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Optimal capacitor placement in distribution systems using a combination fuzzy-GA method

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Abstract

This work presents a combination fuzzy-GA method to resolve the capacitor placement problem. The problem formulation considers three distinct objective functions related to minimize the total cost for energy loss and capacitors to be installed, as well as decreasing the deviation of bus voltage and improving the margin loading of feeders. The novel formulation is a multi-objective and non-differentiable optimization problem. These objective functions are first formulated in fuzzy sets to assess their imprecise nature before introducing a fuzzy satisfying method based on the GA to derive the optimal solution. The proposed approach is implemented in a software package and its effectiveness is verified through numerical examples on the Tai-power system.

Keywords: Capacitor placement; Genetic algorithms; Fuzzy satisfying method; Multi-objective optimization

1. Introduction

Capacitor placement must determine the optimal location, type (fixed or switched), size and the control setting of capacitors to be installed on the buses of a radical distribution system. Many approaches have been proposed to solve the capacitor placement problem. For instance, [1] formulated the problem as a mixed integer programming problem that incorporated power flows and voltage constraints. The problem was decomposed into a master problem and a slave problem to determine the location of the capacitors, and the type as well as size of the capacitors placed on the system. Refs. [2,3] proposed heuristic approaches to identify the sensitive nodes by the levels of effect on the system losses, and to maximize the net saving on system losses. Ref. [4] adopted an equivalent circuit of a lateral branch to simplify the distribution loss analysis, which obtained the capacitor operational strategies according to the reactive load duration curve and sensitivity index. Moreover, optimal capacitor planning based on fuzzy algorithm was implemented to represent the imprecise nature of its parameters or solutions in practical distribution systems [5–7]. Several investigations have recently applied AI techniques to resolve the optimal capacitor placement problem due to the growing popularity of AI. Refs. [8,9] presented a solution methodology based on a simulated annealing (SA) technique, then implemented the solution methodology in a software package and tested it on a real distribution system with 69 buses. Ref. [10] applied the Tabu Search technique to determine the optimal capacitor planning in Chiang et al's [8] distribution system, and compared the results of the TS with the SA. In Refs. [11,12], genetic algorithms (GA) were implemented to obtain the optimal selection of capacitors, but the objective function only considered the capacitor cost and power losses without involving operation constraints.

The capacitor placement problem is formulated as a multiple objective problem herein. The formulation proposed herein considers three distinct objectives related to (1) minimizing the total cost for energy loss and capacitors; (2) increasing feeder loading margin; and (3) enhancing voltage profiles. These objective functions are modelled by fuzzy sets to evaluate their imprecise nature. Moreover, a combination fuzzy-GA method [13–17] solves the constrained and multiple objective problems. The proposed method adopts the GA because it can solve the optimization problem [16,17]. The capacitor placement algorithm proposed herein has the following merits:

(1) It allows the decision maker to obtain an optimal solution.
(2) It considers the loading of feeders and the deviation of bus voltage under varying load levels in the problem formulation.
(3) It quickly and effectively identifies capacitor plans.
(4) It can be applied to large-scale distribution systems.

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The rest of this article is organized as follows: Section 2 describes a novel formulation of the capacitor placement problem. A solution algorithm based on the combination fuzzy-GA method for the multi-objective problems is developed in Section 3. Section 4 describes how to apply the solution algorithm to the capacitor placement problem. Section 5 demonstrates the effectiveness of the solution algorithm on a Tai-power distribution system. Conclusions are finally made in Section 6.

2. Problem formulation

The capacitor placement problem for (i) reducing the total cost of energy loss and capacitors; (ii) increasing the margin loading of feeders and (iii) improving voltage profile under load constraints is formulated in this section.

2.1. Objective functions

2.1.1. Minimize the total cost of energy loss and capacitors

This objective function considered herein consists of a term that denotes the purchase and installation cost of the capacitors, and a second term that denotes the cost of power loss obtained by summing up the power losses at each load level.

$$\mathrm{Min}\, f_1(\bar{X}) = \frac{1}{Y}\left(\sum_{i=1}^{N_\mathrm{b}} N_\mathrm{i}\right) \times C_\mathrm{p} + \sum_{j=1}^{N_t} K_j T_j p_{\mathrm{loss},j}(\bar{X}) \tag{1}$$

where

$\bar{X}$, decision vector, symbolizes the location, size and control setting of capacitors to be installed.
Y, lifetime of capacitors (years).
N_i, the number of capacitor units to be installed on bus i.
N_b, the total number of buses in the considered distribution system.
$C_\mathbf{p}$, the purchased and installation cost of capacitor per unit bank.
N_t, the number of load levels.
K_j, the energy cost per unit for load level j.
T_j, the time duration per year for load level j.
$p_{\mathrm{loss},j}$, the total power loss for the system at load level j denotes the total cost of capacitors and power losses per annum.

2.1.2. Minimize the deviation of bus voltage

Bus voltage is an important power quality index, which can be described as follows

$$\mathrm{Min}\, f_2(\bar{X}) = \max_i |V_i - 1.0|, \qquad i = 1, 2, \ldots N_\mathrm{b} \tag{2}$$

where V_i denotes the voltage on bus i, in per unit, $f_2(\bar{X})$ denotes the maximal deviation of bus voltage in the system. A lower $f_2(\bar{X})$ value indicates a higher quality voltage profile.

2.1.3. Maximize the margin loading of feeders

Feeder security refers to the ability to support unexpected loads and to relieve other feeders with heavy loads. The margin loading of feeders is a simple index to assess the feeder security that can be defined as follows

$$\mathrm{Min}\, f_3(\bar{X}) = 1 - \min_i \left\{ \frac{I_{i\mathrm{Rate}} - I_{i\mathrm{Load}}}{I_{i\mathrm{Rate}}} \right\}, \tag{3}$$

$$i = 1, 2, \ldots N_\mathrm{L}$$

where N_L denotes the total number of feeder branches, $I_{i\mathrm{Load}}$ and $I_{i\mathrm{Rate}}$ represent the load current and rated current of branch i, respectively. $f_3(\bar{X})$ represents the margin loading of feeders. Lower $f_3(\bar{X})$ values indicate the considered feeder is more secure.

The energy loss and voltage profile of the considered system differ with load level, as do the control settings. The decision vector thus appears to be a function of load level. In this article, the problem formulation already considered the factor of load level. The above objective function describes the realistic cost of capacitor placement. However, such a function is non-differentiable; making most optimization techniques awkward to apply.

2.2. Fuzzy modelling

The constraints or objectives for a power system usually have soft limits rather than hard limits. That is, some degree of tolerance is allowed in their limit values. For example, bus voltage value approaching 1 pu indicates that the considered system has higher power quality. Therefore, the three objectives (cost, voltage and loading) may introduce vagueness by permitting gradual transition from degrees of coverage that are considered to be 'good' and those that are not. Considering the imprecise nature of each objective function, these objective functions are formulated as fuzzy sets. A fuzzy set is typically represented by a membership function $\mu_{f_i}(\bar{X})$. The higher value of the membership function implies a greater satisfaction with the solution. The membership function consists of a lower and upper boundary values together with a strictly monotonically decreasing and continuous function. Fig. 1 shows the graph of the possible shape of a strictly monotonically decreasing membership function. The lower and upper bounds, $f_i^{\min}(\bar{X})$, $f_i^{\max}(\bar{X})$, of each objective function under given constraints

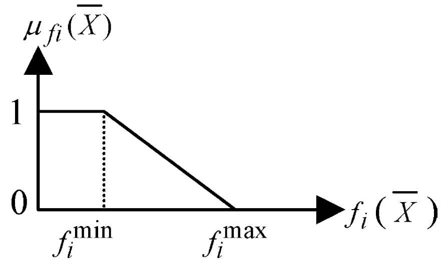


Fig. 1. An example of membership function.

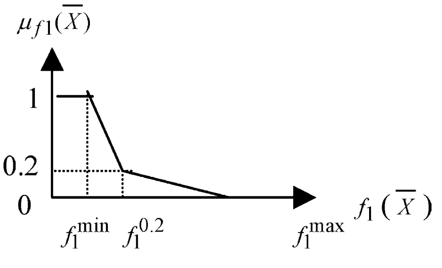


Fig. 2. Membership function $\mu_{f1}(\bar{X})$.

are established to elicit a membership function $\mu_{f_i}(\bar{X})$, for each objective function, $f_i(\bar{X})$. Then, a strictly monotonically decreasing and continuous function $h_i(f_i(\bar{X}))$, which can be linear or non-linear, is determined. A membership function of a minimizing problem can be defined by

$$\mu_{f_i}(\bar{X}) = \begin{cases} 1 \text{ or} \rightarrow 1, & \text{if, } f_i(\bar{X}) < f_i^{\min} \\ h_i(f_i(\bar{X})), & \text{if, } f_i^{\min} \le f_i(\bar{X}) \le f_i^{\max} \\ 0 \text{ or} \rightarrow 0, & \text{if, } f_i^{\max} < f_i(\bar{X}) \end{cases} \tag{4}$$

Figs. 2–4 schematically depict these objective functions (described in Section 2.1) modelling with fuzzy sets. Eq. (4) illustrates the possible model of a fuzzy set only. For different applications, different membership functions could be used to describe the fuzzy set. Using the fuzzy sets to describe the problem formulation with soft degrees reflects practical real world behavior.

2.3. Load constraints

The hypothesized load constraints are the real and reactive power balance constraints described by a set of power flow equations. Fig. 5 shows a typical radial distribution system feeder.

The line impedance between bus i and $i+1$ is $z_i = r_i + jx_i$ and the load considered as constant power sink is $S_{\mathrm{L}} = p_{\mathrm{L}} + jq_{\mathrm{L}}$. The shunt capacitor bank for bus i capacity is $q_{ci} \times v_i$ represents the voltage on bus i. The power flow equations can be expressed by the following recursive set of equations

$$p_i = p_{i+1} + p_{\mathrm{L}i+1} + r_i \frac{p_i^2 + q_i^2}{v_i^2} \tag{5}$$

$$q_i = q_{i+1} + q_{\mathrm{L}i+1} - q_{\mathrm{c}i+1} + x_i \frac{p_i^2 + q_i^2}{v_i^2} \tag{6}$$

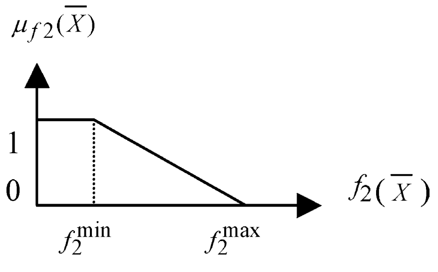


Fig. 3. Membership function $\mu_{f2}(\bar{X})$.

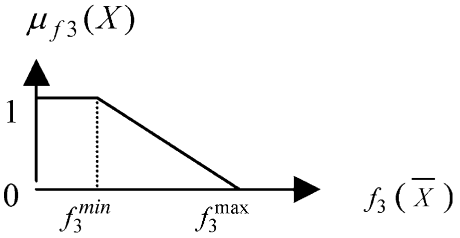


Fig. 4. Membership function $\mu_{f3}(\bar{X})$.

$$v_i^2 = v_{i+1}^2 + 2(r_i p_i + x_i q_i) - (r_i^2 + x_i^2) \frac{p_i^2 + q_i^2}{v_i^2} \tag{7}$$

3. Mutiple objective problem

Consider a multiple objective problem as the following form

$$\mathrm{Min}\, f_i(\bar{X}), \qquad i = 1, 2, \ldots, N_{\mathrm{s}} \tag{8}$$

subject to

$$g_j(\bar{X}) = 0, \qquad j = 1, 2, \ldots, N_{\mathrm{c}} \tag{9}$$

where $f_i(\bar{X})$ are N_{s} distinct objective functions of the decision vector $\bar{X}$, and $g_j(\bar{X}) = 0$ are N_{c} different constraints. Fundamental to the multiple objective problem is the non-inferior solution. Qualitatively, a non-inferior optimal solution of the multiple objective problems is one where an objective function can be improved only at the expense of another. Non-inferior optimal solutions generally consist of an infinite number of points. Notably, some subjective judgments by the decision maker should be added to the quantitative analysis. In this work, we propose a combination fuzzy-GA method to determine the non-inferior optimal solution of the decision maker.

To generate a candidate for the satisfying solution of the formulated problem, the decision maker is asked to specify his or her expected value of the achievement of the membership functions. The expected value is a real number between [0,1] represented the level of importance of each objective function. For the dispatcher's expected membership values $\bar{\mu}_{f_i}$, the following minimax problem is solved to generate the optimal solution, which is closed to

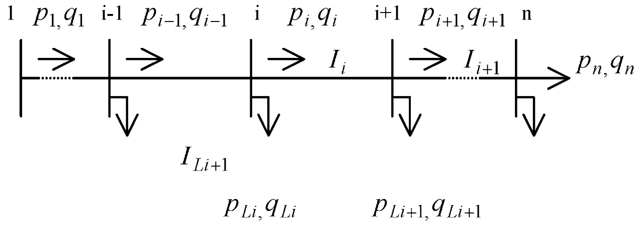


Fig. 5. One line diagram of a radial network.

his requirements.

$$\underset{X\in\Omega}{\mathrm{Min}}\left\{\underset{i=1,2,\ldots N_s}{\mathrm{Max}}\,[\overline{\mu_{f_i}}-\mu_{f_i}(\bar{X})]\right\} \tag{10}$$

where Ω denotes the vector space of $\bar{X}$, and N_s represents the number of total objective functions. Eq. (10) reveals that the value of the above function can be interpreted as the overall degree of satisfaction of the decision maker's goals.

4. Apply GA to the capacitor placement

4.1. Basic operations of the GA

GA is a search mechanism based on the principle of nature selection and population genetics. The required design variables are encoded into a finite string corresponding to chromosomes in a biological system. The basic operations of the GA include reproduction, crossover, and mutation, which perform the tasks of copy strings, exchanging position of strings as well as changing some bits of string. Finally, the string with the largest fitness function value is attained and decoded from the last pool of mature string. GA can rapidly determine the globally optimal point and avoid looking at the local optimum since it searches for a population of points instead of a single point. In addition, it can eliminate the analytical limitations such as discontinuities of search space since it works with a coding of parameter sets and not the parameters themselves. The GA is outlined as follows.

Step 1. Input the parameters of GA and system data.

Step 2. Produce the first population of chromosome.

Step 3. Evaluate all the fitness values of chromosomes in the population.

Step 4. Reproduction.

1. In this operation, the reproduction numbers of a chromosome is given by

$$N_\mathrm{i}=G\left[N_\mathrm{p}\times\frac{F_i}{\sum_{i=1}^{N}F_i}\right] \tag{11}$$

and

$$F_i=\frac{1}{1+\max_i[\overline{\mu_{f_i}}-\mu_{fi}(\bar{X})]} \tag{12}$$

where N_p denotes the population size, F_i represents the fitness value of chromosome $i, G[x]$ round the elements of x to the integers.

2. If the sum of n_i is less than N_p, the deficits are complemented by the best chromosome and its derivations (only change little bits of string of the chromosome randomly).

Step 5. Crossover.

1. The crossover number equals to the product of $(N_\mathrm{p}/2)$ and crossover probability (each crossover generate two chromosomes).
2. The chromosomes unselected are kept in the population.

Step 6. Mutation

The mutation numbers are equal to the product of N_p and mutation probability.

Step 7. Check the stop criterion. If the optimal pattern of $\bar{X}$ keeps unchanged after a preset iteration's number, then output the solution. Otherwise, go to Step 3.

4.2. Main parameters of the capacitor placement

4.2.1. Configuration space

Configuration space is the set of allowed system configurations over which the optimal system configuration is determined. The configuration space design is critical to the performance of the solution algorithm since the domain reduction can markedly increase the efficiency of the solution algorithm without compromising the quality of the final solution. For fixed capacitor placement, the configuration space is defined as $\Omega=[x_1,x_2,\ldots,x_{N_\mathrm{b}}], x_i$ is the capacitor size at bus i. The control setting of the fixed capacitor remains unchanged as the load demands vary. The configuration space of the switched capacitor placement is defined as $\hat{\Omega}=[x_1,x_2,\ldots,x_{N_\mathrm{b}}]$, where $x_i=[x_i^1,x_i^2,\ldots,x_i^{N_\mathrm{t}}]$ and x_i^j is the control setting of the capacitors at bus i during jth load level. The following rules are employed to reduce the domain of configuration space

$$0\le x_i^j\le x_i^{N_i}\le x_i^{\max} \tag{13}$$

where $x_i^{N_i}$ denotes the capacitor size to be installed at bus i, and $x_i^{\max}$ denotes the maximum capacitor size allowed at bus i. For example, seven banks of capacitors is a practical maximum size for Tai-power systems.

4.2.2. Location, size, and type of capacitors

The location, size, and type of capacitors to be installed can be determined according to the following rules

1. The location (bus i) is selected for installing the capacitors when the maximum $x_i^j\ne 0$ for $j=1,2,\ldots,N_\mathrm{t}$; otherwise, the bus i is discarded.
2. The size of capacitors to be installed at bus i can be derived by the relationship $x_i^{N_i}=Q\cdot(\max \text{ of } x_i^j)$.
3. The type of capacitors to be installed at bus i is determined by the following relationship: if $x_i^1=x_i^2=\ldots=x_i^{N_\mathrm{t}}$, then

a fixed type of capacitor is installed at bus i; otherwise, a switched type of capacitor is installed at bus i.

4.2.3. Solution algorithm of the capacitor placement

The solution algorithm for the optimal capacitor placement problem is evaluated as follows.

Step 1. Input data and parameters.

Step 2. Determine the membership functions $\mu_{f_i}(x)$ of each objective.

Step 3. Set the interactive pointer, $p = 0$.

Step 4. Select the initial expected membership value of each objective function, $\overline{\mu_{f_i}^{(0)}}$, for $i = 1, 2, \ldots N_s$.

Step 5. Run the power flow equations and apply GA to solve the minimax problem, $\mathrm{Min}_{x \in \Omega}\{\mathrm{Max}_{i=1,2,\ldots N_s}[\overline{u_{f_i}^{(p)}} - \mu_{f_i}(\bar{X})]\}$.

Step 6. Check the stop criterion: if the values of $\bar{X}$, $f_i(\bar{X})$ and $\mu_{f_i}(\bar{X})$ are satisfied, then go to the next step. Otherwise, set the interactive pointer, $p = p + 1$ and choose a new expected value, $\overline{\mu_{f_i}^{(p)}}, i = 1, 2, \ldots$. Then return Step 5.

Step 7. Determine the optimal setting, size, location of capacitors according to the solution, $\bar{X}$, and produce the total cost as well as the index of power quality and system security.

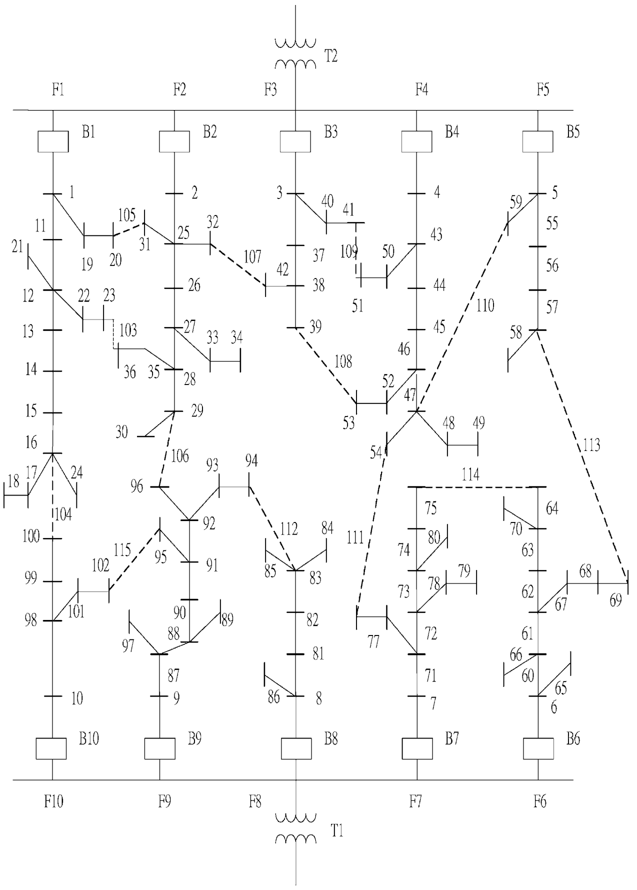
Notably, the decision maker is only involved in Step 6 as the sequence is generated automatically thereafter. Moreover, the decision maker does not need to provide an accurate goal for each objective since the expected value (preferred degree) of an objective is estimated by his experiences or simple trial and error according to the current values of the membership and objective functions. The solution algorithm can generate the most satisfactory global non-inferior solution from the interactive steps.

System planners must determine the optimal solution while satisfying the three objectives. These objectives in such a multiple objective optimization problem are usually non-commensurable and subject to mutual interference. These objectives generally conflict with each other. Identifying a solution is often impossible while simultaneously optimizing all objectives. The proposed trade-off method can be used to resolve conflict among multiple objectives so that a designer can select a compromise or the most satisfactory plan. Note that, if any of the components of these objectives is competing, there is no unique solution for this problem. In multi-objective optimization, as opposed to single-objective optimization, unambiguous optimal solution may not exit there. Instead, the concept of noninferiority (also called Pareto optimality, or no dominated solutions) must be used to characterize the objectives. A non-inferior solution is one in which an improvement in one objective requires a degradation of another. Since any point in that is not a non-inferior point represents a point in which improvement can be attained in all the objectives, it is clear that such a point is of no value. Multi-objective optimization is, therefore, concerned with the generation and selection of non-inferior solution points. The choice of one particular solution depends on the features of the problem and a number of problem-related factors.

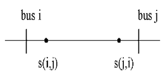
5. Simulation results

5.1. Illustrative example

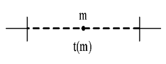
A time-sharing computer program is implemented in C++ with man–machine interactive procedures based on the proposed algorithm. A distribution system of the Tai-Power Company is tested by the proposed method. Fig. 6



(a) system configuration



(b) switch location



(c) tie_switch location

Fn : No. of feeder
Bn : No. of breaker
□: Breaker
—— : Feeder line
...... : Tie line
m : No. of tie switch

Fig. 6. Network structure of the testing system.

Table 1
Parameters of objective functions

Objective function	Parameter
Total cost	$f_1^{\min} = 0.5f_1^{o}$, $f_1^{\max} = 3f_1^{o}$, $f_1^{0.2} = f_1^{o}$
Power quality	$f_2^{\min} = 0.05$, $f_2^{\max} = 0.1$
System security	$f_3^{\min} = 0.8$, $f_3^{\max} = 1.0$

f_1^{o} represents the original cost of energy loss for the considered system without capacitor placement; The lower and upper bounds $f_i^{\min}$ and $f_i^{\max}$ depend on the constraints of the considered problem, for example, let $f_2^{\max} = 0.1$ if the bus voltage is limited in the range (0.9–1.1 pu).

Table 3
Results of the test case

	Before planning	After planning
Total cost ($/year)	189,077	131,941
Capacitor cost ($/year)	–	24,660
Energy loss cost ($/year)	189,077	107,281
Total cost reduced (%)	–	30.2%
Max of deviation of bus voltage (pu)	0.089	0.046
Min of the margin loading among feeders (%)	31.7	40.8

shows that the test system includes: two transformers, 10 feeders, 102 branches, 13 tie lines, and 104 buses. The capacitors placement problem attempts to determine the number (0–7) of capacitor units installed at 104 buses under three load levels (high, normal and heavy) to minimize the total objective cost. Restated, the solution space contains all possible combination of solutions. Table 1 lists the critical parameters of the objective functions. The lower and upper bounds $f_i^{\min}$ and $f_i^{\max}$ of fuzzy set i depend on the constraints of the problem being considered. For example, let $f_2^{\max} = 0.1$ pu if the bus voltage is limited to the range (0.9–1.1 pu). Meanwhile, $f_1^{0.2}$ represents the value of the cost function for the original system without capacitor placement. The parameters of GA and its fitness function utilized in this system are described as follows: population size: 150, crossover probability: 0.95, mutation probability: 0.08. Table 2 lists the parameters for calculating the cost of capacitor.

5.2. Results

Table 3 summarizes the value of the objective function from the test results. The proposed solution algorithm can provide one optimal non-inferior solution in its first run. If the planer is unsatisfied with the results from the first run, then he or she has another opportunity to select his subjective preference according to the interactive procedure in this program. The objectives to be selected for changing their expected values in the interactive procedure after the first run can be selected according to the network situation or the policies of the utilities. The solution algorithm can generate the most satisfactory global non-inferior solution from the interactive steps. Table 3 includes the cost of energy losses and capacitors, a voltage profile of the test system, and the loading margin of the feeders. Table 4 lists the optimal locations, types, and control settings of the capacitors to be installed in the test system.

Table 2
Parameters of cost function

Load level	*L*	*N*	*H*
	0.8	1.0	1.2
Time duration T_j, (h)	1000	6560	1200
Energy cost K_j($/kWh)	0.04	0.06	0.08
$Q = 30$ kvar/unit, $Y = 10$ years, $C_p = 900$\$/bank			

Although the run time for a planning problem such as the capacitor placement problem is not crucial for practical applications, the test case considered here confirms that the proposed method can be implemented in a practical system, and moreover the run time equals that for application in an on-line system. Indeed, a plan was obtained at one interactive cycle of the proposed algorithm in under 36 s on a Pentium-CELERON 300A PC for the test case in this work. The following observations are based on the results:

- all bus voltages are in a limited range under each load level,
- energy loss and total cost can be reduced by 43.3 and 30.2% per year with proper capacitor installation, and
- the described method can be implemented in a practical system with promising results.

6. Conclusion

This study presents a combination fuzzy-GA method for multi-objective programming to solve the capacitor placement problem in distribution systems. Three distinct objectives are considered to minimize the amount of total cost for energy loss and capacitors, as well as increase the margin loading of feeders and improve voltage profile. GA is applied to the proposed algorithm to derive the optimal solution because it can search many paths to solve the problem with non-linear and non-differentiable objective functions. Finally, the method developed herein is tested on

Table 4
Optimal capacitor planning

Location, # of bus	Setting (L,N,H)	Type	Size (kvar)	Location, # of bus	Setting (L,N,H)	Type	Size (kvar)
BusF1	2,3,2	S	90	BusF6	1,1,1	F	30
Bus1	1,4,3	S	120	Bus6	4,4,4	F	120
Bus11	1,4,2	S	120	Bus60	2,5,5	S	150
Bus12	7,7,7	F	210	Bus61	6,7,7	S	210
Bus13	4,7,7	S	210	Bus62	6,6,6	F	180
Bus14	2,7,7	S	210	Bus63	7,7,7	F	210
Bus15	7,7,7	F	210	Bus64	0,3,3	S	90
Bus16	6,7,7	S	210	Bus66	0,1,1	S	30
Bus17	7,7,7	F	210	Bus67	7,7,6	S	210
Bus18	4,4,4	F	120	Bus68	6,6,6	F	180
Bus19	1,2,2	S	60	Bus7	0,0,2	S	60
Bus20	1,4,4	S	120	Bus71	0,0,1	S	30
Bus21	1,0,1	S	30	Bus72	1,1,0	S	30
Bus22	1,5,6	S	180	Bus73	0,2,2	S	60
Bus23	7,7,6	S	210	Bus74	2,1,2	S	60
Bus27	2,2,0	S	60	Bus75	1,1,0	S	30
Bus28	1,0,0	S	30	Bus77	1,1,1	F	30
Bus29	0,0,1	S	30	Bus78	4,4,4	F	120
Bus30	0,1,0	S	30	Bus80	0,1,1	S	30
Bus32	1,1,0	S	30	Bus82	0,0,1	S	30
Bus33	1,1,0	S	30	Bus83	0,1,2	S	60
Bus34	1,1,1	F	30	Bus9	1,2,1	S	60
Bus3	0,0,1	S	30	Bus87	5,7,7	S	210
Bus37	0,0,1	S	30	Bus88	7,7,7	F	210
Bus38	2,2,2	F	60	Bus89	1,1,1	F	30
Bus42	1,1,0	S	30	Bus90	2,6,6	S	180
Bus43	5,7,5	S	210	Bus91	4,7,7	S	210
Bus44	2,3,3	S	90	Bus92	7,7,7	F	210
Bus45	7,7,7	F	210	Bus93	5,5,7	S	210
Bus46	7,7,7	F	210	Bus94	1,1,0	S	30
Bus47	6,7,7	S	210	Bus95	2,6,6	S	180
Bus48	1,6,6	S	180	Bus96	1,1,1	F	30
Bus50	3,6,6	S	180	Bus97	0,0,1	S	30
Bus52	6,7,7	S	210	Bus10	1,1,0	S	30
Bus53	1,0,1	S	30	Bus99	3,2,0	S	90
Bus54	0,4,4	S	120	Bus101	0,1,1	S	30
Bus58	1,0,2	S	60	Bus102	4,4,1	S	120

F, fixed; s, switched.

a Tai-Power distribution system to verify the practical feasibility and performance of the proposed algorithm. Based on the test results, we conclude the following:

1. The dispatcher can obtain the optimal solution among multiple objectives by employing the proposed fuzzy-GA method.
2. The proposed solution algorithm can efficiently obtain the capacitor planning for various load levels.

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