	0.3174
4	5	0.2243	0.3749	43	44	0.5198	0.2903	20	83	0.8393	0.3011
5	6	0.2571	0.4297	44	45	0.3341	0.1866	83	84	0.2133	0.1191
6	7	0.134	0.2239	9	46	0.349	0.1949	84	85	0.3645	0.2036
7	8	0.2986	0.4991	10	47	0.5771	0.3223	85	86	0.3206	0.1791
8	9	0.1953	0.3265	47	48	0.3598	0.2009	22	87	0.7675	0.4286
9	10	0.5097	0.8519	48	49	0.7688	0.4294	24	88	1.5914	0.5709
10	11	1.5303	1.5101	49	50	0.2599	0.1451	25	89	0.702	0.3921
11	12	0.1889	0.1864	50	51	0.8654	0.4833	25	90	20.743	0.7441
12	13	0.1816	0.1793	10	52	0.5248	0.5179	90	91	0.678	0.2432
13	14	0.0661	0.0653	52	53	0.1737	0.1714	91	92	0.5738	0.3205
14	15	0.4115	0.4061	53	54	0.6148	0.6068	27	93	0.5913	0.3303
15	16	0.2584	0.255	54	55	0.198	0.1954	28	94	1.1865	0.3124
16	17	0.2033	0.2006	55	56	0.198	0.1954				
17	18	0.7243	0.7148	56	57	0.285	0.2813				
18	19	0.2162	0.2134	57	58	0.1429	0.141				
19	20	0.35	0.3454	58	59	0.3409	0.1904				
20	21	1.4775	0.3891	59	60	0.3679	0.2055				
21	22	0.45	0.1185	60	61	0.3591	0.2006				
22	23	0.771	0.203	61	62	0.3503	0.1957				
23	24	0.885	0.2331	62	63	0.4219	0.2356				
24	25	0.9915	0.2611	63	64	1.538	0.5517				
25	26	0.384	0.1011	64	65	0.9788	0.3511				
26	27	0.7245	0.1908	65	66	1.4911	0.5349				
27	28	1.185	0.3121	11	67	0.969	0.2552				
28	29	1.2353	0.6899	67	68	0.6705	0.1766				
29	30	0.3557	0.1987	12	69	0.4354	0.2432				
30	31	0.9494	0.3406	13	70	0.4631	0.2586				
31	32	0.6899	0.3853	70	71	0.2707	0.1512				
32	33	1.5707	0.8773	15	72	0.6683	0.3732				
5	34	1.2655	0.454	72	73	0.8525	0.4762				
5	35	0.1688	0.0943	16	74	0.3314	0.1851				
35	36	0.2741	0.1531	18	75	0.405	0.2262				
36	37	0.2552	0.1425	19	76	0.4367	0.2439				
6	38	0.4165	0.2326	19	77	0.3416	0.1908				
6	39	1.4835	0.3907	77	78	0.2113	0.118				

Table 10
Load data of actual realistic 94 bus Portuguese RDS.

Bus number	Active power (kW)	Reactive power (kvar)	Bus number	Active power (kW)	Reactive power (kvar)
2	22.5	10.9	57	31.5	15.3
3	240.3	116.4	58	521.1	252.4
4	24.3	11.8	59	212.4	102.9
7	28.8	14	60	39.6	19.2
14	57.6	27.9	61	45	21.8
17	18.9	9.2	62	17.1	8.3
20	55.8	27	63	21.6	10.5
21	40.5	19.6	64	35.1	17
23	54	26.2	65	70.2	34
26	46.8	22.7	66	34.2	16.6
29	13.5	6.5	67	22.5	10.9
30	3.6	1.7	68	45.9	22.2
31	18	8.7	69	33.3	16.1
32	21.6	10.5	70	36.9	17.9
33	9	4.4	71	45	21.8
34	64.8	31.4	72	75.6	36.6
35	65.7	31.8	73	67.5	32.7
36	59.4	28.8	74	27.9	13.5
37	13.5	6.5	75	38.7	18.7
38	161.1	78	76	53.1	25.7
39	26.1	12.6	77	65.7	31.8
40	134.1	65	78	63	30.5
41	85.5	41.4	79	67.5	32.7
42	41.4	20.1	80	45	21.8
43	41.4	20.1	81	9	4.4
44	41.4	20.1	82	16.2	7.8
45	21.6	10.5	83	67.5	32.7
46	25.2	12.2	84	296.1	143.4
47	45.9	22.2	85	72	34.9
48	36.9	17.9	86	76.5	37.1
49	63.9	31	87	90.9	44
50	68.4	33.1	88	72	34.9
51	27.9	13.5	89	63	30.5
52	81	39.2	90	21.6	10.5

impression on the solutions. In our paper Pareto solution method is used to solve the problem. Too, the MOPSO method was compared with other Pareto solution methods and showed better results (Tables 3 and 4).

In proposed MOPSO, objective functions are: reducing line losses, increasing voltage stability index and the index of balancing of sections current. Improvement in the objective functions of the systems using proposed method with fuzzy selection and load uncertainty are showed in Table 8. It is seen from this table, Ploss is reduced almost 90% in 94 bus actual RDS that shows good applicability of proposed method in simultaneous placement of DGs and SCBs.

Voltage stability index and voltage profile

Higher VSI for each bus states the better stability and proper condition for that relevant bus .The results shows that VSI has been improved fundamentally after proper installation of DGs and SCBs. The results are depicted in Figs. 10 and 15. In additions to with increasing of VSI and considering voltage level of buses as a constraint (Eq. (10)); voltage profile has been improved very well.

Balancing current of sections

Supplying active and reactive power near to loads may increase or decrease current levels in some sections of the network. As a result balancing current of sections is very important after installing of active and reactive power resources. The results represent that current of sections have been balanced and reserve capacity of sections is increased (Figs. 11 and 16).

Economical saving

By using the proposed method in addition to its technical advantages, an economic saving or benefit is obtained after 10 years. The worth of the saving of reduction purchased energy for a 33 and a 94 bus systems are 16,116,055 $ and 22,403,500 $, respectively. Also final benefit including the total costs for a 33 and a 94 bus systems are 2,943,269 $ and 5,217,130 $, respectively (Tables 6 and 7).

Simulation results

Simulation results demonstrate proposed method has better performance in cases of simultaneous placement of DGs and SCBs, load uncertainty and fuzzy decision in comparing with SPEA,NSGA, MODE and ICA/GA in reducing line losses, improving voltage profile, increasing voltage stability index and balancing of sections current

Conclusion

In this paper, fuzzy MOPSO algorithm has been applied to find the best solution of DGs and SCBs sizing and locating problem simultaneously with considering load uncertainty as fuzzy data theory. The decreasing active power losses, improving voltage stability for buses and balancing current in systems sections are multi objective optimization functions. The proposed method first uses Pareto optimal solutions to solve the problem and finally the best optimum solution are extracted by a fuzzy-based mechanism. The method was implemented on IEEE 33 bus RDS and an actual realistic 94 bus Portuguese RDS and the results were compared with methods of SPEA, NSGA MODE and ICA/GA.

Numerical results show that the performance of the fuzzy proposed MOPSO method is better than the other methods in MO optimization problems of systems with load uncertainty in terms of using DGs and SCBs simultaneously, power losses reduction, voltage stability maximization, voltage profile improvement, load balancing. In addition to improving technical problems; economic benefit provided that optimal placement of DGs and SCBs is the main motivation in power distribution system planning.

Appendix 1. Equations for calculating economic evaluation

The mathematical formulation for different terms of costs presented is as follows:

1. SCBs installation cost

SCBs installation cost is presented as follows:

$$C_{cap} = \sum_{i=1}^{n_{sc}} K_{cni} \cdot Q_{cni} + k_{dni} \tag{34}$$

2. DGs installation cost

The cost of DGs installation can be formulated as following equation:

$$C_{IDG} = \sum_{i=1}^{N_{DG}} C_{DGni} \cdot K_{IDG} \tag{35}$$

3. Operation and maintenance cost of DGs

This cost is equal to cost of active power generation of DGs (operation cost) and DGs maintenance cost and can be evaluated by:

$$C_{o\&mDG} = \sum_{y=1}^{nyr} \sum_{i=1}^{N_{DG}} PW^{y} \cdot P_{g\ ni} \cdot K_{EDG} \cdot T \tag{36}$$

In which worth (PW) factor [18] is formulated as:

$$PW = \frac{1 + InfR}{1 + IntR} \tag{37}$$

4. Economical saving

Purchased power's cost from substation which includes losses for a passive RDS is equals to:

$$C_{SS}^{\mathrm{bef}.plac.} = \sum_{y=1}^{nyr} PW^{y} \cdot K_{SS} \cdot \left(Real\left(V_{ss} \cdot I_{inj.}^{*}\right)^{bef.} \cdot T\right) \tag{38}$$

By installing DGs, the distribution companies can provide their portion of power demands from these resources and also compensating losses by both DGs and capacitors. In this case, after installing DGs and capacitors, the cost of purchased power from substation for an active RDS is reduced to:

$$\left(C_{SS}^{\mathrm{bef}.plac.} - C_{SS}^{\mathrm{aft}.plac.}\right) = \sum_{y=1}^{nyr} PW^{y} \cdot K_{SS} \cdot \left(\mathrm{Real}\left(V_{ss} \cdot I_{inj.}^{*}\right)^{bef.} - \mathrm{Real}\left(V_{ss} \cdot I_{inj.}^{*}\right)^{aft.}\right) \cdot T \tag{39}$$

In fact an economical saving or benefit is yielded. The benefit which includes total costs of the DGs and capacitors in period their life time can be formulated as follow:

$$\text{Final benefit} = \left(C_{SS}^{\mathrm{bef}.plac.} - C_{SS}^{\mathrm{aft}.plac.}\right) - \left(C_{IDG} + C_{o\&mDG} + C_{cap}\right) \tag{40}$$

Appendix 2. Actual realistic Portuguese system data

See Tables 9 and 10.

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