Journal of ELECTRICAL ENGINEERING, VOL. 58, NO. 4, 2007, 189–199

OPTIMAL CAPACITOR PLACEMENT IN ACTUAL CONFIGURATION AND OPERATIONAL CONDITIONS OF DISTRIBUTION SYSTEMS USING RCGA

Rahmat-Allah Hooshmand — Mohammad Ataei *

One of the most important methods in loss reduction and controlling the voltages of distribution systems is the utilization of the fixed and switched capacitors. To do this, real modelling of the system in actual operational conditions including unbalanced or balanced loading and for actual feeder structure, *ie*, radial/meshed configuration, are required. In this paper, a new technique for finding the optimal values of the fixed and switched capacitors in the distribution networks with above properties based on the real coded genetic algorithm (RCGA) is presented. For this purpose, the modelling of the loads at different load levels are simulated with low voltage and medium voltage capacitors that are available on the market. Regarding the above factors in addition to the various parameters in the optimization problem, RCGA is used to find the best and real optimal network with the best rate for the capacitors.

Finally, this methodology is tested on a region of the distribution network of the city of Ahvaz in Iran and satisfactory results are obtained. These results show that in addition to the decreasing of the network losses and improvement of the voltage profile, the benefit saving due to application of capacitors is increased.

K e y w o r d s: unbalanced distribution networks, optimization, genetic algorithm, capacitor placement

1 INTRODUCTION

One of the most effective and useful methods in reducing the power losses of distribution networks is utilization of optimal capacitor placement. By using shunt capacitors, the reactive power needed for loads is provided so that besides the reduction of losses the voltage profile of nodes is also improved. There are, of course, numerous difficulties in optimal placement of capacitors in the purpose of reducing losses. These problems include: a) non-clarity of the behaviour of feeders' loads, particularly domestic loads, b) complexity of distribution networks, c) uncertainty of electric distribution companies in returning the initial capital expenditure used for capacitor placement and d) variety of the type of network loads. With due regard to these difficulties, in many researches made so far, some assumptions in capacitor placements have been considered to solve the problem in a more simple method [1–18], which have not been appealing to distribution companies, so that the losses are still high in the network.

Most of the consumption loads in distribution networks are single phase domestic loads which are unbalanced. Therefore, it is useful to investigate the capacitor placement for unbalanced distribution networks [1–3]. However, it has not been regarded in most of the previous works [4–18]. On the other hand, in the methods presented in [6–15, 17] the loss reduction has been accomplished only by using the fixed capacitors. Moreover, in many previous methods, the medium voltage capacitors which are more expensive than low voltage ones are used [2, 3, 5–18].

One of the important issues in the placement of capacitors is considering the load variations of the network. In some methods [2, 3, 5, 15–17], load variation has been considered at several different levels, and in some other methods [1, 6–14, 18], it has not been considered at all, and the load has been presented in a fixed form. Moreover, capacitor placement is also advised to be done with the daily real value in the market, so that the distribution companies may be assured of its productivity. This has been taken into consideration but only in references [3, 6, 16].

In the previous works presented by researchers, capacitor placement has been done on the basis of different techniques including: integer programming method [2], nonlinear programming method [1, 3], method of sensitivity analysis [12, 16], method of optimization of the equal area criterion for selecting the sites of fixed capacitors [13], dynamic programming method [8], and some methods based on the experimental criteria. In these methods, in order to solve the capacitor placement problem, some assumptions have been considered on the type of the objective function and also on the type and number of problem restrictions. There is also the difficulty of trapping the answer of the problem in a local optimal solution. Moreover, since the capacitor banks contain discontinuous values, solving the problem in a continuous domain and then approximating the results leads to a large error in optimal solution. With due regard to the above problems, the genetic algorithm is a very useful tool in solving the optimization problems [4–11, 17, 18].

* Department of Elec. Eng., University of Isfahan, Isfahan, Iran. E-mail: Hooshmand_r@yahoo.com, Ataei@eng.ui.ac.ir

ISSN 1335-3632

In this research, the objective is to find the optimal location and values of the fixed and switched capacitors in distribution networks by using the real coded genetic algorithm. The important characteristics of this new method are:

1. Network modelling for both balanced and unbalanced load cases.
2. Considering the meshed and/or radial configurations for distribution networks, which are less considered in previous papers.
3. Utilization of fixed and switched capacitors available in the market and at low and medium voltages with their real prices.
4. Utilization of the load model of the network at different load levels.
5. Using of standard values of capacitors in proposed method based on the RCGA instead of using the estimated values.

For this purpose, at first, a brief review of RCGA is explained in the second section. Then the modelling of the network elements is presented in Section 3. In Section 4, the direct load flow analysis in unbalanced or balanced cases for meshed and/or radial configurations is briefly presented. Then the algorithm for designing fixed and switched capacitors will be presented in Section 5. Finally, in order to test the presented algorithm, this algorithm has been implemented on feeder No. 3062 in Kian-Pars region of Ahvaz. Well acceptable results show the effectiveness of the proposed algorithm.

2 THE STRUCTURE OF REAL–CODED GENETIC ALGORITHM

The genetic algorithm (GA) initiates the mechanism of the natural selection and evolution and aims to solve an optimization problem with object function $f(x)$ where $x = [x_1, x_2, \dots, x_N]$ is an N-dimensional vector of optimization parameters. It has proved to be an effective and powerful global optimization algorithm for many combinatorial optimization problems, especially for problems with discrete optimization parameters, non-differentiable and/or a discontinuous objective function [19].

Genes and chromosomes are the basic building blocks of the GA. The conventional standard GA (SGA) encodes the optimization parameters into a binary code string. A gene in SGA is a binary code. A chromosome is a concatenation of genes that takes the form

$$\mathit{chromosome} = \left[g_1^1 g_2^1 \dots g_{L_1}^1 \; g_1^2 g_2^2 \dots g_{L_2}^2 \; \dots \; g_1^N g_2^N \dots g_{L_N}^N\right] = [x_1\, x_2\, \dots\, x_N] \tag{1}$$

where g_j^i is a gene, and L_i is the length of the code string of the ith optimization parameter and

$$x_k = \left[g_1^k g_2^k \dots g_{L_k}^k\right]. \tag{2}$$

The genetic algorithm used in this paper is RCGA. Real number encoding has been confirmed to have better performance than either binary or gray encoding for constrained optimization problems [20]. Then, in RCGA, a gene is the optimization parameter itself selected from the alphabet set. The chromosome takes the form:

$$\mathit{chromosome} = [x_1 x_2 \dots x_N]. \tag{3}$$

The RCGA structure is summarized as follows:

1) Initial population: The RCGA operates on a population of N_{pop} chromosomes simultaneously. The initial population of real numbered vectors is created randomly. Each of these vectors represents one possible solution to the search problem. The population size (N_{pop}) generally varies from 2 to 2.5 times the number of genes. Once the initialization is completed, the population enters the main GA loop and performs a global optimization for searching the optimal solution of the problem. In a GA loop, the stages 2 to 7 are carried out in turn. The GA loop continues until the termination conditions in stage 3 are fulfilled.

2) Scaling: The scaling operator, a preprocessor, is usually used to scale the object function into an appropriate fitness function. It aims to prevent premature convergence in the early stages of the evolution process and to speed up the convergence in the more advanced stages of the process.

3) Termination criterion: After the fitness has been calculated, it has to be determined if the termination criterion has been met. This can be done in several ways. The algorithm used here stops when a finite generation number has been reached and the best fit among the population is declared the winner and solution to the problem.

4) Selection: The selection (or reproduction) operator selects good chromosomes on the basis of their fitness values and produces a temporary population, namely, the mating pool. This can be achieved by many different schemes, but the most common method is the roulette wheel selection. The roulette wheel is biased with the fitness of each of solution candidates. The wheel is spun M-times where M is the number of strings in the population. This operation generates a measure that reflects the fitness of the previous generation's candidates.

5) Crossover: The crossover operator is the main search tool. It mates chromosomes in the mating pool by pairs and generates candidate offspring by crossing over the mated pairs with probability P_{cross}. The probability of parent-chromosome crossover is assumed to be between 0.6 and 1.0. Many variations of crossover have been developed, *eg*, one-point, two-point and N-point, and random multipoint crossover. Here, the arithmetical one-point crossover is used and introduced.

6) Mutation: After crossover, some of the genes in the candidate offspring are inverted with probability P_{mut}. This is the mutation operation for the GA. The mutation operator is included to prevent premature convergence by ensuring the population diversity. A new population

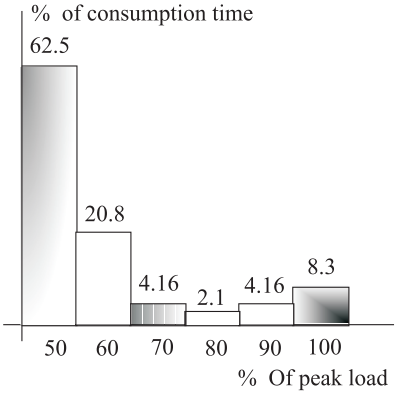

Fig. 1. Load variation in the form of percentage of the peak load in terms of percentage of time

is therefore generated. In this paper, the probability of mutation (P_{mut}) is assumed to be between 0.01 and 0.1.

7) Elitism: The postprocessor is the elisit model. The worst chromosome in the newly generated population is replaced by the best chromosome in the old population if the best number in the newly generated population is worse than that in the old population. It is adopted to ensure the algorithm convergence. This method of preserving the elite parent is called elitism.

3 MODELLING OF THE NETWORK ELEMENTS

In the optimal capacitors placement, in order to reduce the losses and to control the network voltage, all the practical aspects and the realities dominating the distribution network should be taken into account. These issues include the precise modelling of network and loads, performing the unbalanced three-phase load flow with radial and/or meshed configuration, and utilizing real usable capacitors, which will be discussed in the coming sections.

3.1 Network Modelling

In order to design a practical algorithm, a proper model of the network is required. For this purpose, great care should be taken to model the network properly, and the inductance and resistance of the three-phase lines with due regard to the variety of the wires used in the distribution network are considered in the program. Moreover, it should be possible to consider intricate subbranches and meshed network in the algorithm under discussion. All these points have been taken into consideration in the proposed method.

3.2 Three-phase Load Modelling in the Distribution Network

In distribution networks, wide ranges of various electric loads such as domestic loads, industrial trade loads, and street lamps are encountered. Besides, each of these loads has lots of fluctuations within a year, which creates many difficulties in modelling of the load in the networks. One of the important methods to overcome this problem, which needs little information in this respect, is to extend the use of load fluctuations of the feeding post to the consumers' loads. For this purpose, at first, the curve of the three-phase feeder's 24 hour active load should be extracted from the post, then the load variation diagram should be drawn in the form of percentage of load peak versus the percentage of consumption time. Figure 1 shows an example of this diagram, which indicates that the feeder's load is 50 % of the peak load in 62.5 % of 24 hours, and it forms 80 % of the peak load in 2.1 % of 24 hours. Now this three-phase load distribution of the post can be extended to all the three-phase loads of feeder's branches.

Thus, in this method the variations of load with a good approximation by using little information have been considered.

3.3 Real Modelling of Capacitors

In finding the optimal values of capacitors, the problem should be designed in such a way that utilization of the range of capacitors available in the market of the electric industries may become possible. Otherwise, rounding of the amount of the designed capacitors to the nearest value of the available capacitor will not minimize the nonlinear cost function. To overcome this problem in this algorithm, at first a list of available capacitors in the market is prepared, then a suitable combination with due regards the purchasing costs, installation, and maintenance is formed and used as an alphabet collection for selecting the genes of every chromosome in the real coded genetic algorithm to design fixed and switchable capacitors. This problem is discussed in the next sections.

In finding the values of capacitors, the selection criterion should not be the capacitors' fixed reactive powers because their reactive power varies by variation of the feeder's voltage. Therefore, the capacitor modelling should be performed on the basis of fixed impedance. In other words, the reactive power of every capacitor (Q_C) is calculated in each stage of load distribution repeatedly by using the following equation:

$$Q_C = \frac{V_C^2}{X_C}\,. \tag{4}$$

Another important problem in the placement of capacitors that should be considered is the rate of growth of investment costs for designing the capacitors. From the economical point of view an acceptable design is the one whose productivity is more than the initial investment costs plus the growth rate of initial costs. Therefore, the initial costs including the costs of purchase, erection, lateral equipment and maintenance must be multiplied by the coefficient for capital turnover. That is,

$$A_C = C_c\Big[\frac{i(1+i)^n}{(1+i)^n-1}\Big]. \tag{5}$$

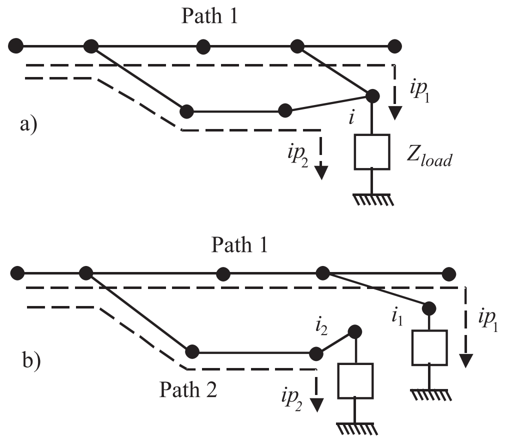

Fig. 2. Calculation of loop node current

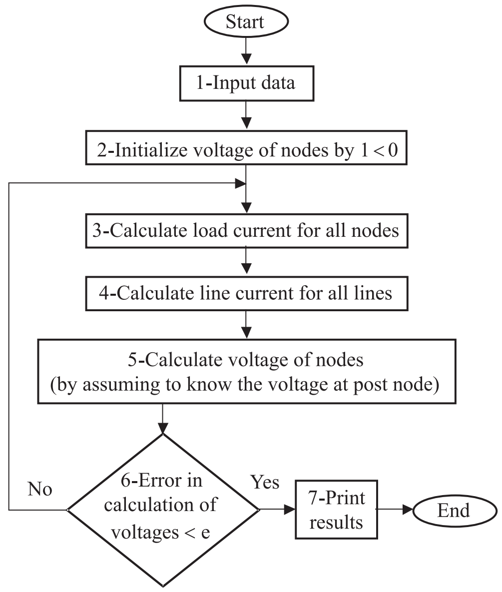

Fig. 3. Load flow algorithm with forward-backward method

In this equation, i stands for the annual rate of growth of money, and n for the life-span of the project (in years). Finally, it can be said that by real modelling of available capacitors in the market and by considering the growth rate of money, all the relevant economic problems have been taken into consideration, so that the system directors may be quite satisfied about purchasing capacitors.

4 THREE–PHASE LOAD FLOW ANALYSIS

In this section a direct power flow method with meshed/radial configurations for balanced and unbalanced distribution networks is explained [21].

4.1 Solution for Networks with Radial Lines

In this method, by applying Kirchhoff's laws and inserting the source bus in all equations by representing the loads as constant impedances, a set of voltage equations can be written as the following matrix form:

$$\mathbf{V}_s = \mathbf{ZI}\,. \tag{6}$$

In the above equation, $\mathbf{V}_s$ is the column vector of source node voltages and $V_s = 1$ pu. Moreover, $\mathbf{I}$ is a column vector in which each element is the current following to one load node of the network. $\mathbf{Z}$ is the impedance matrix of the network [21]. By solving equation (6), the current vector of the nodes load of the network is determined and then all nodes voltages can be calculated.

4.2 Solution for Networks with Radial and Loop Lines

Distributions networks that have both radial and loop lines are at first converted into a radial system and then they are solved by the presented method for radial networks.

The procedure of breaking the loop lines and making an equivalent radial system is shown in Fig. 2. As shown in this figure, i_{p1} and i_{p2} are the currents through path 1 and path 2. Their sum flows in the load impedance Z_{load}. Therefore, the following equations can be written:

$$\begin{aligned} V_s &= Z_{com}(i_{p1}+i_{p2}) + Z_{path1}i_{p1} + Z_{load}(i_{p1}+i_{p2})\,,\\ V_s &= Z_{com}(i_{p1}+i_{p2}) + Z_{path2}i_{p2} + Z_{load}(i_{p1}+i_{p2}) \end{aligned} \tag{7}$$

where $Z_{com}, Z_{path1}, Z_{path2}$ and Z_{load} are the impedances of the common path of the current, path1, path2 and load, respectively. Equation (7) can be rearranged as follows:

$$\begin{aligned} V_s &= (Z_{com}+Z_{path1}+Z_{load})i_{p1} + (Z_{com}+Z_{load})i_{p2}\,,\\ V_s &= (Z_{com}+Z_{load})i_{p1} + (Z_{com}+Z_{path2}+Z_{load})i_{p2}\,. \end{aligned} \tag{8}$$

Thus, the loop node i is broken into nodes i_1 and i_2. In fact, the meshed network is converted into two radial networks. Finally, after load flow analysis and determining the voltage and current values of these nodes, as shown in Fig. 2, the voltages of these nodes are equal to the voltage of the i node and it can be written:

$$\begin{aligned} V_{i1} &= V_{i2} = V_i\,,\\ V_i &= Z_{load}(i_{p1}+i_{p2})\,. \end{aligned} \tag{9}$$

4.3 Solution for Unbalanced Networks

In unbalanced distribution networks, the model of equivalent impedance of the lines and network components are represented in a single phase form for each node in 3×3 matrices. Information of the loads powers is presented and modelled for each phase separately. As a result, the presented method for balanced networks can be used also for unbalanced three-phase networks, which leads to well acceptable results.

Because of three-phase representation, each load node will represent three loops. For the nth load node, $[3(n-1)+1]$th, $[3(n-1)+2]$th and $[3(n-1)+3]$th loops will represent the a, b and c phases, respectively. Formation of the $\mathbf{Z}$ matrix is as simple as in the single-phase case. Because of the three-phase representation, network identity between the ith and $(i+1)$th load nodes will appear in the $[3(i-1)+1]$ and $[3(i+1-1)+1]$th rows of the $\mathbf{Z}$ matrix. Similar to the balanced case, there is no need for inverting the impedance matrix and the load distribution problem can be solved by using the LU factorization.

4.4 Solution for Balanced Networks

One of the useful load flows in the balanced distribution networks, which are done without any primary approximate assumption, is the forward-backward method, which is based on repetitative method as shown in Fig. 3, which is common in load distribution.

At the beginning of this method, the voltage of the buses is pre-estimated for $1 <$pu (2^{nd} stage of flowchart). Then by knowing the active and reactive power of loads (determined in sub-section 3-2), first the load's current (stage 3) and then the current of all the network lines (stage 4) are obtained. Up to this stage is the backward stage of the algorithm. In the forward stage by knowing the voltage of the feeding bus (post bus or primary bus) for $1 < 0$ pu, and specifying the current of all the lines in the backward stage, the voltage of all the nodes are calculated again (stage 5). After calculating the voltage of nodes, the backward stage (which is same calculation of the loads' current and the lines' current) is executed. This cycle is repeated up to the stage where the voltage calculated for all the buses becomes less than the authorized amount of error (stage 6).

5 TECHNIQUE OF DESIGN BASED ON THE RCGA

In this section the proposed design procedure of optimal capacitor placement is discussed. For this purpose, at first the detailed procedure for the case of fixed capacitors is presented. Then, the design flowchart of switched capacitors in the peak load level of the system is provided.

5.1 The Design Procedure of Fixed Capacitors

In this sub-section the proposed algorithm for optimal designing of fixed capacitors by utilizing RCGA is discussed step by step as follows:

1) Entering the input data: In this stage, the network data and constant parameters should be entered.

2) Determining the three–phase load flow at different cases: In this step, the initial three-phase load flow at all load levels for both balanced and unbalanced cases is done without any capacitors such that the annual energy loss of three-phases may be calculated.

3) Forming the initial population randomly: The primary population is selected at random in this stage.

4) Performing the three – phase load flow at all load levels for every Chromosome: The capacitors exist in every gene are injected into the system for every chromosome, and the three-phase load flow is performed.

5) Determining the three-phase losses, energy losses, and fitness amount for each chromosome: Now the Annual Energy Loss (AEL) of the system can be obtained for each chromosome as follows:

$$AEL = \sum_{i=1}^{NLL}\left[\begin{pmatrix}\text{power lossin}\\ \text{load level } i\end{pmatrix} * \begin{pmatrix}\text{time percentage of}\\ \text{year for load level } i\end{pmatrix} * 365 * 24\right] \tag{10}$$

and the Average Daily Energy Loss ($ADEL$) is also calculated as following:

$$ADEL = \frac{AEL}{365}\,. \tag{11}$$

In order to calculate the value of saving resulted from capacitor placement for every chromosome, the difference of annual loss of energy with and without using capacitors is calculated. Then, the amount of reduced energy loss is multiplied by the cost for every kWh. The difference between the annual cost of the used capacitors and the saving resulted from capacitor placement, is the annual net benefit (ANB) of capacitor placement for each chromosome, which is considered as the objective function. In other words,

$$ANB = \left[\begin{pmatrix}AEL\text{ with}\\ \text{capacitors}\end{pmatrix} - \begin{pmatrix}AEL\text{ without}\\ \text{capacitors}\end{pmatrix}\right] * (\text{cost of every kWh}) - \begin{pmatrix}\text{The annual cost}\\ \text{of capacitors}\end{pmatrix} \tag{12}$$

Then, by normalizing the amount of the objective function for each chromosome, the fitness value for each chromosome is obtained. Furthermore, for each chromosome by three-phase load flow analysis, the voltage of all the nodes is evaluated so that the voltage of nodes may not be less than its authorized limit. If the voltage of all the nodes is not within their authorized limits, the related chromosome does not appear in the new population.

6) Checking the population Convergence: In this stage it is checked whether the related population has converged? If it is in case, the procedure has been finished and the results should be printed by going to step 11. Otherwise, go to step 7.

7) Choosing the new chromosomes by selection operator: Based on the selection mechanism that presented in Section 2, the new chromosomes are selected in this step.

8) Performing the crossover operator: In this stage the crossover operator is performed on the new population that generated in the previous step.

9) Performing the mutation operator: The mutation operator is performed on the new population that generated in the step 8 so that finally the new population is prepared to repeat the process.

10) Forming the new population of fixed capacitors: By accomplishing the steps 7-9, the new population for repeating the process is obtained and the procedure is followed again from the forth step.

11) Monitoring the results: By converging of the population on the basis of the best amount of fitness for every chromosome in the population (at step 6), it can be concluded that optimal capacitor placement in the purpose of the loss reduction and network voltage control with real available capacitors in the market has been satisfactory performed. So, the final results can be printed.

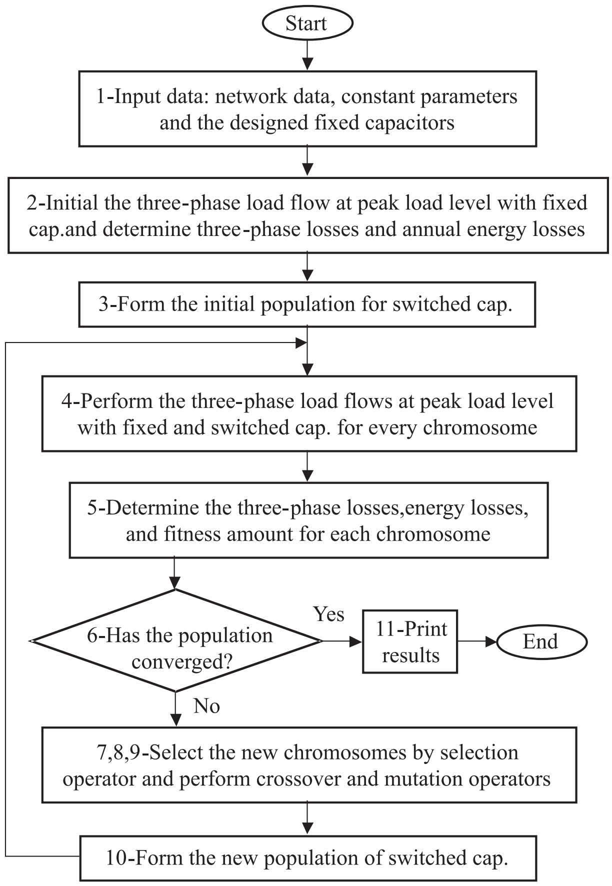

Fig. 4. Flowchart of solving the problem of switched and fixed capacitors by utilizing RCGA

Table 1. Load percentage of feeder No 3062 in proportion to its time percentage

Percentage of maximum load	Time percentage of year
$100\,\%\,P_{\max}$	$42\,\%$ (equal to 5 months)
$55\,\%\,P_{\max}$	$29\,\%$ (equal to 3.5 months)
$25\,\%\,P_{\max}$	$29\,\%$ (equal to 3.5 months)

5.2 Designing of Fixed and Switched Capacitors

In the distribution networks where load variations in different seasons of year are intensive and network is in the unbalanced status, utilization of switched capacitors in a peak load beside the fixed capacitors have economic justifications. Of course, in the networks where load variations of the feeders during the year are not very intensive, if the fixed capacitors are designed properly, switched capacitors are not economically justifiable. This is because the control and switching of this type of capacitors, in addition to the difficulties created in exploitation, will increase exploitation and capacitor placement investment costs in a peak load. For the three-phase networks with high load variations in each phase, the flowchart for finding the optimal location and value of switched capacitors in a peak load beside the fixed capacitors designed by utilization of RCGA have been shown in Fig. 4.

The basic differences of this flowchart with the procedure of fixed capacitor placement is that the switched capacitors have only been considered for peak load and naturally the three-phase load flow analysis is done only at the peak load level (stage 4). Moreover, during the design of switched capacitors, the optimal amount of fixed ones, which has been designed based on the algorithm presented in sub-section 5.1, is permanently and constantly considered in the network. It should be noted that in stage (5) in determining of the fitness value of each chromosome, the annual costs of capacitors include costs of both fixed capacitors and switched ones.

6 CASE STUDY

6.1 Network Specifications and Initial Data

In this simulation, it has been considered that the rate of investment growth is $10\,\%$, the cost of energy per kWh is 100 Rials (Iranian currency) and the life span of capacitors placement for 30 years is assumed. Also, the N_{pop} is considered as 2.5 times the number of genes, P_{cross} equals to 0.8 and P_{mut} is assumed to be between 0.01 and 0.1. This simulation has been performed on feeder No. 3062 in Kian-Pars region in Ahvaz/Iran. The percentage of load variation of the consumers of this feeder versus time percentage has been shown in Table 1. The single line diagram of this feeder has been shown in Fig. 5. By connecting the node No. 5 to No. 18 and the node No. 45 to No. 67, the network is converted to a meshed/radial configuration. In this figure, the sign $\otimes$ stands for location of distribution transformers 11 kV/400V and $\bullet$ indicates a node on whose basis no capacitor placement is possible. With due regard to the fact that capacitor placement is done by capacitors available in the market; the cost of low voltage capacitors available in the local market has been shown in Table A of Appendix A.

The specifications and parameters of the lines of this feeder and the maximum loading ($P_{\max}$) of distribution transformers have been shown in Table B of Appendix B.

6.2 The Capacitor Placement Design for Unbalanced Network

In this network, in nodes 21, 30, and 59 single-phase load is considered on phase a, in nodes 22, 31, and 60 single-phase load is put on phase b, and in nodes 23, 32, and 61 single-phase load is considered in phase c. Therefore, in spite of having 9 nodes with single-phase load on different phases, the network is in an unbalanced status and it is desired to minimize the network loss. In this sub-section, simulation results are provided for three different cases including: without capacitor placement, with fixed capacitors, and mixed fixed and switched capacitors placement.

Table 2. The minimum voltage of unbalanced three-phase network without any capacitors

	First Load Level (Peak Loaded)	Second Load Level (Normal Loaded)	Third Load Level (Light Loaded)
Minimum voltage in phase a	10.4735	10.8105	10.8920
Minimum voltage in phase b	10.4765	10.8193	10.8986
Minimum voltage in phase c	10.4741	10.8130	10.8941
The average of minimum voltage in three-phases	10.4744	10.8143	10.8949

Table 3. The simulation results in different cases of capacitors placement for unbalanced network

	Case I Without Capacitors	Case II With Fixed Capacitors	Case III With Fixed and Switched Capacitors
Minimum voltage in peak load of phase a	10.4735	10.5698	10.6887
Minimum voltage in peak load of phase b	10.4765	10.5763	10.6913
Minimum voltage in peak load of phase c	10.4741	10.5701	10.6901
Average of minimum voltage in peak load of three-phase	10.4744	10.5727	10.6900
Average daily energy loss in phase a (kWh/day)	938.47	732.55	1346.45
Average daily energy loss in phase b (kWh/day)	914.08	698.96	1323.49
Average daily energy loss in phase c (kWh/day)	928.88	703.62	1336.76
Average daily energy loss in three-phases (kWh/day)	2775.43	2135.13	4006.7
Average daily energy consumption in three-phases (kWh/day)	138756.3	129207.16	215876.09
Daily cost of used capacitors (Rials/day)	—	19723.16	22428.56
Average daily saving (Rials/day)	—	25336.32	95813.03

Table 4. The simulation results in different cases of capacitors placement for balanced network

	Case I Without Capacitors	Case II With Fixed Capacitors	Case III With Fixed and Switched Capacitors
Average of minimum voltage in peak load of three-phase	10.4687	10.5565	10.6566
Average Daily energy loss in three-phase (kWh/day)	2990.38	2476.27	4353.66
Average Daily energy consumption in three-phases (kWh/day)	150358.89	149844.66	234616.13
Daily cost of used capacitors (Rials/day)	—	22796.87	25575.27
Average daily saving (Rials/day)	—	28614.06	108425.65

Case I: The network status without capacitor placement

Since the network loads during a year have been considered in three different load levels, in the first case, three-phase load flow in these levels without any capacitor placement is accomplished. The minimum voltage in three phases a, b, and c in three different load levels is provided in Table 2 which is related to the node No. 69. It should be noted that the first load level is the peak loaded and is $P_{\max}$, the second load level is intermediate (or normal) loaded and is $0.55\,P_{\max}$, and the third load level is light loaded which is $0.25\,P_{\max}$. By calculating the loss of these three load flows, the average daily energy losses for phases a, b, and c are 938.47 kWh, 914.08 kWh, and 928.88 kWh respectively, and the mean value of the total daily energy loss becomes 2775.43 kWh. The total amount of the daily energy consumption in the three phases is equal 138765.3 kWh and the power factor of the feeder in the load peak is 0.825. These results are presented in Table 3. In addition to the node No. 69 which has the least value of voltage, 14 nodes of 72 feeder nodes have also the voltage less than 10.50 kV that shows the undesired voltage profile for this feeder.

Case II. With fixed capacitor placement

In the implementation of the algorithm presented in sub-section 5.1, it does not have economic justification to use medium voltage fixed capacitors at level 11 kV. This is due to the large number of transformers and the short length of lines, which causes the annual costs of capacitor placement to exceed the cost of loss reductions per year in the network, and this makes the project uneconomical.

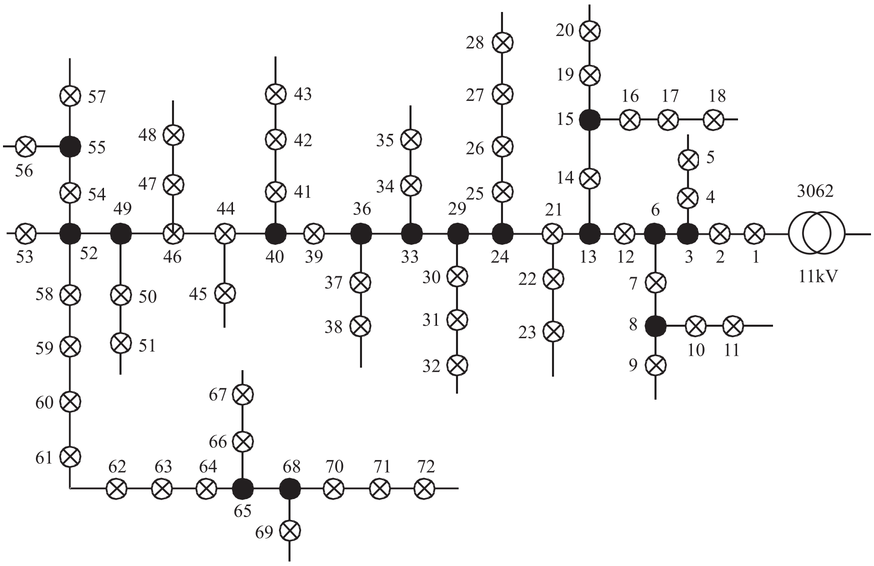

Fig. 5. The single line diagram of the feeder No 3062 in Kian-Pars of Ahvaz

With due regard to the low price of the low voltage capacitors, it is more economical to use them in the secondary positions of distribution transformers. By implementing the fixed capacitors design algorithm, the resulted values of capacitors are as shown in Fig. 6 and the simulation results are provided in the second column of Table 3. By using these designed values of capacitors, the three-phase ADEL per year has decreased from 2775.43 kWh to 2135.13 kWh. The average value of daily energy consumption decreases from 138765.3 kWh to 129207.16 kWh. On the other hand, the daily cost of used capacitors with the values shown in Fig. 6 is 19723.16 Rials. By comparison, it is found that an average daily saving of 25336.32 Rials is achieved. The importance of this type of optimal capacitor placement will be more appeared when we find that by using this method, the profile of the system voltage has improved favourably. To show this, the network's three-phase load flow is done with optimal fixed capacitor placement. It is found that the minimum voltage in the peak load level and for three phases in bus No. 69 has increased from 10.4744 kV to 10.5727 kV which is an indication of improvement of the voltage profile in the entire network.

Case III. With fixed and switched capacitor placement

Regarding that in this feeder the maximum load of the network during summer, late spring and early autumn has been very high in Ahvaz, and in winter months this reaches 30 % of the maximum load, so it seems that utilization of switched capacitors in parallel with fixed capacitors in this type of network is economical. Therefore, the design algorithm of fixed and switched capacitors in this feeder was performed. The designed values of switched capacitors in the peak time of the load have been shown in Fig. 7 and third column of the Table 3 as well. By placing switched capacitors beside fixed capacitors in the peak load level of the feeder, the average daily energy loss in the peak load has reached to 4006.6 kWh and the daily energy consumption also is reduced to 215876.09 kWh. It should be noted that the above mentioned values are related to the peak load level; therefore the daily energy loss in this level is more than the average daily energy loss per year. The feeder's power factor in the peak load is also increased to 0.973, which indicates the improvement in the status of the distribution network in the case of using fixed and switched capacitors simultaneously. Furthermore, with due regard to the price of the fixed and switched capacitors and the amount of the reduced loss of energy in different load levels, the average daily saving is 95813.03 Rials in the peak load. The total saving in a year will be 21287342.8 Rials, which is a considerable quantity for a feeder in the region of Ahvaz.

Furthermore, regarding the voltage profile of the nodes in the peak load and in the presence of fixed and switched capacitors it is found that the minimum voltage of the network in node No. 69 in this state has increased to 10.6900 kV. Thus, the network voltage control in addition to the loss reduction and well acceptable economical justifications, have been achieved in a favorable manner.

6.3. The Capacitor Placement Design for Balanced Network

In order to complete the examination of this case study, the network in the balanced status with radial configuration is considered. This configuration is achieved by switching off the connection nodes 5 to 18 and also nodes 45 to 67. The simulation results are provided in Table 4 which shows the minimum network voltage without capacitor placement in the peak load is equal 10.4687 kV that is less than allowable limit. Fixed capacitor placement with the values presented in Fig. 8, causes the reduc-

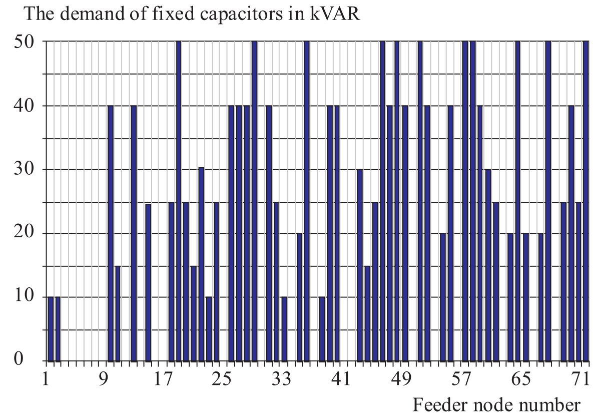

Fig. 6. Resulting fixed capacitors placement for unbalanced network in feeder No 3062

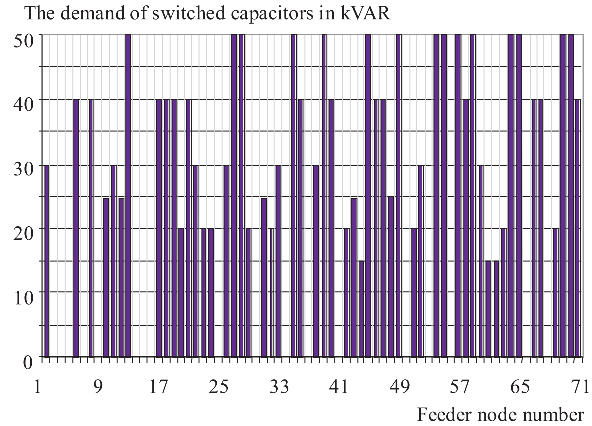

Fig. 7. Resulting switched capacitors placement for unbalanced network in feeder No 3062

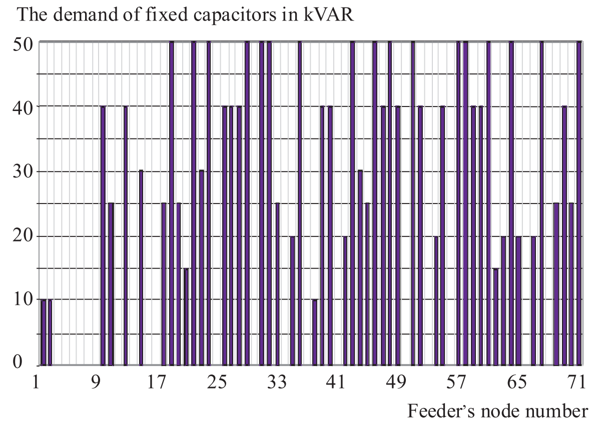

Fig. 8. Resulting fixed capacitors placement for balanced network in feeder No 3062

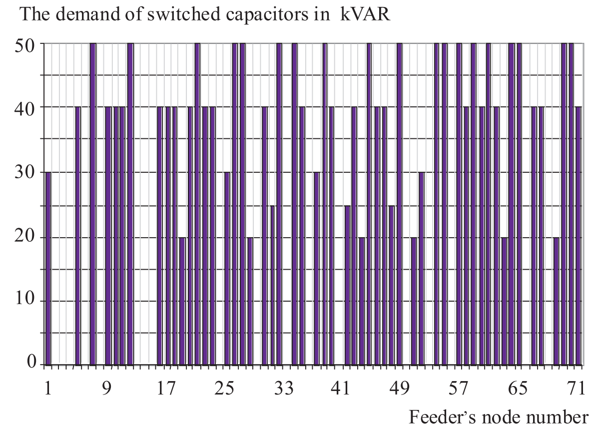

Fig. 9. Resulting switched capacitors placement for balanced network in feeder No 3062

tion of the average daily energy loss from 2990.38 kWh to 2476.27 kWh. Regarding the daily cost of capacitor placement, which equals 22796.87 Rials/day, it is found that total average of daily saving is 28614.06 Rials/day.

Since the load variation of the network in the peak, normal and light load levels is high, it is concluded that switched capacitors besides the fixed ones in the peak load may be economically useful. Therefore, the switched capacitors are designed as Fig. 9. In this case, the average daily energy loss reaches 4353.66 kWh in the peak load. Regarding the cost of the daily capacitor placement for both fixed and switched capacitors equal 25575.27 Rials/day, the average daily saving in the peak load of the network is 108425.6 Rials/day and total saving per year is equal 22096624.10 Rials, which is considerable for each year. Moreover, minimum voltage in the peak load is increased to 10.6566 kV which improves the voltage profile of the network.

7 CONCLUSION

In this paper, a new method for optimal capacitor placement in actual distribution networks in the unbalanced case with meshed/radial configuration based on RCGA technique was presented. With due regard to the many constraints and the practical restrictions in distribution networks, application of the RCGA in order to find a real optimal and applicable solution for the quantity and place of fixed and switched capacitors is very effective. At first, it is tried to model the network and also to consider the balanced and unbalanced feeder's loads at different levels so that the load modelling may be performed with minimum assumptions. Moreover, by considering the real model and prices of capacitors which are available in the market, it was found that the fixed and switched capacitor placement can be executed at the low voltage level (380 V) and medium voltage level (11 kV, 20 kV and 33 kV). Then, the algorithm of fixed and switched capacitors was implemented on the feeder No. 3062 in the city of Ahvaz in Iran.

The obtained results indicate that the proposed method has a realistic view to this important practical problem and causes the reduction in the energy loss and annual energy consumption in the network which is attractive in the economic point of view. It has also improved the feeder's nodes voltage and controls the voltage in a favourable manner.

Appendix A. Specifications of Low Voltage Capacitors

The range of low voltage capacitors available in the market and their prices is wide and various, but in this simulation, the norm quantities of capacitors available in the market with their approximate prices have been utilized according to Table A.

Appendix B. The Specification of Feeder No. 3062 in Ahvaz

Feeder No. 3062 in Kian-Pars region of Ahvaz is contains 72 line pieces, which naturally include 72 nodes (without the node concerning the feeder post). The specifications of these lines with the scale of loading from the distribution transformers in the last node of these lines have shown in Table B. In this table, the line number, sending and receivering node numbers, resistance (R), and reactance (X) of the line pieces, the three-phase active and reactive powers received in the peak load by the loads available at the end nodes of the lines have been specified in the term of kW and kVAR.

List of Symbols

a, b, c	Three phases of distribution networks
$\mathbf{V}_s$	Voltage vector
$\mathbf{I}$	Load node's Current vector
V_s	Source bus voltage
I_i	ith load node's current
Z_{load}	The load impedance
NLL	Number of load levels
P, Q	Load active and reactive power
R, X	Resistance and reactance of line
Q_C	Reactive power of capacitor
V_C	Voltage of capacitor
X_C	Reactance of capacitor
A_c	Annual cost of capacitor
C_c	Initial cost of capacitor
e	Authorized amount of error
AEL	Annual Energy Loss
$ADEL$	Average Daily Energy Loss
ANB	Annual Net Benefit

Table A. Specifications of low voltage capacitors

Capacitor Number	Capacity (kVAR)	Nominal Voltage (V)	Approx. price including lateral equipments (Rials)
0	0	380	0.0
1	10	380	680,000
2	15	380	850,000
3	20	380	1,000,000
4	25	380	1,200,000
5	30	380	1,300,000
6	40	380	1,600,000
7	50	380	2,000,000

Table B. The specifications of lines and loads in feeder No 3062

Line Number	Send Node	End Node	Impedance ($R + jX$)	Load Power in End Node (kW + j kVAR)
1	0	1	$0.05136 + j0.09146$	$97.75 + j60.58$
2	1	2	$0.03455 + j0.06153$	$120.00 + j63.22$
3	2	3	$0.00467 + j0.00831$	$0.0 + j0.0$
4	3	4	$0.01401 + j0.02494$	$160.65 + j99.56$
5	4	5	$0.01404 + j0.02494$	$160.65 + j99.56$
6	3	6	$0.04903 + j0.08730$	$0.0 + j0.0$
7	6	7	$0.03362 + j0.05987$	$160.65 + j99.56$
8	7	8	$0.030535 + j0.05405$	$0.0 + j0.0$
9	8	9	$0.00934 + j0.01663$	$115.13 + j71.35$
10	8	10	$0.01588 + j0.02827$	$136.04 + j84.31$
11	10	11	$0.00934 + j0.01663$	$192.78 + j119.47$
12	6	12	$0.02335 + j0.04157$	$34.0 + j21.07$
13	12	13	$0.01167 + j0.02079$	$0.0 + j0.0$
14	13	14	$0.02802 + j0.04989$	$217.6 + j134.86$
15	14	15	$0.00794 + j0.01414$	$0.0 + j0.0$
16	15	16	$0.01261 + j0.02245$	$47.6 + j29.5$
17	16	17	$0.00934 + j0.01663$	$160.65 + j99.56$
18	17	18	$0.00467 + j0.00831$	$160.65 + j99.56$
19	15	19	$0.03269 + j0.05820$	$86.7 + j53.73$
20	19	20	$0.03502 + j0.06236$	$127.5 + j79.02$
21	13	21	$0.01634 + j0.02910$	$243.65 + j151.0$
22	21	22	$0.04529 + j0.08065$	$227.58 + j141.05$
23	22	23	$0.03362 + j0.05987$	$110.5 + j68.48$
24	21	24	$0.01634 + j0.02910$	$0.0 + j0.0$
25	24	25	$0.01494 + j0.02661$	$102.0 + j63.21$
26	25	26	$0.00654 + j0.01164$	$144.58 + j89.61$
27	26	27	$0.04950 + j0.08814$	$255.0 + j158.04$
28	27	28	$0.02802 + j0.04989$	$160.65 + j99.56$
29	24	29	$0.01541 + j0.02744$	$0.0 + j0.0$
30	29	30	$0.03502 + j0.06236$	$210.8 + j130.64$
31	30	31	$0.01167 + j0.02079$	$155.29 + j96.24$
32	31	32	$0.01401 + j0.02494$	$160.65 + j99.56$
33	29	33	$0.01868 + j0.03326$	$0.0 + j0.0$
34	33	34	$0.02802 + j0.04989$	$179.39 + j111.18$
35	34	35	$0.02568 + j0.04573$	$232.97 + j144.37$
36	33	36	$0.01634 + j0.02910$	$0.0 + j0.0$
37	36	37	$0.01201 + j0.03742$	$165.65 + j99.56$
38	37	38	$0.02802 + j0.04989$	$289.0 + j179.11$
39	36	39	$0.00934 + j0.01663$	$160.65 + j99.56$
40	39	40	$0.00747 + j0.01330$	$0.0 + j0.0$
41	40	41	$0.03175 + j0.05654$	$248.2 + j153.82$
42	41	42	$0.01868 + j0.03326$	$160.65 + j99.56$
43	42	43	$0.01961 + j0.03490$	$248.52 + j154.10$
44	40	44	$0.01634 + j0.02910$	$160.65 + j99.56$
45	44	45	$0.03175 + j0.05654$	$294.52 + j182.53$
46	44	46	$0.01681 + j0.02993$	$204.0 + j126.43$
47	46	47	$0.01868 + j0.03326$	$321.32 + j199.13$
48	47	48	$0.03736 + j0.06652$	$163.32 + j101.23$
49	46	49	$0.01634 + j0.02910$	$0.0 + j0.0$
50	49	50	$0.00794 + j0.01414$	$204.0 + j126.43$
51	50	51	$0.02802 + j0.04989$	$272.0 + j168.57$
52	49	52	$0.01027 + j0.01829$	$0.0 + j0.0$
53	52	53	$0.02942 + j0.05238$	$238.0 + j147.5$
54	52	54	$0.01261 + j0.02245$	$207.4 + j128.53$
55	54	55	$0.03129 + j0.05571$	$0.0 + j0.0$
56	55	56	$0.02008 + j0.03575$	$176.8 + j109.57$
57	55	57	$0.02335 + j0.04157$	$160.65 + j99.56$
58	52	58	$0.02568 + j0.04573$	$160.65 + j99.56$
59	58	59	$0.01728 + j0.03076$	$22.1 + j13.69$
60	59	60	$0.02008 + j0.03575$	$144.58 + j89.61$
61	60	61	$0.00887 + j0.01580$	$178.5 + j110.63$
62	61	62	$0.00560 + j0.00998$	$187.0 + j115.89$
63	62	63	$0.00560 + j0.00998$	$160.65 + j99.56$
64	63	64	$0.06304 + j0.11225$	$238.0 + j147.50$
65	64	65	$0.02335 + j0.04157$	$0.0 + j0.0$
66	65	66	$0.02335 + j0.04157$	$30.60 + j18.96$
67	66	67	$0.01401 + j0.02494$	$129.71 + j80.39$
68	65	68	$0.00467 + j0.00831$	$0.0 + j0.0$
69	58	69	$0.05603 + j0.09978$	$160.65 + j99.56$
70	68	70	$0.01401 + j0.02494$	$160.65 + j99.56$
71	70	71	$0.00934 + j0.01663$	$187.0 + j115.89$
72	71	72	$0.03829 + j0.06818$	$20.4 + j12.64$

References

[1] CARPINELLI, G.—VARILONE, P.—Di VITO, V.—ABUR, A.: Capacitor Placement in Three-phase Distribution Systems with Nonlinear and Unbalanced Loads, IEE Proc.-Gener. Trans. Distrib, **152** No. 1 (2005), 47–52.

[2] WANG, J.—CHIANG, H.—NAN MINU, K.—DARLING, G. Capacitor Placement and Real Time Control in Large-Scale Unbalanced Distribution Systems: Part I & II: IEEE Trans. On Power Delivery **12** (1997), 953–964.

[3] CHIANG, H.—WANG, J.—DARLING, G.: Optimal Capacitor Placement, Replacement and Control in Large-Scale Unbalanced Distribution Systems: Part I & II, IEEE Trans. On Power Systems **10** (1995), 356–369.

[4] HOOSHMAND, R.—JOORABIAN, M.: Optimal Choice of Fixed and Switched Capacitors for Distribution Systems by Genetic Algorithm, AUPEC Conference, 2002; Melbourne, Australia.

[5] SOUZA, B. A.—NASCIMENTO, H. D.—FERREIRA, H. A.: Microgenetic Algorithms and Fuzzy Logic Applied to the Optimal Placement of Capacitor Banks in Distribution Networks, IEEE Trans. On Power Systems **19** (2004), 942–947.

[6] MENDES, A.—FRANCA, P. M.—LYRA, C.—PISSARRA, C.—CAVELLUCCI, C.: Capacitor Placement in Large-sized Radial Distribution Networks, IEE Proc. Gener. Trans. Distrib. **152** No. 4 (2005), 496–502.

[7] MASOUM, M. A. S.—LADJEVARDI, M.—JAFARIAN, A.—FUCHS, E. F.: Optimal Placement, Replacement and Sizing of Capacitor Banks in Distorted Distribution Networks by Genetic Algorithms, IEEE Trans. On Power Delivery **19** (2004), 1794–1801.

[8] DLFANTI, M.—GRANELLI, G. P.—MARANNINIO, P.: Optimal Capacitor Placement Using Deterministic and Genetic Algorithm, IEEE Trans. On Power Systems **15** (2000), 1041–1046.

[9] KIM, K. H.—YOU, S. K.: Voltage Profile Improvement by Capacitor Placement and Control in Unbalanced Distribution Systems Using GA, IEEE Power Engineering Society Summer Meeting, 1999, Vol. 2, pp. 18–22.

[10] SANTOS, J. R.—EXPOSITO, A. G.—RAMOS, J. L. M.: A Reduced-Size Genetic Algorithm for Optimal Capacitor Placement on Distribution Feeders, IEEE MELECON 2004, May 12–15, 2004, Dubrovnik, Croatia, pp. 963–966.

[11] SUNDHARAJAN, PAHWA, A.: Optimal Selection of Capacitors for Radial Distribution Systems Using a Genetic Algorithm, IEEE Trans. On Power Systems **9** (1994), 1499–1507.

[12] HUANG, Y. C.—YANG, H. T.—HUANG, C. L.: Solving the Capacitor Placement Problem in a Radial Distribution System Using Tabu Search Application, IEEE Trans. On Power Systems **11** (1996), 1868–1873.

[13] GRAINGER, J. J.—LEE, S. H.: Optimum Size and Location of Shunt Capacitors for Reduction of Losses on Distribution Feeders, IEEE Trans. On Power Appar. A. Syst. **PAS-100** (1981), 1105–1118.

[14] SOCHULIAVOKA, D.—NIEBUR, D.—RICHARDSON, D.: Identification of Capacitor Position in a Radial System, IEEE Trans. On Power Delivery **14** (1999), 1368–1373.

[15] FAWAZI, T. H.—El-SOBKI, S. M.—ABDEL-HALIM, M. A.: A New Approach for the Application of Shunt Capacitors to the Primary Distribution Feeders, IEEE Trans. on Power Appar. A. Syst. **PAS-102** (1983), 10–13.

[16] GALLEGO, R. A.—MONTICELLI, A. J.—ROMERO, R.: Optimal Capacitor Placement in Radial Distribution Networks, IEEE Trans. On Power Systems **16** (2001), 630–637.

[17] LEVITIN, G.—KALYUZHNY, A.—SHENKMAN, A.—CHERTKOV, M.: Optimal Capacitor Allocation in Distribution Systems Using a Genetic Algorithm and a Fast Energy Loss Computation Technique, IEEE Trans. On Power Delivery **15** (2000), 623–628.

[18] PONNAVAIKKI, M.—PRAKASA RAO, K. S.: Optimal Choice of Fixed and Switched Capacitors on Radial Distributions by the Method of Local Variables, IEEE Trans. On Power Appar. A. Syst. **102** (1983), 1607–1615.

[19] GOLDBERG, D. E.: Genetic Algorithm, in Search, Optimization & Machine Learning, Addison-Weseley Publishing Company, 1989.

[20] ESHELMAN, L.—SCHAFFER, J.: Real-Coded Genetic Algorithms and Interval-Schemata, in (L. Whitely, ed.), vol. 2, Morgan Kaufmann Publishers, San Francisco, 1993, pp. 187202.

[21] GOSWAMI, S. K.—BAU, S. K.: Direct Solution of Distribution Systems, IEE Proceedings-C **138** No. 1 (Jan.1991), 78–88.

Received 17 April 2006

Rahmat-Allah Hooshmand (1967) received the BSEE degree from the University of Mashhad in 1989, the MSEE from the University of Tehran, Iran and PhD degree from Tarbiat Modarres University Iran in 1990 and 1995, respectively all in electrical engineering. Since 1995, he has been with the Department of Electrical Engineering at the University of Isfahan, Iran as an associate professor. His main areas of research interest are modelling of Power Systems and Distribution Networks.

Mohammad Ataei (1971) received the BS degree from the Isfahan University of Technology, Iran, in 1994, the MS degree from the Iran University of Science and Technology, Iran, in 1997, and PhD degree from K. N. University of Technology, Iran, in 2004 (joint project with the University of Bremen, Germany) all in electrical engineering. Since 2004, he has been with the Department of Electrical Engineering at the University of Isfahan, Iran. He has worked on time series analysis of chaotic systems, robust control, and application of intelligent systems. His main areas of research interest are also modelling of systems, and tracking systems.