OPTIMAL CAPACITOR PLACEMENT USING FUZZY AND REAL CODED GENETIC ALGORITHM FOR MAXIMUM SAVINGS

[1]M. Damodar Reddy, [2]Prof. V.C. Veera Reddy
[1]Associate Professor, Department of E.E.E., S.V. University, Tirupati, Andhra Pradesh, India.
[2]Professor, Department of E.E.E., S.V. University, Tirupati, Andhra Pradesh, India.

ABSTRACT

This paper presents a new methodology using fuzzy and Real Coded Genetic Algorithm (RCGA) for the placement of capacitors on the primary feeders of the radial distribution systems to reduce the power losses and to improve the voltage profile. A two-stage methodology is used for the optimal capacitor placement problem. In the first stage, fuzzy approach is used to find the optimal capacitor locations and in the second stage, Real Coded Genetic Algorithm is used to find the sizes of the capacitors. The sizes of the capacitors corresponding to maximum annual savings are determined. The proposed method is tested on 15-bus, 34-bus and 69-bus test systems and the results are presented.

Keywords - *Capacitor placement - fuzzy approach – Real Coded Genetic Algorithm -maximum annual savings*.

1. INTRODUCTION

Radial distribution systems are typically spread over large areas and are responsible for a significant portion of total power losses. Reduction of total power loss in distribution system is very essential to improve the overall efficiency of power delivery. This can be achieved by placing the optimal value of capacitors at proper locations in radial distribution systems. Capacitors are installed at strategic locations to reduce the losses and to maintain the voltages within the acceptable limits.

Application of shunt capacitors to the primary distribution feeders is a common practice in most of the countries. The advantages anticipated include boosting the load level of the feeder so that additional loads can be carried by the feeder for the same maximum voltage drop, releasing a certain kVA at the substation that can be used to feed additional loads along other feeders and reducing power and energy losses in the feeder.

The objective of the capacitor placement problem is to determine the locations and sizes of the capacitors so that the power loss is minimized and annual savings are maximized. Even though considerable amount of research work was done in the area of optimal capacitor placement [1]-[10], there is still a need to develop more suitable and effective methods for the optimal capacitor placement.

Although some of these methods to solve capacitor allocation problem are efficient, their efficacy relies entirely on the goodness of the data used. Fuzzy logic provides a remedy for any lack of uncertainty in the data. Fuzzy logic has the advantage of including heuristics and representing engineering judgments into the capacitor allocation optimization process. Furthermore, the solutions obtained from a fuzzy algorithm can be quickly assessed to determine their feasibility in being implemented in the distribution system.

H. Ng *et al.* [9] proposed the capacitor placement problem by using fuzzy approximate reasoning. In the first stage, the method proposed by H. Ng *et al.* [9] is adapted to determine the optimal capacitor locations using fuzzy logic.

The global optimization method is most useful in obtaining the optimal capacitor sizes corresponding to maximum annual savings. In that sense, Real Coded Genetic Algorithm (RCGA) is one of the popular meta-heuristic methods in all the engineering fields. In the second stage, RCGA is proposed to find the sizes of the capacitors. The capacitor placement problem is modeled with the objective function, which maximizes the annual savings. The proposed method is tested on 15-bus, 34-bus, and 69-bus test systems and the results are presented.

2. TOTAL REAL POWER LOSS IN A DISTRIBUTION SYSTEM

The total I^2R loss (P_L) in a distribution system having *n* number of branches is given by

$$P_L = \sum_{i=1}^{n} I_i^2 \, Ri \qquad (1)$$

Here I_i is the magnitude of the branch current and R_i is the resistance of the i^{th} branch respectively. The branch current can be obtained from the load flow solution. The branch current has two components, active component (I_a) and reactive component (I_r). The loss associated with the active and reactive components of branch currents can be written as

$$P_{La} = \sum_{i=1}^{n} I_{ai}^2 \, Ri \qquad (2)$$

$$P_{Lr} = \sum_{i=1}^{n} I_{ri}^2 \, Ri \qquad (3)$$

Note that for a given configuration of a single-source radial network, the loss P_{La} associated with the active component of branch currents cannot be minimized because all active power must be supplied by the source at the root bus. However, supplying part of the reactive power demand locally can minimize the loss P_{Lr} associated with the reactive component of branch currents. This paper presents a method that minimizes the loss due to the reactive component of the branch current by optimally placing the capacitors and thereby reduces the total loss in the distribution system.

3. IDENTIFICATION OF OPTIMAL CAPACITOR LOCATIONS USING FUZZY APPROACH

This paper presents a fuzzy approach to determine suitable locations for capacitor placement. Two objectives are considered while designing a fuzzy logic for identifying the optimal capacitor locations. The two objectives are: (i) to minimize the real power loss and (ii) to maintain the voltage within the permissible limits. Voltages and power loss indices of distribution system nodes are modeled by fuzzy membership functions. A fuzzy inference system (FIS) containing a set of rules is then used to determine the capacitor placement suitability of each node in the distribution system. Capacitors can be placed on the nodes with the highest suitability.

For the capacitor placement problem, approximate reasoning is employed in the following manner: when losses and voltage levels of a distribution system are studied, an experienced planning engineer can choose locations for capacitor installations, which are probably highly suitable. For example, it is intuitive that a section in a distribution system with high losses and low voltage is highly ideal for placement of capacitors. Whereas a low loss section with good voltage is not ideal for capacitor placement. A set of fuzzy rules has been used to determine suitable capacitor locations in a distribution system.

In the first step, load flow solution for the original system is required to obtain the real and reactive power losses. Again, load flow solutions are required to obtain the power loss reduction by compensating the total reactive load at every node of the distribution system. The loss reductions are then, linearly normalized into a [0, 1] range with the largest loss reduction having a value of 1 and the smallest one having a value of 0. Power Loss Index value for n^{th} node can be obtained using equation 4.

$$PLI_{(n)} = \frac{(Lossreduction_{(n)} - Lossreduction_{(\min)})}{(Lossreduction_{(\max)} - Lossreduction_{(\min)})} \quad \text{--------} \quad (4)$$

These power loss reduction indices along with the p.u. nodal voltages are the inputs to the Fuzzy Inference System (FIS), which determines the node more suitable for capacitor installation.

In this paper, two input and one output variables are selected. Input variable-1 is power loss index (PLI) and Input variable-2 is the per unit nodal voltage (V). Output variable is capacitor suitability index (CSI). Power Loss Index range varies from 0 to 1, P.U. nodal voltage range varies from 0.9 to 1.1 and Capacitor suitability index range varies from 0 to 1.Five membership functions are selected for PLI. They are **L, LM, M, HM and H**. All the five membership functions are triangular as shown in Figure 1. Five membership functions are selected for Voltage. They are **L, LN, N, HN and H**. These membership functions are trapezoidal and triangular as shown in Figure 2. Five membership functions are selected for CSI. They are **L, LM, M, HM and H**. These five membership functions are also triangular as shown in Figure 3.

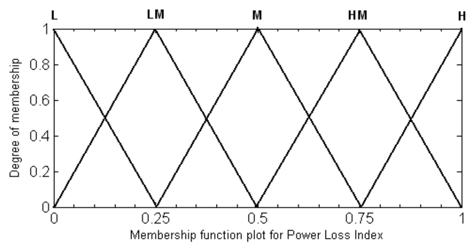

Figure 1. Membership function plot for P.L.I.

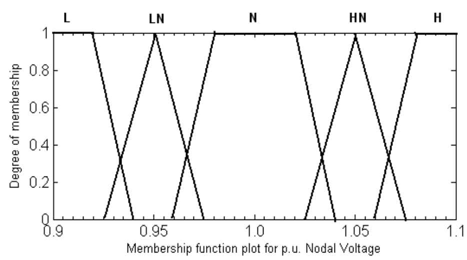

Figure 2. Membership function plot for p.u. nodal voltage.

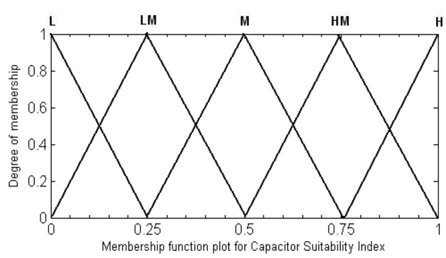

Figure 3. Membership function plot for C.S.I.

For the capacitor allocation problem, rules are defined to determine the suitability of a node for capacitor installation. Such rules are expressed in the following form:

IF premise (antecedent), THEN conclusion (consequent).

For determining the suitability of capacitor placement at a particular node, a set of multiple-antecedent fuzzy rules has been established. The inputs to the rules are the voltage and power loss indices and the output is the suitability of capacitor placement. The rules are summarized in the fuzzy decision matrix in Table I. The consequents of the rules are in the shaded part of the matrix.

Table I. Decision matrix for determining the optimal capacitor locations

AND		**Voltage**				
		L	LN	**N**	HN	**HH**
PLI	L	LM	LM	L	L	L
	LM	M	LM	LM	L	L
	M	HM	M	LM	L	L
	HM	HM	HM	M	LM	L
	H	H	HM	M	LM	LM

4. REAL CODED GENETIC ALGORITHM WITH NEW CROSS OVER TECHNIQUE

4.1. Introduction

Genetic algorithms are practical, robust optimization and search methods. Genetic algorithms were invented by Holland to mimic some of the processes of natural evolution and selection. These algorithms are different from most of the traditional optimization methods and these algorithms need design space to be converted into genetic space. A more striking difference between genetic algorithms and most of the traditional optimization methods is that GA uses a population of points at one time, in contrast to the single point approach by traditional optimization methods. The most interesting aspect of GA is that they do not require any prior knowledge of the function to be optimized and they exhibit very good performance on the majority of the problems applied.

The genetic algorithm repeatedly modifies a population of individual solutions. At each step, the genetic algorithm selects individuals at random from the current population to be parents and uses them to produce the children for the next generation. Over successive generations, the population evolves towards an optimal solution. The genetic algorithms can be used to solve a variety of optimization problems that are not well suited for standard optimization algorithms.

The basic structure of the genetic algorithm is given below:

Initial population: The GA operates on a population of consisting of a number of chromosomes simultaneously. The initial population of real numbered vectors is created randomly. Each of these vectors represents one possible solution to the search problem. Based on the size of search space the population size needs to be selected.

Fitness evaluation: Fitness evaluation is a procedure to determine the fitness of each string in the population. The fitness value is the only information available to the GA and the performance of the algorithm is highly sensitive to the fitness values. As the algorithm proceeds, we would expect to increase the individual fitness of the best chromosome as well as the total fitness of the population as a whole.

Termination criterion: After the calculation of fitness values of each chromosome the next step is to check the termination criterion. Termination criterion of the GA decides whether to continue searching or stop the search.

Reproduction: During the reproductive phase of the GA, good chromosomes (parents) in pairs are selected from the current generation's population for producing offspring and placing them in the next generation's population. Parents are selected randomly from the population using a scheme which favours the more fit individuals. Good individuals will probably be selected several times in a generation; poor ones may not be at all. This can be achieved by many different schemes, but the most common method is the roulette wheel selection. Roulette wheel with a pointer is shown in Figure 4.

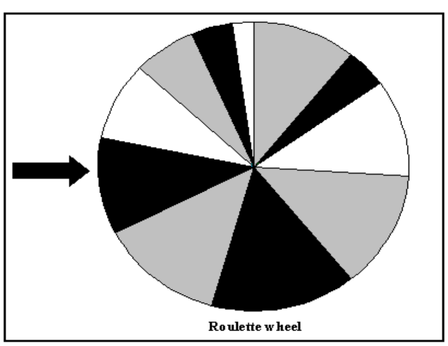

Figure 4. Roulette wheel with a pointer

Elitism: The copying of the best population in the current generation's population to the next generation's population is called "Elitism" as shown in Figure 5. The elitism can be implemented by arranging the population in the descending order according to their fitness value. The probability of elitism is P_e.

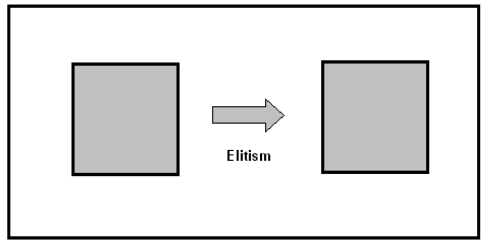

Figure 5. Elitism

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_c as shown in Figure 6. There are many types of crossover techniques available in the literature.

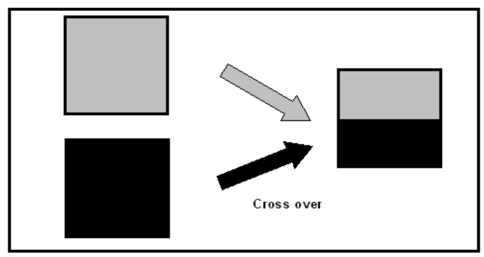

Figure 6. Crossover

Mutation: After crossover, some of the genes in the candidate offspring are modified with a small mutation probability P_m as shown in Figure 7. The mutation operator is included to prevent premature convergence by ensuring the population diversity.

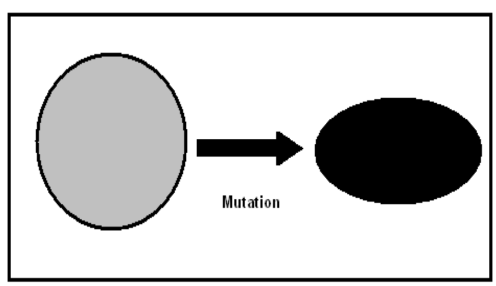

Figure 7. Mutation

4.2. Algorithm to find the capacitor sizes using RCGA

After identifying the *n* number of candidate locations using fuzzy approach, the capacitor sizes in all these *n* candidate locations are obtained by using the Real Coded Genetic Algorithm (RCGA). In this proposed method, the real number encoding has been used to determine the sizes of *n* number of capacitors in the *n* candidate locations.

Step 1: Initial population of [*nop* x *n*] number of real numbers is generated randomly within the limits, where *nop* is the initial population size and *n* is the number of capacitors. Each row represents one possible solution to the optimal capacitor-sizing problem. Iteration count is set to one.

Step 2: By placing all the *n* capacitors of each chromosome at the respective candidate locations and load flow analysis is performed using the branch current load flow method to find the total real power loss P_L. The same procedure is repeated for the *nop* number of chromosomes to find the total real power losses. Fitness value corresponding to each chromosome is evaluated.

Fitness value corresponding to each particle is evaluated using the equation (5) for maximum annual savings.

Fitness function for maximum savings (considering the capacitor cost) is given by

$$F_A = K_P.\ \Delta P + K_E.\ \Delta E - K_C.\ Q_C \qquad (5)$$

Where S is the savings in \$/year,
K_P is a factor to convert peak power losses to dollars,
K_E is a factor to convert energy losses to dollars,
K_C is the cost of capacitors in dollars,
ΔP is the reduction in peak power losses,
ΔE is the reduction in energy losses, and
Q_C is the size of the capacitor in kVAr.

The capacitor sizes corresponding to maximum savings are required. For any one chromosome, the negative F_A value indicates that savings are negative and F_A is fixed at F_A(minimum) and capacitor sizes corresponding to that chromosome are fixed at Q_C(minimum).

Step 3: The population is arranged in the descending order according to their fitness values. Maximum fitness and average fitness values are calculated.

$$\text{Error} = (\text{maximum fitness} - \text{average fitness}) \qquad (6)$$

Error is calculated using the equation (6). If this error is less than a specified tolerance then go to step 9.

Step 4: The best chromosomes are directly copied to the next generation population to perform the elitism with a probability of P_e.

Step 5: Parents are selected in pairs by using the roulette wheel selection technique based on their fitness values.

Step 6: Crossover is performed using the two crossover operators. These two crossover operators are the arithmetic crossover and the heuristic crossover. A random number *r* is generated between zero and one. If the random number *r* is less than 0.5 then arithmetic crossover operator is used to produce the offspring, otherwise heuristic crossover operator is used to produce the offspring.

Arithmetic crossover

Arithmetic crossover technique linearly combines two parent chromosomes to produce two new offspring. Two offspring are created according to the following equations.

$$\text{Offspring1} = a * \text{Parent1} + (1-a) * \text{Parent2} \qquad (7)$$

$$\text{Offspring2} = (1-a) * \text{Parent1} + a * \text{Parent2} \qquad (8)$$

Where ***a*** is a random number between zero and one, which is generated before each crossover operation.

Heuristic crossover

A new heuristic crossover operator is proposed based on the evolutionary direction provided by each parent, the fitness ratio of best chromosome and each parent, and the distance between the best chromosome and each parent. The crossover operator can improve the convergence speed of RCGA by using the heuristic information [11].

$h(i,j)_{new} = K_1 * h(i,j)_{old} + K_2 * K_3 * (Parent(1,j) - Parent(i,j))$ ------- (9)

Where $h(i,j)_{new}$ is the latest value of heuristic crossover operator of j^{th} gene of i^{th} parent
$h(i,j)_{old}$ is the old value of heuristic crossover operator of j^{th} gene of i^{th} parent. Initially $h(i,j)_{old}$ is set to zero for all genes of all the chromosomes.
$h(i,j)_{new}$ must be within the limits of $(-h(i,j)^{max})$ and $h(i,j)^{max}$. Where $h(i,j)^{max}$ is the maximum allowable step size.

$$-h(i,j)^{max} \geq h(i,j)_{new} \leq h(i,j)^{max} \quad (10)$$

$$K_1 = \{K_1^{max} - [(K_1^{max} - K_1^{min}) * t / T]\} \quad (11)$$

K_1 is the adjustable coefficient between K_1^{max} and K_1^{min}
t is the current iteration (generation) number
T is the maximum number of iterations
K_2 is the random number between zero and two
K_3 is the ratio of best fitness and fitness of i^{th} parent
Parent(1,j) is the j^{th} gene in the best chromosome
Parent(i,j) is j^{th} gene of i^{th} parent

$$Offspring(i,j) = Parent(i,j) + h(i,j)_{new} \quad (12)$$

Each gene of offspring is produced from each gene of parent using the equation (12).

Step 7: The iteration count is incremented and whether this iteration count is greater than iteration maximum or not is checked. If it is greater than iteration count then go to step 9.

Step 8: After performing the elitism and crossover operators, the new population is generated from the old population. In this present work mutation operator is eliminated. Go to step 2 to repeat the same procedure.

Step 9: Stop the procedure and print the results.

5. RESULTS

Fuzzy approach is used to find the optimal capacitor locations and RCGA is used to find the optimal capacitor sizes for maximum annual savings. Convergence criterion of RCGA is error must be less than 0.000000001 dollars.

The data shown below is used for finding the optimal capacitor sizes:
nop = 30, T = 1000, $K_1^{max} = 0.66$ and $K_1^{min} = 0.3$

5.1. Results Of 15-Bus System

The proposed algorithm is applied to 15-bus system [12]. Optimal capacitor locations are identified based on the C.S.I. values. For this 15-bus system, five optimal locations are identified. Capacitor sizes in the five optimal locations, total real power losses before and after compensation are shown in Table 2.

Table 2. Results of 15-bus system

Bus No.	Capacitor size in kVAr
4	274
6	193
7	143
11	267
15	143
Total kVAr	1020
Total power loss in kW (before)	61.7944
Total power loss in kW (after)	30.5522
Savings in dollars	$ 16,007.2322

5.2. Results Of 34-Bus System

The proposed algorithm is applied to 34-bus system [7]. Optimal capacitor locations are identified based on the C.S.I. values. For this 34-bus system, seven optimal locations are identified. Capacitor sizes in the seven optimal locations, total real power losses before and after compensation are shown in Table 3.

Table 3. Results for 34-bus system

Bus No.	Capacitor size in kVAr
20	683
21	145
22	144
23	143
24	143
25	143
26	228
Total kVAr	1629
Total power loss in	221.7235

kW (before)	
Total power loss in kW (after)	168.9548
Savings in dollars	$ 27,505.5511

5.3. Results Of 69-Bus System

The proposed algorithm is applied to 69-bus system [4]. Optimal capacitor locations are identified based on the C.S.I. values. For this 69-bus system, two optimal locations are identified. Capacitor sizes in the two optimal locations, total real power losses before and after compensation are shown in Table 4.

Table 4. Results for 69-bus system

Bus No.	Capacitor size in kVAr
61	1029
64	207
Total kVAr	1236
Total power loss in kW (before)	225.0044
Total power loss in kW (after)	152.0541
Savings in dollars	$ 43,105.2581

The results show that $16,007 annual savings for 15-bus system, $27,505 for 34-bus system and $43,105 for 69-bus system is possible as shown in Tables 2, 3 and 4 respectively and bus voltages are also improved substantially.

6. CONCLUSIONS

In this paper, a two-stage methodology of finding the optimal locations and sizes of shunt capacitors for reactive power compensation of radial distribution systems is presented. Fuzzy approach is proposed to find the optimal capacitor locations and RCGA method is proposed to find the optimal capacitor sizes. Based on the simulation results, the following conclusions are drawn:

By installing shunt capacitors at all the potential locations, the total real power loss of the system has been reduced significantly and bus voltages are improved substantially. The proposed fuzzy approach is capable of determining the optimal capacitor locations based on the C.S.I. values. The proposed RCGA method iteratively searches the optimal capacitor sizes effectively for the maximum annual savings.

REFERENCES

[1]. Duran H., “Optimum number, location and size of shunt capacitors in radial distribution feeders: A dynamic programming approach”, *IEEE Transactions on Power Apparatus and Systems*, vol. - 87, no. 9, pp. 1769-1774, September 1968.

[2] Bae Y.G., “Analytical method of capacitor allocation on distribution primary feeders”, *IEEE Transactions on Power Apparatus and Systems*, vol. PAS- 97, no. 4, pp. 1232-1238, July 1978.

[3] Grainger J.J and S.H. Lee, “Optimum size and location of shunt capacitors for reduction of losses on distribution feeders” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS- 100, no. 3, pp. 1105-1118, March 1981.

[4] Baran M.E. and Wu F.F., “Optimal capacitor placement on radial distribution systems”, *IEEE Transactions on Power Delivery*, vol.4, no-1, pp. 725-734, January 1989.

[5] Baran M.E. and Wu F.F., “Optimal sizing of capacitors placed on a radial distribution system”, *IEEE Transactions on Power Delivery*, vol.4, no-1, pp. 735-743, January 1989.

[6] Sundhararajan S. and Pahwa A., “Optimal selection of capacitors for radial distribution systems using a genetic algorithm”, *IEEE Transactions on Power Systems*, vo1.9, no.3, pp. 1499-1507, August 1994.

[7] Chis M., Salama M.M.A. and Jayaram S., “Capacitor placement in distribution systems using heuristic search strategies”, *IEE proceedings on Generation, Transmission and Distribution*, vol. 144, no.3, pp. 225-230, May 1997.

[8] Haque M.H., “Capacitor placement in radial distribution systems for loss reduction”, *IEE Proceedings on Generation, Transmission and Distribution*, vol. 146, no-5, pp 501-505, September 1999.

[9] Ng H.N., Salama M.M.A. and Chikhani A.Y., “Capacitor allocation by approximate reasoning: fuzzy capacitor placement”, *IEEE Transactions on Power Delivery*, vol. 15, no.1, pp 393 – 398, January 2000.

[10] Prakash K. and Sydulu M., “Particle swarm optimization based capacitor placement on radial distribution systems”, *IEEE Power*

Engineering Society general meeting 2007, pp. 1-5, June 2007.

[11] Jianwu Li and Yao Lu, "An efficient real-coded genetic algorithm for numerical optimization problems" *IEEE Third International Conference on Natural Computation ICNC-2007.*

[12] Das D., Kothari D.P. and Kalam A., "Simple and efficient method for load flow solution of radial distribution networks", *Electrical Power & Energy Systems*, vol. 17, no. 5, pp. 335-346,1995.