黎明學報　第二十四卷　第二期　中華民國一○二年七月三十一日
JOURNAL OF LEE-MING INSTITUTE OF TECHNOLOGY
VOL. 24, NO.2, JUL. 2013

Enhancement of Capacitor Placement in Distribution Systems Using an Interactive Fuzzy Satisfying Method

應用交談式模糊滿足法解決配電系統中電容器容量配置問題

Ching-Yang Chien, Chien-hung Lin
簡靖陽　林建宏
Hung-Liang Chen, Pao-Hua Liao
陳宏良　廖寶華
Department of Electrical Engineering, Lee-Ming Institute of Technology
黎明技術學院電機工程系

Abstract

This work presents an interactive fuzzy satisfying method to resolve the capacitor placement problem. The problem formulation proposed herein considers three different objective functions related to minimizing the amount of total cost for energy loss and capacitors installed, as well as increasing system security and improving power quality. The new formulation is a multi-objective and non-differentiable optimization problem. In this work, we first formulate these objective functions in fuzzy sets to evaluate their imprecise nature. Then introduce an interactive fuzzy satisfying method based on genetic algorithms to decide the optimal solution. The effectiveness of the proposed approach is implemented in a software package and verified through numerical examples on the Tai-power system with very promising results.

Key Words: capacitor placement, multi-objective programming, interactive fuzzy satisfying method, genetic algorithms.

摘　要

本文針對配電系統提出一套交談式模糊滿足法來解決電容器配置問題，此問題涵蓋的三個不同目標函數計有線路損失及電容器安裝成本最小化、增加系統安全度及改善電力品質，此計算規劃法係為多目標且無法最佳化，在此，上

述目標函數首先皆以模糊歸屬函數來表示以符合其非精準特性，然後利用交談式模糊滿足法及基因演算技術來尋求最佳化解答。本文藉由台電配電系統來做模擬，結果亦顯示本文所提規畫方法極為有效率且令人滿意。

關鍵詞：線路電容器配置、多目標規畫法、交談式模糊滿足法、基因演算法

1. INTRODUCTION

The capacitor placement problem is to determine the optimal location, types, size, and the settings of capacitors to be installed on the buses of a radical distribution system. In general, placement of shunt capacitor can reduce the energy loss, increase system security, and improve power quality. In practice, a dispatcher recommends the planning of the problem according to his or her practical experience. With the increasingly complex nature of distribution systems, determining capacitor planning is extremely difficult, particularly for new dispatchers. Therefore, a method must be developed to assist dispatchers in drawing up capacitor placement plans.

Many approaches have been proposed to solve the capacitor placement problem from different perspectives. For instance, researchers [1] formulated the problem as a mixed integer programming problem which incorporated power flows and voltage constraints. They decomposed the problem into a master problem and a slave problem in order to decide the location of the capacitors, and the type as well as size of the capacitors placed on the system respectively. In [2,3], heuristic approaches were proposed first to identify the sensitive nodes in orders by the levels of effect on the system losses, then optimize the net saving on system losses. M.Y. Cho and Y. W. Chen [4] used a equivalent circuit of lateral branch to simplify distribution loss analysis and obtained the capacitor operation strategies according to reactive load duration curve and sensitivity index. Furthermore, optimal capacitor planning based on fuzzy algorithm has been implemented to represent the imprecise nature of its parameters or solutions in practical distribution systems [5-7].

Recently, with the growing popularity of AI, several researches have applied AI techniques to resolve the optimal capacitor placement problem. In [8,9], Chiang presented a solution methodology based on simulated annealing (SA) technique, then implemented the solution methodology in a software package and tested it on a real distribution system with 69 buses. Hong-Tzer Yang et al. [10] used Tabu Search (TS) technique to find the optimal capacitor planning in Chiang's distribution system and compared the results of the TS with the SA. In [11,12], Genetic Algorithms were also implemented to decide the optimal selection of capacitors, but the objective function only considered the capacitors cost and system losses without involving operation constraints.

In light of above developments, this work formulates the capacitor placement problem as a multiple objective problem. The problem formulation proposed herein considers three different objectives related to (1) minimizing the amount of total cost for energy loss and capacitors installed, (2) increasing system security (feeder load margin) and (3) improving power quality (voltage profiles). These objective functions are modeled with fuzzy sets to evaluate their imprecise nature. Moreover, this study proposes an interactive satisfying method [13-15] to solve the constrained multiple objective problem. Analyzing the results from the former interactive and updating the expected value of each objective function via the interactive procedure allow us to derive the compromised or satisfied solution efficiently. The proposed method adopts the genetic algorithm (GA) owing to its appropriateness in solving the optimization problem [16, 17]. The capacitor placement algorithm proposed herein has the following merits:

(1) Simultaneously allows the dispatcher to obtain the optimal locations as well as the sizes, types, and settings of the capacitors at different load levels, without knowing the sensitivity nodes of the considered system in advance.
(2) Considers system security and power quality.
(3) Identifies capacitor plans quickly and effectively.
(4) Successfully applied to large-scaled distribution systems.

The rest of this paper is organized as follows. Section 2 describes a novel formulation of the capacitor placement problem. In section 3, we propose the interactive fuzzy satisfying method for multi-objective programming. Section 4 describes how to apply the interactive method to the capacitor placement problem. Section 5 then demonstrates the effectiveness of the solution algorithm on a Tai-power distribution system. Conclusions are finally made in section 6.

2. PROBLEM FORMULATION

Capacitor placement in distribution systems involves determining the optimal location, types, and size of the capacitors to be installed on the buses of a radical distribution, and the settings of capacitors at different load levels. Meanwhile the operation constraints for voltage profiles and feeder load margins are included. In this section, we formulate the capacitor placement problem as to minimize the amount of total cost for energy loss and capacitors installed, increase system security (feeder load margin) and improve power quality (voltage profiles) under load constraints.

2.1 Objective Functions

(1) Minimize the total cost for energy loss and capacitors installed

$$\text{Min } f_1(\overline{X}) = \frac{1}{Y}\left(\sum_{i=1}^{N_b} Ni\right)\times C_p + \sum_{j=1}^{n_t} K_j T_j p_{loss,j}(\overline{X}) \quad (1)$$

where,

$\overline{X}$: variable vector, each $\overline{X}$ represents a new planning of capacitors for the distribution.

Y : life duration for capacitors (years).

N_i : the number of capacitors units to be installed at bus i.

Nb : total number of buses in the distribution system.

C_p : the purchased and installed cost for each capacitor unit.

n_t : number of load levels.

K_j : energy cost per unit at load level j.

T_j : time duration per year for load level j.

p_{loss_j}: the total power loss for the system at load level j

(2) Power quality

Bus voltage is one of the most important power quality indexes, which can be described as follows.

Min $f_2(\overline{X}) = \max_i |V_i - 1.0|$, i =1,2,… N_b (2)

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

(3) System security

From the operator's view, the system security is the ability to support unexpected loads and to relieve other feeders with high loads. A simple index to assess the system security is the margin loading of a feeder.and a transformer. Their definitions are described as follows.

Min $f_3(\overline{X})$ = 1 - $\min_i \{\frac{I_{iRate} - I_{iLoad}}{I_{iRate}}\}$, i = 1,2,.. N_L (3)

where N_L denotes the total number of the feeder lines, I_{iLoad} and I_{iRate} represent the load current and rated current of branch i respectively. $f_3(\overline{X})$ is the complement of the minimum loading margin among the feeders. Lower values of $f_3(\overline{X})$ indicate higher secure in the considered system.

2.2 Load constraints

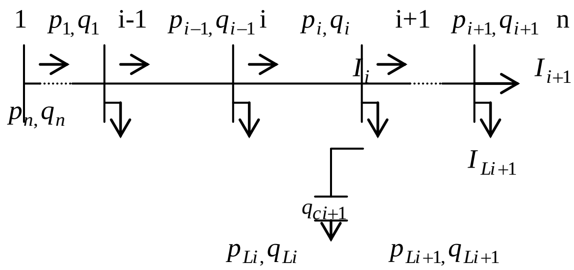

Fig. 1. One line diagram of a radial network.

The real and reactive power balance of each branch is evaluated by deriving the distribution power flow equations. These equations are described by a set of recursive equations. .By considering a radial network in Fig. 1, the line impedance between bus i and i+1 is $z_i = r_i + jx_i$ and load considered as constant power sink is $S_L = p_L + jq_L$. The capacitance of the shunt capacitor banks for bus i is q_{ci}. The equations of real power, reactive power, bus voltage magnitude, and line current are described as the follows, respectively.

$$p_i = p_{i+1} + p_{Li+1} + r_i \frac{p_i^2 + q_i^2}{v_i^2} \quad (4)$$

$$q_i = q_{i+1} + q_{Li+1} - q_{ci+1} + x_i \frac{p_i^2 + q_i^2}{v_i^2} \quad (5)$$

$$v_i^2 = v_{i+1}^2 + 2(r_i p_i + x_i q_i) - (r_i^2 + x_i^2)\frac{p_i^2 + q_i^2}{v_i^2} \quad (6)$$

$$I_i = I_{i+1} + I_{Li+1} \quad (7)$$

$$I_{Li+1} = \frac{\sqrt{p_{Li+1}^2 + (q_{Li+1} - q_{ci+1})^2}}{\sqrt{3} v_{i+1}} \quad (8)$$

where I_{Li+1} denotes the load current of the bus i+1 and I_i represents the current flowing from bus i.

3. INTERACTIVE FUZZY SATISFYING METHOD

Consider a multiple objective problem as the following form:

$$\text{Min } f_i(\bar{x}),\ i=1,2,\ \ldots,\ k \qquad (9)$$

subject to

$$g_j(\bar{x})=0,\ j=1,\ 2,..,\ m \qquad (10)$$

where $f_i(\bar{x})$ are k distinct objective functions of the decision vector $\bar{x}$, and $g_j(\bar{x})=0$ are m different constraints. Fundamental to the multiple objective problem is the noninferior solution. Qualitatively, a noninferior optimal solution of the multiple objective problems is one where an objective function can be improved only at the expense of another. Noninferior optimal solutions generally consist of an infinite number of points. Notably, some subjective judgement by the decision-maker should be added to the quantitative analysis. In this section, we propose an interactive fuzzy satisfying method to determine the compromised or satisfied solution of the decision-maker.

3.1 Fuzzy Membership Function

While considering the imprecise nature of each objective function, we formulate these objective functions as fuzzy sets. A fuzzy set is generally represented by a membership function $\mu_{fi}(\bar{X})$. The higher the value of a membership function implies a greater satisfaction with the solution. The membership function consists of a lower and upper bound value together with a strictly monotonically decreasing and continuous function. Figure 2 illustrates the graph of the possible shape of a strictly monotonically decreasing membership function. To elicit a membership function $\mu_{fi}(\bar{X})$ for each objective function $f_i(\bar{x})$, we first decide the individual minimum $f_i^{min}(\bar{x})$ and maximum $f_i^{max}(\bar{x})$ of each objective function under given constraints. Next, a strictly monotone decreasing and continuous function $h_i(f_i(\bar{x}))$ is determined which can be linear or nonlinear. For a minimizing problem, a membership function is defined by

$$u_{fi}(\bar{X})=\begin{cases}1 \quad or \rightarrow 1, & if,\ \ f_i^{\min} < f_i(\bar{X}) \\ h_i(f_i(\bar{X})), & if,\ \ f_i^{\min} \le f_i(\bar{X}) \le f_i^{\max} \\ 0 \quad or \rightarrow 0, & if,\ \ f_i(\bar{X}) < f_i^{\max}\end{cases} \qquad (11)$$

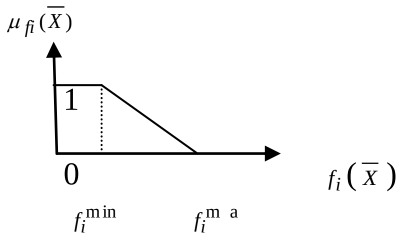

Fig. 2. An example of membership function.

3.2 Interactive Fuzzy Satisfying Method

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 $\bar{u}_{fi}$, the following minimax problem is solved to generate the optimal solution, which is closed to his requirements.

$$\underset{X \in S}{Min}\ \{ \underset{i=1,2,..k}{Max} [\overline{\mu_{fi}} - \mu_{fi}(\overline{X})] \} \quad (12)$$

where S denotes the vector space of $\overline{X}$, and k represents the number of total objective functions. Above equation reveals that the value of the above function can be interpreted as the overall degree of satisfaction of the decision maker's goals. Now, the interactive optimization technique can be described as follows.

Step1: Input data and set the interactive pointer, $v = 0$.

Step2: Determine the upper and lower bounds for every objective function, f_i^{min} and f_i^{max}, and elicit the strictly monotonically decreasing function to formulate the membership functions, $\mu_{fi}(x)$.

Step3: Set the initial expected value of each objective function, $\overline{\mu_{fi}^{(0)}} = 1$, for i = 1, 2, … k.

Step4: Apply GA (described in the next section) to solve the minimax problem.

Step5: Calculate the values of $\overline{X}$, $f_i(\overline{X})$ and $\mu_{fi}(\overline{X})$, if they are satisfactory then go to next step. Otherwise, set the interactive pointer, $v = v + 1$ and choose new expected value $\overline{\mu_{fi}^{(v)}}$, i = 1,2,…$k$. Then go to step 4.

Step6: Output the most satisfied feasible solution, $\overline{X}$, $f_i(\overline{X})$ and $\mu_{fi}(\overline{X})$ for i = 1, 2, … k.

4. SOLUTION ALGORITHM FOR CAPACITOR PLACEMENT PROBLEM

In this section, we introduce how to implement the fuzzy interactive satisfying method to solve the capacitor placement problem.

4.1 Mathematical model of objective function

Three objective functions considered in the capacitor placement problem are represented in fuzzy sets with the lower and upper bounds as well as a strictly monotonically decreasing function. The three different objectives are to (1) minimize the total cost for energy loss and capacitors installed, (2) improve the power quality, and (3) increase the system security.

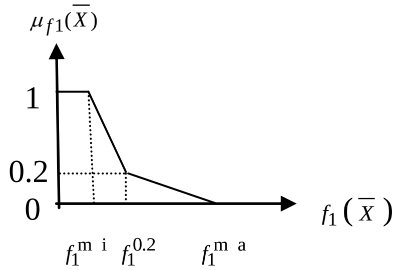

Fig. 3. Membership function $\mu_{f1}(\overline{X})$.

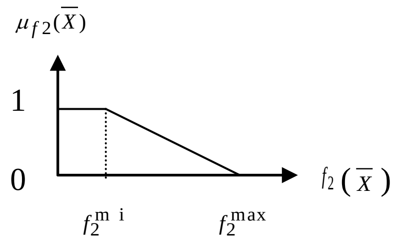

Fig. 4. Membership function $\mu_{f2}(\overline{X})$.

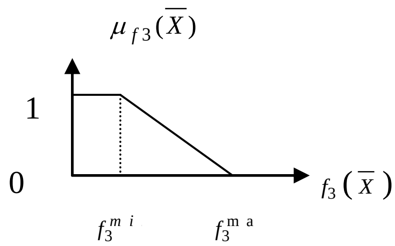

Fig. 5. Membership function $\mu_{f3}(\overline{X})$.

Figures 3 to 5 schematically depict these objective functions. Table 1 lists the critical parameters of the objective functions.

Table1. Parameters of objective functions

Objective function	Parameter
Total cost	f_1^{min} =0.5 $f_1(\overline{X_0})$, f_1^{max} =3 $f_1(\overline{X_0})$, $f_1^{0.2} = f_1(\overline{X_0})$
Power quality	f_2^{min} =0.05,　f_2^{max} =0.1
System security	f_3^{min} =0. 8, f_3^{max} =1.0

Remark: $f_1(\overline{X_0})$ represents the original cost for energy loss in the uncompensated system. 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 (0.9-1.1p.u.).

4.2 Genetic Algorithm

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. Basic operations 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 value of fitness function is found and decoded from the last pool of mature string. Since GA searches for a population of points, not a single point, it can arrive at the globally optimal point rapidly and meanwhile avoid looking at local optimum. In addition, since it works with a coding of parameter sets, not the parameters themselves, it can eliminate the analytical limitations, such as discontinuities of search space. The GA is outlined as follows.

Step1: Input the parameters of GA and system data.

Step2: Produce the first population of chromosomes.

Step3: Evaluate all the fitness values of chromosomes in the population.

Step4: Reproduction.

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

$$n_i = G[N \times \frac{C_i}{\sum_{i=1}^{N} C_i}] \tag{13}$$

and

$$C_i = \frac{1}{1 + \max_i \left[\overline{u_{fi}} - u_{fi}\left(\overline{X}\right) \right]} \tag{14}$$

where N denotes the population size, C_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, the deficits are complemented by the best chromosome and its derivations (only change some genes randomly).

Step5: Mutation

The mutation numbers, n, are equal to the product of N and mutation probability. And we mutate n chromosomes from N populations by changing their genes randomly.

Step6: Crossover.

1. The crossover number equals to the product of (N/2) and crossover probability (each crossover generate two chromosomes).
2. The chromosomes unselected are kept in the population.

Step7: Check the stop criterion. If the optimal pattern of $\overline{X}$ keeps unchanged after a preset iteration's number, then output the solution. Otherwise, go to step 3.

Remark:

(1) Coding method

In the GA operation, each chromosome $\overline{X}$ represents a new planning of capacitors in the distribution system. We express $\overline{X}$ as follows.

$$\overline{X} = \begin{bmatrix} N_1^L & N_2^L & . & . & N_i^L & . & . & N_{Nb}^L \\ N_1^N & N_2^N & . & . & N_i^N & . & . & N_{Nb}^N \\ N_1^H & N_2^H & . & . & N_i^H & . & . & N_{Nb}^H \end{bmatrix} \quad (15)$$

where N_i^L, N_i^N, N_i^H which are encoded into binary codes are different settings of capacitor banks installed at bus i under different load levels L, N, H. And

$$0 \le N_i^L, N_i^N, N_i^H \le N_i^{\max} \quad (16)$$

where $N_i^{\max}$ is the maximum limit of capacitor units installed at bus i. (in this paper, $N_i^{\max}= 7$)

(2) Decision of types, sizes and locations of capacitors

After the optimal solution of $\overline{X}$ is derived, the types, sizes and locations of capacitors can be decided according to N_i^L, N_i^N, N_i^H. They are decided as following sequence.

1. The capacitors are located at bus i if *max*{ N_i^L, N_i^N, N_i^H } $\neq$ 0, otherwise, we discard the location.
2. The size of capacitor installed equals to *Cap* × *max* { N_i^L, N_i^N, N_i^H }, where *Cap* is the capacitance per capacitor unit.
3. And the type of capacitor installed can be fixed type if $N_i^L = N_i^N = N_i^H$, otherwise, assigned switching type.

(3) Operational procedure

The vector space of chromosome $\overline{X}$ can be interpreted as the combinations of all possible number of capacitors to be installed at all buses under different load levels. When the system is large, the coding of $\overline{X}$ becomes a difficult task. In this paper, we divide the whole system into several subsystems according to their main feeders. Then we can solve the capacitor placement problem one by one, because the energy saving of one main feeder subsystem always contributes to the whole system energy saving.

(4) Special GA technique

In order to prevent the solution looking at the local solution, we place mutation procedure before crossover and force these mutated chromosomes crossing-over with other ones in the populations Otherwise, the mutated chromosome might be discarded before reproduction (Because the fitness of the mutated chromosome is always bad).

4.3 Solution algorithm

The solution algorithm for the capacitor placement problem is evaluated as following procedures.

Step1: IInput data and required parameters.

Step2: DDetermine the membership functions, $\mu_{fi}(x)$ of each objective.

Step3: SSet the interactive pointer, v = 0.

Step4: SSelect the initial expected membership value of each objective function, $\overline{\mu_{fi}^{(0)}}$, for i = 1, 2, … *k*.

Step5: FFor each $\overline{X}$, run power flow equations and apply GA to solve the minimax problem $\underset{X \in S}{Min}\ \{\underset{i=1,2,..k}{Max}\ [\overline{u_{fi}^{(v)}} - \mu_{fi}(\overline{X})]\}$.

Step6: CCheck the stop criterion: if the values of $\overline{X}$, $f_i(\overline{X})$ and $\mu_{fi}(\overline{X})$, are satisfied, then go to next step. Otherwise, set the interactive pointer, $v = v + 1$ and choose new expected value $\overline{\mu_{fi}^{(v)}}$, i = 1, 2, …*k*. Then go to step 5.

Step7: SDecide the optimal settings, types, sizes, allocations of capacitors according to the solution, $\overline{X}$, and output the total cost saving, power quality and system security.

Notably, the decision-maker is invoked only in step 6 and, thereafter, the sequence is generated automatically. The expected value (preferred degree) of an objective is achieved by the decision-maker without much difficulty.

5. SIMULATION RESULTS

5.1 Illustrative Example

Based on the proposed algorithm, a time-sharing computer program is implemented in C++ with man-machine interactive procedures. A 11.4 KV distribution system of the Tai-Power company is tested by the proposed method. This system includes two transformers, ten main feeders, 102 branches, thirteen tie lines, and 102 buses. Fig. 6 illustrates the network structure of the system. The capacitors placement problem attempts to determine the different number (0~7) of capacitor units installed at 102 buses under three load levels for minimizing the total cost. Restated, the solution space contains 8^{306} possible combinations. The searching space is so large that most optimum algorithms can not effectively solve the problem. The parameters of GA and its fitness function used in this system are described as follows: population size: 150, crossover probability: 0.95, mutation probability: 0.08. And the parameters for calculating the total cost are illustrated in Table 2.

Table 2.　Parameters for total cost

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

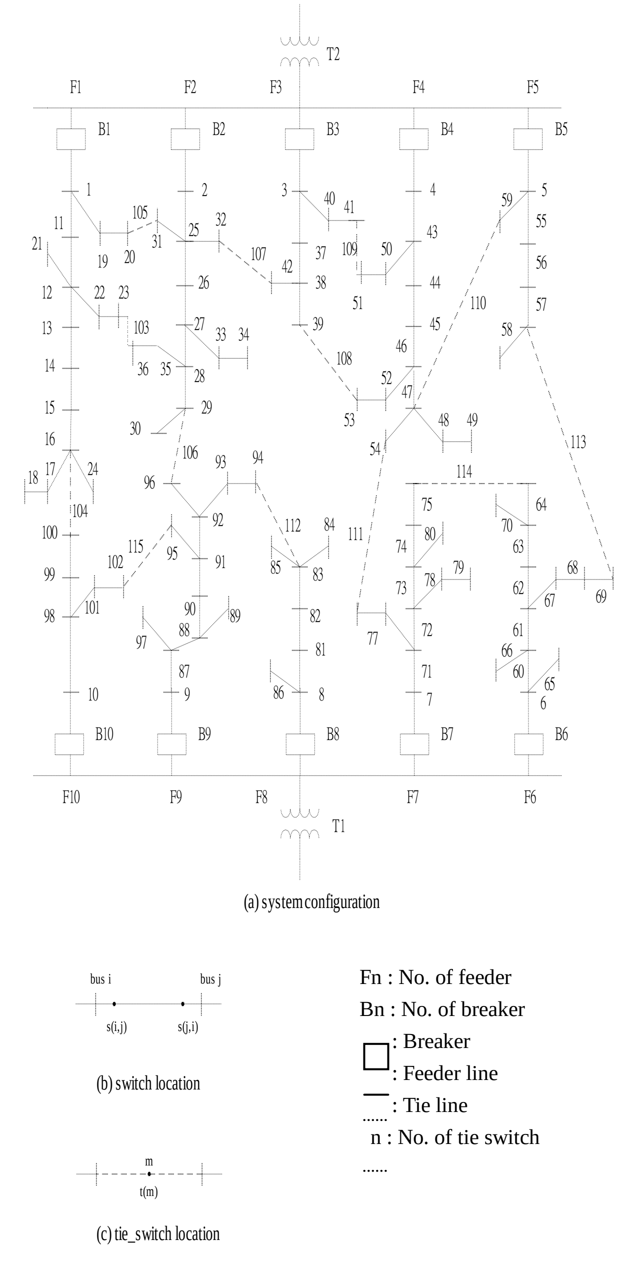

Fig. 6 Network structure of the testing system.

5.2 Results

The program has been tested on a Pentium-CELERON 300A PC. Table 3, 4 summary the results of the test case. As compared with the data before reconfiguration, we can find that the total cost per year for the uncompensated system has been reduced about 32%, and the power quality and service reliability also have been improved after capacitors installed (maximum voltage deviation is from 0.0886 to 0.0446 p.u., and minimum load margin is from 3 1.69% to 41.75%) .

From this test case, these results reveal that the proposed method can be implemented in practical system. In addition, the run time is reasonable for application in capacitor planning problem.

Table 3. Results of the test case.

	Before Planning	After planning
Total cost ($/year)	189076.95	128384.61
Cost reduced (%)	---	32.099%
Max. of deviation of bus voltage (pu)	0.088656	0.044619
Min of the margin loading among feeders (%)	31.69%	41.74%
CPU time (sec)	750	
Iteration number	10000	

Table 4 Optimal Capacitor planning

Bus Num. Setting (L N H)	Type	Cap. (kvar)
F1-- (0, 0, 0)	---	---
BUS1----(3, 5, 5)	S	150
BUS11-- (6, 7, 7)	S	210
BUS12-- (7, 7, 7)	F	210
BUS13-- (7, 7, 7)	F	210
BUS14-- (7, 7, 7)	F	210
BUS15-- (7, 7, 7)	F	210
BUS16-- (7, 7, 7)	F	210
BUS17-- (7, 7, 7)	F	210
BUS18-- (0, 0, 0)	----	---
BUS19-- (0, 0, 0)	---	---
BUS20-- (2, 4, 3)	S	120
BUS21-- (2, 2, 0)	S	60
BUS22-- (5, 6, 6)	S	180
BUS23-- (5, 7, 7)	S	210
BUS24-- (0, 0, 0)	---	---
F2-- (0, 1, 1)	S	30
BUS2--- (0, 0, 0)	---	---
BUS25-- (0, 0, 0)	---	---
BUS26-- (2, 0, 2)	S	60
BUS27-- (1, 1, 1)	F	30
BUS28-- (2, 3, 3)	S	90
BUS29-- (0, 0, 0)	---	---
BUS30-- (0, 0, 0)	---	---
BUS31-- (0, 0, 0)	---	---
BUS32-- (0, 0, 0)	---	---
BUS33-- (0, 0, 0)	---	---
BUS34-- (0, 0, 0)	---	---
BUS35-- (0, 0, 0)	---	---
BUS36-- (0, 0, 0)	---	---
F3-- (0, 0, 0)	---	---
BUS3--- (0, 0, 0)	---	---
BUS37--(0, 0, 0)	---	---
BUS38--(2, 2, 1)	S	60
BUS39--(0, 0, 0)	---	---
BUS40--(0, 0, 0)	---	---
BUS41--(0, 0, 0)	---	---
BUS42--(0, 0, 0)	---	---
F4--(0, 0, 0)	---	---
BUS4---(1, 1, 1)	F	30
BUS43- (7, 7, 7)	F	210
BUS44- (5, 5, 5)	F	150
BUS45- (7, 7, 7)	F	210
BUS46- (7, 7, 7)	F	210
BUS47- (7, 7, 7)	F	210
BUS48- (7, 7, 7)	F	210
BUS49- (0, 0, 0)	---	---
BUS50- (0, 0, 0)	---	---
BUS51- (0, 0, 0)	---	---
BUS52- (6, 7, 7)	S	210
BUS53- (0, 0, 0)	---	---
BUS54- (5, 6, 6)	S	180
F5- (1, 0, 1)	S	30
BUS5---(0, 0, 0)	---	---
BUS55--(0, 0, 0)	---	---
BUS56--(0, 0, 0)	---	---
BUS57--(1, 1, 0)	S	30
BUS58--(0, 0, 0)	---	---
BUS59--(0, 0, 0)	---	---

Bus Num. Setting (L N H)	Type	Cap (kvar)
F6-- (0, 0, 0)	---	---
BUS6--- (1, 1, 0)	S	30
BUS60-- (5, 5, 5)	F	150
BUS61-- (7, 7, 7)	F	210
BUS62-- (3, 5, 5)	S	150
BUS63-- (7, 7, 7)	F	210
BUS64-- (5, 6, 6)	S	180
BUS65-- (0, 1, 0)	S	30
BUS66-- (0, 0, 0)	---	---
BUS67-- (5, 6, 5)	S	180
BUS68-- (7, 7, 7)	F	210
BUS69-- (0, 1, 1)	S	30
BUS70-- (0, 0, 0)	---	---
F7-- (0, 0, 0)	---	---
BUS7--- (0, 0, 0)	---	---
BUS71-- (1, 1, 1)	F	30
BUS72-- (4, 4, 2)	S	120
BUS73-- (1, 1, 1)	F	30
BUS74-- (0, 0, 0)	---	---
BUS75-- (0, 0, 0)	---	---
BUS76-- (0, 0, 0)	---	---
BUS77-- (0, 0, 0)	---	---
BUS78-- (0, 0, 0)	---	---
BUS79-- (1, 1, 1)	F	30
BUS80-- (0, 0, 0)	---	---
F8-- (0, 0, 0)	---	---
BUS8---(0, 0, 0)	---	---
BUS81-- (0, 0, 0)	---	---
BUS82-- (1, 1, 1)	F	30
BUS83-- (0, 0, 0)	---	---
BUS84-- (1, 1, 1)	F	30
BUS85-- (0, 0, 0)	---	---
BUS86-- (0, 0, 0)	---	---
F9-- (0, 0, 0)	---	---
BUS9---(2, 2, 1)	S	60
BUS87-- (7, 7, 7)	F	210
BUS88-- (7, 7, 7)	F	210
BUS89-- (0, 0, 0)	---	---
BUS90-- (5, 7, 7)	S	210
BUS91-- (7, 7, 7)	F	210
BUS92-- (7, 7, 7)	F	210
BUS93-- (7, 7, 7)	F	210
BUS94-- (0, 0, 0)	---	---
BUS95-- (7, 7, 7)	F	210
BUS96-- (0, 0, 0)	---	---
BUS97-- (0, 0, 0)	---	---
F10- (0, 0, 0)	---	---
BUS10-- (1, 1, 0)	S	30
BUS98-- (0, 0, 0)	---	---
BUS99-- (0, 0, 0)	---	---
BUS100- (0, 0, 0)	---	---
BUS101- (3, 3, 3)	F	90
BUS102- (0, 0, 0)	---	---

----: UNINSTALLED
F: FIXED
S: SWITCHED

6. CONCLUSIONS

This study presents an interactive fuzzy satisfying method for multi-objective programming to solve the capacitor placement problem in a distribution system. Three different objectives considered herein are to minimize the amount of total cost for energy loss and capacitors installed, as well as increase system security and improve power quality. Owing to the multi-path search ability of GA to solve the problem with nonlinear and non-differentiable objective functions, this investigation applies GA to our solution algorithm to derive the optimal solution. Finally, the proposed method has been implemented and tested on practical distribution system of Tai-Power. Based on the test results, we conclude the following:

1. For the tested system with a large search space, the proposed method can obtain the optimal solution rapidly and accurately;
2. By using the interactive fuzzy satisfying method, the dispatcher can obtain the most satisfactory solution among multiple objectives; and
3. The proposed solution algorithm can obtain the capacitor planning efficiently under different load levels.

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