A FUZZY-GENETIC ALGORITHM FOR OPTIMAL CAPACITOR PLACEMENT IN RADIAL DISTRIBUTION SYSTEMS

P.V. Prasad[1], S. Sivanagaraju[2] and N.Sreenivasulu[3]
[1]Electrical and Electronics Engineering Department, Chaitanya Bharathi Institute of Technology, Hyderabad, India
[2]J.N.T.U.College of Engineering, Anantapur, India
[3]Vaagdevi Institute of Technology and Science, Proddututu, India
E-mail: pvp_reddy@yahoo.co.uk

ABSTRACT

Reduction of total losses 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. The proposed methodology is a fuzzy-genetic approach. The best location of the capacitor is determined using fuzzy set theory and the sizing of the capacitor is obtained based on genetic algorithm. The objective function is to place the optimal value of capacitors at best locations, which maximizes net savings in the distribution system. The proposed method is very powerful and directly gives the best locations and identifies the optimal size. The proposed method is tested on 15 node and 69 node radial distribution systems.

Keywords: capacitor placement, distribution system, fuzzy set theory, genetic algorithm.

1. INTRODUCTION

Capacitors are widely used in electric power distribution systems to achieve power and energy loss reduction and to maintain a voltage profile within permissible limits. The scope of these benefits depends on the location, size, type and number of capacitors. Many attempts have been made to solve the problem using nonlinear optimization techniques [1-5], heuristics [6,7] and the combinatorial optimization techniques such as simulated annealing [8]. Although all these methods to solve capacitor allocation problem have various merits, their efficacy relies entirely on the goodness of the data used.

At the present stage of research, load-flow on radial feeders is used to evaluate the fitness of arbitrary solutions. Optimum capacitor placement is achieved using sophisticated methods such as neural networks, fuzzy logic, and genetic algorithms (GA)[9-11]. Fuzzy set theory (FST) provides a remedy for any lack of uncertainty in the data. Furthermore fuzzy logic has the advantage of including heuristics and representing engineering judgments into the capacitor allocation optimization process.

Many of the previous strategies for capacitor allocation in the literature are also limited for the application to planning, expansion or operation of distribution systems. Very few of these capacitor allocation techniques have the flexibility of being applicable to more than one of the above problems. Hence, this paper presents a fuzzy-genetic approach to determine suitable locations for capacitor placement and the sizing of the capacitor. This approach has the versatility of being applied to the planning, expansion, and operation studies of distribution systems. The proposed method was tested on two distribution systems consisting of 15 node and 69 node distribution systems.

2. MATHEMATICAL FORMULATION

The proposed method identifies the best location using fuzzy set theory and determines the optimal size of the capacitors by maximizing the objective function which is stated as,

$$Max.\, S = KP + KF + KE - KC \qquad (1)$$

Where
S = Net savings ($)
KP = Benefits due to released demand (kW)
KF = Benefits due to released feeder capacity (kVA)
KE = Benefits due to saving in energy (kWh)
KC = Cost of installation of the capacitor ($)

(a) Benefits due to released demand

$$KP = \Delta KP \times CKP \times IKP \qquad (2)$$

Where
ΔKP = Reduced demand (kW)
CKP = Cost of generation (taken as $200/kW)
IKP = Annual rate for generation cost (taken as 0.2)

(b) Benefits due to released feeder capacity

$$KF = \Delta KF \times CKF \times IKF \qquad (3)$$

Where
ΔKF = Released feeder capacity
CKF = Cost of the feeder (taken as $ 3.43/kVA)
IKF = Annual rate of cost of feeder (taken as 0.2)

(c) Benefits due to savings in energy

$$KE = \Delta KE \times \mathrm{r} \qquad (4)$$

Where
ΔKE = Savings in energy
= (Annual energy losses before installing the capacitor)-(Annual energy losses after installing capacitor)
r = Rate of energy (taken as $ 0.06/kWh).

(d) Cost of installation of capacitor

$$KC = Q_c \times ICKC \times IKC \qquad (5)$$

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Where
Q_C = Total kVAR
ICKC = Cost of capacitor (taken as $ 4 /kVAR)
IKC = Annual rate of cost of capacitor (taken as 0.2)

2.1 Fuzzy based capacitor location

Node voltages and power loss indices are the inputs to the fuzzy expert system to determine the suitability of a node in the capacitor placement problem. The suitability of a node is chosen from the capacitor suitability index (CSI) at each node. The higher values of CSI are chosen as best locations for capacitor placement.

To determine the power loss indices, calculate the power loss reduction by compensating the self-reactive power at each node at a time by conducting the vector based distribution load flow method [13]. These loss reductions are then linearly normalized into a (0, 1) range with the largest loss reduction having a value of '1' and the smallest loss reduction having a value of '0' for calculation of power loss indices (PLI). The fuzzy framework consists of the use of numerical procedures that are coupled to the FES (Fuzzy Expert System) to solve the optimal capacitor location problem. The FES contains a set of rules, which are developed from qualitative descriptions. In a conventional Expert System a rule is either fired or not fired, where as in FES rules may be fired with some degree using fuzzy inferencing system. For the capacitor placement, rules are fired with some degree of membership to determine the suitability of a node.

The power loss indices are calculated as

$$PLI(i) = \frac{(X(i)-Y)}{(Z-Y)} \quad \text{for } i = 2,3\ldots nn. \tag{6}$$

Where
X = Loss reduction
Y = Minimum reduction
Z = Maximum reduction
nn = Number of nodes

Fuzzy variables PLI, voltage in p.u. and CSI are described by fuzzy terms low, low-medium, medium, high-medium and high. The fuzzy variables described above are represented by membership functions as shown in Tables 1 and 2.

Table-1. Power loss indices and voltage membership functions.

Description of the variables	Low	Low - Medium	Medium	High-Medium	High
Power loss indices	< 0.25	0-0.5	0.25-0.75	0.5-1	> 0.75
Voltage	< 0.94	0.92-0.98	0.96-1.04	1.02-1.08	1.06-1.1

Table-2. Capacitor suitability index membership function.

Description of the variables	Low	Low – Medium	Medium	High-Medium	High
CSI	< 0.25	0-0.5	0.25-0.75	0.5-1	≥ 0.75

To determine the location of capacitor the voltage and power loss index at each node shall be calculated and are represented in fuzzy membership function. By using these voltages and PLI, rules are framed and are summarized in the fuzzy decision matrix as given in Table-3.

Table-3. Decision matrix for determining suitable capacitor locations.

And		**Voltage (p.u)**				
		Low	**Low-Medium**	**Medium**	**High-Medium**	**High**
PLI	**Low**	Low	Low	Low	Low-Medium	Low-Medium
	Low-Medium	Low	Low	Low-Medium	Low-Medium	Medium
	Medium	Low	Low	Low-Medium	Medium	High-Medium
	High-Medium	Low	Low-Medium	Medium	High-Medium	High-Medium
	High	Low-Medium	Low-Medium	Medium	High- Medium	High

2.1.1 Fuzzy Inferencing and De-fuzzification Techniques

After the FES receives inputs from the load flow program, several rules may fire with some degree of membership. The MAX-MIN METHOD involves truncating the consequent membership function of each fired rule at the minimum membership value of all the antecedents. A final aggregated membership function is achieved by taking the union of all the truncated consequent membership functions of the fired rules. For the capacitor location problem, resulting capacitor placement suitability membership function, μ_S, of node i for k fired rules is

$$\mu_S (i) = \max_k [\min [\mu_p (i), \mu_v (i)]] \quad (7)$$

Where μ_p and μ_v are the membership functions of the power loss index and voltage respectively. Once the suitability membership function of a node is calculated, it must be defuzzified in order to determine the node suitability ranking. The centroid method of defuzzification is used; this finds the center of area of the membership function. Thus, the capacitor suitability index is determined by

$$S = \int \frac{\{\mu_s(z) \times z\, dz\}}{(\mu_s(z)\, dz)} \quad (8)$$

Where
μ_s (z) is the membership function
Z is the height of the membership function

2.2 Algorithm for candidate node identification

Following algorithm explains the methodology to identify candidate nodes, which are more suitable for capacitor placement.

1. Read line and load data of radial distribution system.
2. Determine total active power loss of base case system by conducting load flow.
3. By compensating the self-reactive power at each node and conduct the load flows to determine the total active power losses in each case.
4. Calculate the power loss reduction and power loss indices.
5. The PLI and the per-unit node voltages are the inputs to the fuzzy expert system.
6. The outputs of FES are defuzzified. This gives the ranking of CSI. The nodes having the highest value of CSI are the most suitable for capacitor placement.
7. Stop.

2.3 Implementation of GA based capacitor sizing

In this section, the capacitor-sizing problem is implemented using GA. GA is applied to calculate the optimum values of capacitors required to be placed at locations using FES on a radial distribution system, so as to maximize the objective function, while keeping the voltages at nodes within limits. The candidate nodes for the placement of capacitors are found in section 2.1

The simulation considers each string as a list of numbers varying from 0 to 3. Each digit represents the number of capacitor banks at a node. The number of digits in a string depends on the number of candidate nodes selected. Each digit is weighed by the size of the capacitor and it depends on reactive power compensation. Binary coding of the string is not implemented because of the large size of the search space for which the execution time is very high. So, integer representation is employed to represent capacitor size. During mutation one of the digits is replaced by another digit, which is randomly generated from the list (0,1,2,3).

Evaluation of fitness function

The fitness function should be capable of reflecting the objective and directing the search towards optimal solution. For each population or string size, the calculated capacitors are placed at the candidate nodes and the load flow method [13] is conducted and the losses, net savings are calculated and these net savings become the fitness function of the GA (as savings are maximized).

Genetic operations

In the proposed algorithm, roulette-wheel selection method is employed. In this method, the diversity of population can be maintained and the best individuals can survive in new generation. Cross over and mutation has done on the best fitness individuals. After all the genetic operations are performed, then chromosomes are selected for new generation.

Terminating rule

The process of generating new trials with the best fitness will be continued based on the difference between best fitness and average fitness is less than specified error.

2.4 Algorithm for GA based capacitor sizing

The GA based capacitor sizing algorithm is given below:

1. Generate the random population at candidate nodes for size(s) of capacitors for Gen = 1.
2. Perform load flows to determine various node voltages, active power losses.
3. Determine the fitness function values.
4. Select parent strings by roulette wheel selection process.
5. Perform crossover and mutation on the selection strings and obtain new strings for next generation.
6. Repeat steps 2 to 5 until the difference between best fitness and average fitness is less than specified error.
7. Stop.

3. RESULTS AND ANALYSIS

The proposed method is illustrated with two different test systems, consisting of 15-node and 69-node systems. The location for placement of capacitors is determined by fuzzy set theory and the capacitor sizes are evaluated using GA.

VOL. 2, NO. 3, JUNE 2007 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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3.1 Example 1

The proposed algorithm is tested on 15-node radial distribution system [14]. The GA control parameters selected are population size (ps) 20, cross over probability (p_c) 0.5, and mutation probability (p_m) 0.01.The total active power losses and minimum voltage before and after compensation is given in Table-4. From results it was observed that active power losses are reduced from 61.9547 to 30.4411 kW i.e., 50.864% losses reduction and minimum voltage is improved from 0.9424 to 0.9677 p.u due to reactive power compensation.

Table-4. Test results of 15-node system before and after compensation.

Capacitor (kvar)	**Total losses (kW)**		**Min.voltage (p.u)**	
	Before compensation	After compensation	Before compensation	After compensation
$Q_{C\,4)}$ = 200 **$Q_{C\,(6)}$ = 100** **$Q_{C\,(7)}$ = 300** **$Q_{C(11)}$ = 300** **$Q_{C(15)}$ = 200**	61.9547	30.4411	0.9424	0.9677

3.2 Example 2

The proposed algorithm is also tested on 69-node radial distribution system [2]. The test results are given in Table.5. The GA control parameters selected are population size (ps) 20,cross over probability (p_c) 0.8, and mutation probability (p_m) 0.01. From the results it was observed that active power losses are reduced from 225.0238 to 152.7234 kW i.e., 32.14% losses reduction and minimum voltage is improved from 0.9092 to 0.9288 p.u due to reactive power compensation.

Table-5. Test results of 69-node system before and after compensation.

Total kVAR	**Description**	**Before compensation**	**After compensation**
1200	Total losses (kW)	225.0238	152.7234
	Min.voltage (p.u)	0.9092	0.9288

The summary of results by placing capacitor for 15 and 69-node systems are given in Table-6. It is found that losses are reduced and an improved voltage profile is obtained.

Table-6. Summary of test results of different systems before and after compensation.

Description	**15-Node system**		**69-Node system**	
	Before compensation	**After compensation**	**Before compensation**	**After compensation**
QC required (kVAR)	1100	---	1200	---
Released reactive power (kVAR)	--	1111.7	-----	1231.4
Min.voltage (p.u)	0.9424	0.9677	0.9092	0.9288
Total losses (kW)	61.9547	30.4411	225.0238	152.723
Loss reduction (%)	---	50.86	---	32.14
Released demand (kW)	---	11.7486	---	72.5604
Released feeder capacity (kVA)	---	536.0572	---	649.8138
Net savings ($)	---	1.6521X104	---	4.0389X104

4. CONCLUSIONS

This paper has presented a novel method to determine suitable candidate nodes in distribution systems for capacitor installation using fuzzy approach and capacitor-sizing problem for loss minimization using GA method. The proposed method has tested with several systems. Compared to conventional methods, the FES considers loss reduction and voltage profile simultaneously when deciding which nodes are the most suitable for capacitor placement.

Genetic control parameters (i.e., p_m, p_c and population size) play an important role in the performance of genetic algorithm and some permutations and combinations of these parameters are to be tested to get the best performance. But the results indicate that genetic algorithm can provide approximate global optimum solution. This method does not require any training of data and will never have convergence problems.

A new convergence criterion based on the difference between best fitness and average fitness has also been proposed. The convergence criteria can provide not only sufficient reduction in CPU time but also acceptable accuracy in overall results.

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