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Loss Reduction in Electrical Distribution Systems using Artificial Intelligence

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Abstract

In this paper, the artificial intelligence tools are used in identifying the optimal locations and sizes of shunt capacitors to be placed in radial distribution system for loss reduction. The overall economy considers the saving due to energy loss minimization and the cost of capacitors. Capacitor banks are added on radial distribution system for power factor correction, loss reduction and voltage profile improvement. For this purpose, two-stage methodology is used in this paper. In first stage, the load flow of pre-compensated distribution system is carried out and the power loss reduction index (PLRI) is calculated. Fuzzy Logic identifies the candidate number of buses on the basis of load flow solution and PLRI. In the second stage, Genetic Algorithm is used to identify the size of the capacitors for minimizing the energy loss cost and capacitor cost. The developed algorithm is tested for 33-bus and IEEE 69-bus radial distribution systems at 12.66 kV medium voltage distribution systems.

Key words: *loss reduction, shunt capacitors placement and sizing, Fuzzy Logic, Genetic Algorithm.*

Introduction

The power loss in a distribution system is significantly high because of lower voltage and hence high current, compared to that in a high voltage transmission system. The pressure of improving the overall efficiency of power delivery has forced the power utilities to reduce the loss, especially at the distribution level. In this paper a radial distribution system is studied because of its simplicity. The same technique can be applied to other types of feeders. The loss can be reduced by adding shunt capacitors to supply a part of the reactive power demands. Shunt capacitors not only reduce the loss but also improve the voltage profile, power factor and stability of the system [1]. The active power demands at all nodes and losses must be supplied by the source at the root node, as distribution system is mainly radial. However, addition of shunt capacitors can generate the reactive power and therefore it is not necessary to supply all reactive power demands and losses by the source. Thus, there is a possibility to minimize the loss associated with the reactive power flow through the branches. In addition, shunt capacitors could also accommodate voltage regulation. For capacitor placement, general considerations are:

- The number and location
- Type (fixed or switched)
- The size

Fuzzy logic theory

Fuzzy Logic has been applied in various power system problems [2]. Fuzzy Logic rests on the fact that all things admit to certain degree of truth. Fuzzy Logic deals with ambiguities and the uncertainties of the system [3, 4]. Fuzzy Logic consists of a group of elements (fuzzy sets, membership functions, fuzzy inference systems and defuzzification).

Fuzzy Sets

Fuzzy Logic starts with the concept of a fuzzy set. A fuzzy set is a set without a crisp, clearly defined boundary. It can contain elements with only a partial degree of membership. The year seasons are used as example to illustrate the deference between the fuzzy sets and classical sets. A classical set is shown on the left in Fig. 1 (with sharp edge, wholly includes or wholly excludes) and the fuzzy set is shown on the right (with a partial degree of membership).

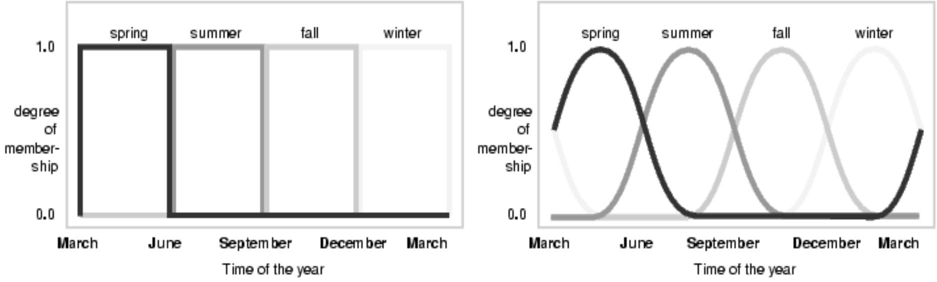

Fig. 1: A classical set & a fuzzy set

Membership Functions

A membership function (MF) is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1 [5].

The Shapes of Membership Functions

The only condition, a membership function must really satisfy is that it must vary between 0 and 1. The function itself can be an arbitrary curve whose shape can be defined as a function that suits from the point of view of simplicity, convenience, speed and efficiency. Different shapes of the membership functions can be proposed such as Triangular, Trapezoidal or Gaussian.

Fuzzy Inference Systems

Fuzzy inference is the process of formulating the mapping from a given input to an output using Fuzzy Logic. There are two types of fuzzy inference systems. Mamdani type and Sugeno type [6].

Mamdani-Type Inference

The Mamdani is based on the collection of fuzzy if-then rules. The advantage of this type is that the rule base is generally provided by an expert and hence to a certain degree it is transparent to interpretation and analysis. Because of its simplicity, the Mamdani model is the most widely used technique for solving many real world problems.

Sugeno-Type Inference

The second category of the fuzzy model is based on Takagi-Sugeno-Kang (TSK) method of reasoning. These types of models are formed by if-then rules that have a fuzzy antecedent part and functional consequent. It is generally implemented in two forms, depending upon the type of consequent. If the consequent is a linear function, then it is called a first order TSK model, and if consequent is simply a constant, then it is termed as a zero order TSK model. The main advantage of this approach is its computational efficiency.

Defuzzification Process

Defuzzification is a process of converting the output of the fuzzy rule from fuzzy to crisp values. This process depends on the output fuzzy set which is generated from the fired rules. The methods are commonly used is Centroid, Bisector, Smallest of Maximum, Middle of Maximum and Largest of Maximum.

A typical fuzzy rule based system is depicted in Fig. 2. The fuzzifier converts real numbers of inputs into fuzzy sets with number between zero and one indicating the actual degree of membership. The knowledge base includes a fuzzy rule-base and a database. Membership functions of the linguistic terms are contained in the database. The rule base consists of if-then rules, which represents the relationship between input and output variables.

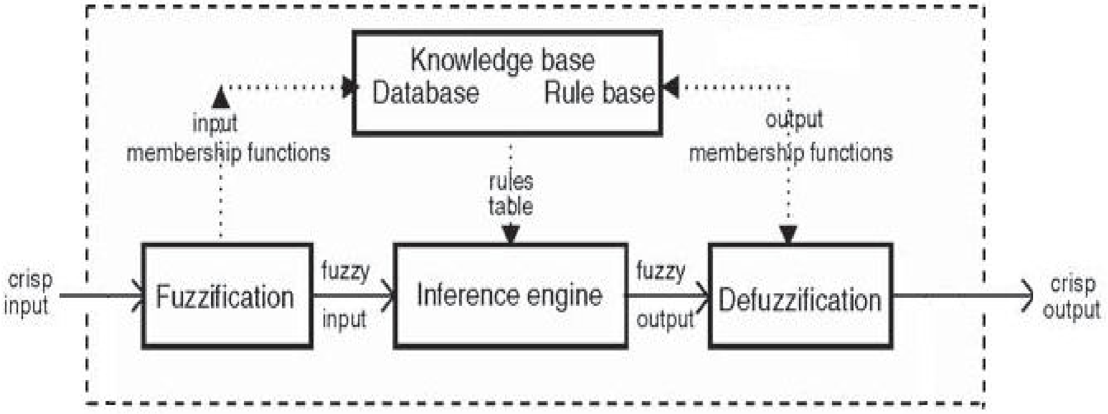

Fig. 2: Main elements of a fuzzy rule-based system

Genetic algorithm

Genetic Algorithm (GA) has been applied in various power system problems [7, 8]. GA is adaptive heuristic search algorithms based on the evolutionary ideas of natural selection and natural genetics [9, 10]. GA operates on a number of potential solutions called a population. Typically, a population is composed of between 30 and 100 individuals. GA uses a “Chromosomal” representation which requires the solution to be coded as a finite length string.

A simple genetic algorithm that yields good results in many practical problems is composed of three operators: selection, recombination and mutation.

Selection

Select two parent chromosomes from a population according to their fitness (the better fitness, the bigger chance to be selected). According to Darwin's theory of evolution the best ones survive to create new offspring. The fitness function measure the quality of the represented solution and it is always problem dependent. There are many methods in selecting the best chromosomes such as roulette wheel selection method, stochastic universal sampling.

Recombination (Crossover)

The basic operator for producing new chromosomes in the GA is that of crossover. Like its counterpart in nature, crossover produces new individuals that have some parts of both parent's genetic material. There are many methods to execute the crossover such as single-point crossover, multi-point crossover and uniform crossover.

Mutation

In natural evolution, mutation is a random process where an often part of chromosome is replaced by another to produce a new genetic structure. Mutation results in slight changes in the new solution structure and maintains diversity of solutions.

Parameters of GA

There are two basic parameters of GA, crossover probability and mutation probability.

Crossover Probability (P_c)

If crossover probability is 100%, then all offspring are made by crossover. If it is 0%, whole new generation is made from exact copies of chromosomes from old population. Typical values for P_c lie within the range of (0.6, 0.95)

Mutation Probability (P_m)

The typical values for P_m lie within the range of (0.001, 0.01). High mutation rates promote diversity among the population.
Steps in Basic Genetic Algorithm:

1. [Start] Generate random population of n chromosomes (suitable solutions for the problem).
2. [Fitness] Evaluate the fitness f(x) of each chromosome x in the population.
3. [New population] Create a new population by repeating following steps until the new population is complete.
   a. [Selection] Select two parents' chromosomes from a population according to their fitness.
   b. [Crossover] With a crossover probability cross over the parents to form new offspring (children).
   c. [Mutation] With a mutation probability mutate new offspring at each locus (position in chromosome).
   d. [Accepting] Place new offspring in the new population.
4. [Replace] Use new generated population for a further run of the algorithm.
5. [Test] If the end condition is satisfied, stop and return the best solution in current population.
6. [Loop] Go to step 2.

Fuzzy based capacitors locations

Firstly, the power loss reduction index (PLRI) and the voltage index (VI) are set to be the input variables of the Fuzzy Logic. The capacitors placement suitable index (CPSI) is the output variable of the Fuzzy Logic. The structure of Fuzzy Logic is shown in Fig. 3.

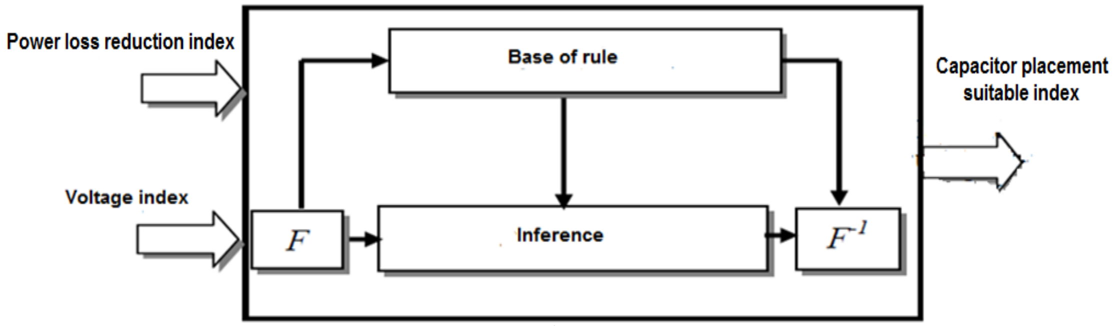

Fig. 3: Structure of Fuzzy Logic (where: F = fuzzification; F^{-1} = defuzzification)

To determine the candidate busses, the voltage index (VI) (output from the base case load flow) and power loss reduction index (PLRI) at each node will be calculated and are represented in fuzzy membership function. By using VI and PLRI, rules are framed and are summarized in the fuzzy decision matrix as given in Table 1. The linguistic variables are defined as {L, LM, M, HM, H} [11], where L means low, LM means low medium, HM means high medium and H means high. Five membership functions are used. The membership functions of the Fuzzy Logic are shown in Fig. 4, Fig. 5 and Fig. 6.

Mamdani type fuzzy inference will be used. According to Table (1) the rules are formulated as (if PLRI is L and VI is H, then CPSI is L).

Table 1: Fuzzy decision matrix

		VI				
CPSI		H	HM	M	LM	L
PLRI	L	L	L	LM	LM	M
	LM	L	LM	LM	M	HM
	M	LM	LM	M	HM	HM
	HM	LM	M	HM	HM	H
	H	M	HM	HM	H	H

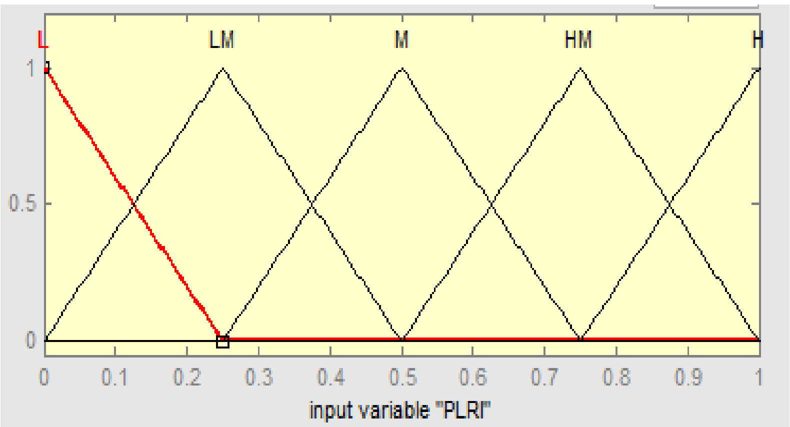

Fig. 4: Power loss reduction index membership functions

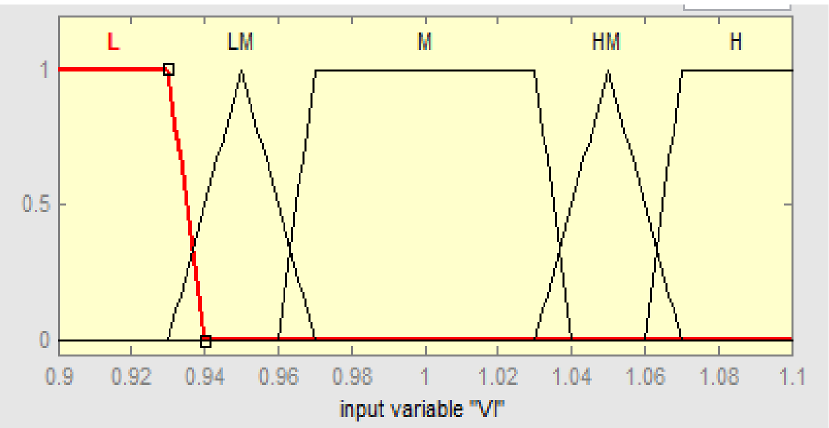

Fig. 5: Voltage index membership functions

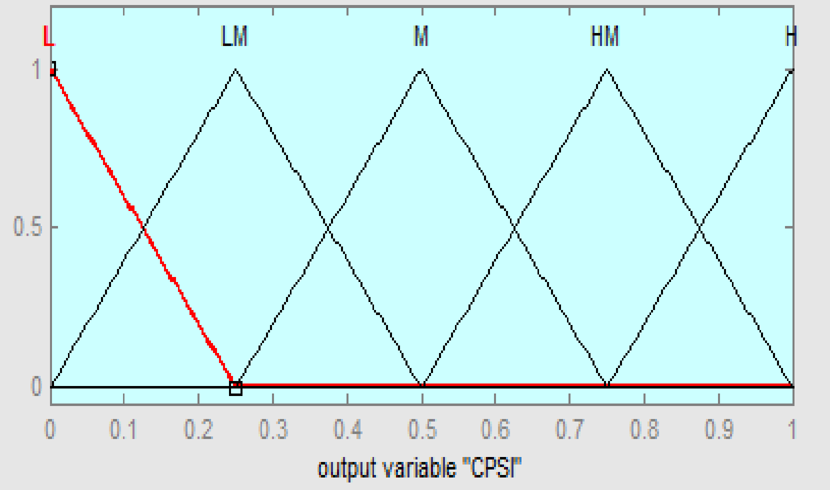

Fig. 6: Capacitor placement suitable index membership functions

Algorithm for candidate busses identification

The following algorithm presents the methodology to identify candidate busses, which are more suitable for capacitor placement.
Step 1: Read line and load data of power system.
Step 2: Calculate power flow by Newton Raphson method.
Step 3: Determine total active power loss and bus voltage magnitude.
Step 4: By compensation the self reactive power at each node and calculate the power flow to determinate the total active power losses in each case.
Step 5: Calculate the power loss reduction index (PLRI) as in (1):

$$PLRI\ (k) = \frac{loss\ reduction\ at\ bus\ (k) - minimum\ reduction}{maximum\ reduction - minimum\ reduction} \quad (1)$$

Where,
Loss reduction at bus (k) = base case loss – compensation loss
Step 6: PLRI and VI (VI is equal to per-unit voltage magnitude) are the inputs to the Fuzzy Logic.

Step 7: The outputs of Fuzzy Logic are deffuzzified (using Centroid Method). This gives the ranking of CPSI. The nodes having the highest value of CPSI are the most suitable for capacitor placement.

Step 8: Stop.

Genetic algorithm based capacitors sizing

After identifying the candidate buses, the sizing is determined using GA. An integer representation of the chromosome is used.

Initialization and Objective Function

Initialization is the generation of initial population. Here, the initial population is generated randomly which is the capacitors of different size (kVAR ratings) to be installed at the candidate buses. The string (individual) length is equal to the number of buses selected for the shunt capacitors.

After generating population of required size, the corresponding power flow solution was run for evaluating the objective function 'S' and the fitness function 'F' for each chromosome string as given in (2) and (3):

$$S = Ce \times \sum_{j=1}^{n} EL_j + \sum_{k=1}^{m} (Cci + Ccv \times Qc_k) \quad (2)$$

$$F = \frac{1}{1+s} \quad (3)$$

Where:

S is the cost function (objective function) for minimization.

Ce is the energy rate.

EL_j is energy loss (kW) in section-j in time duration T.

n is the number of sections.

Cci is the constant installation cost of capacitor (cost per location).

Ccv is the price of capacitor per kVAR.

Qc_k is the price of capacitor on bus-k in kVAR.

m is the number of capacitors.

The power flow solution and evaluation of objective function are repeated for all the strings in the population. The procedure to determine the fitness function 'F' is very much application oriented. It is directly associated with the objective function value in the optimization problem. In the capacitor placement problem the objective function is minimization of cost function.

The main constraint for capacitor placement is that all voltage magnitudes should be within the lower and upper limits after addition of capacitor on the feeder. Voltage constraints can be taken into account by specifying lower and upper bounds of the voltage magnitude (V) in per-unit as given in (4).

$$(V_{min})\ 0.94 \le V \le 1.05\ (V_{max}) \quad (4)$$

Results

The methodology of the capacitor design in distribution system is as following:

Step 1: Read the distribution system branch impedance values and the bus real and reactive power data.

Step 2: Run the power flow of distribution system to find out voltage magnitudes at the buses and total power loss.

Step 3: Select the candidate buses by using Fuzzy Logic.

Step 4: Set GEN = 0.

Step 5: Form initial population of integer numbers, which is randomly selected value of capacitors to be installed at the candidate buses for compensation.

Step 6: Update the reactive power at candidate buses.

Step 7: Run the power flow of distribution system with updated reactive power at the candidate buses for each population. Also calculate total power loss for each population.

Step 8: Calculate the total energy loss cost and capacitor cost for population.

Step 9: For each population, evaluate the objective function and the fitness value. The objective function for each population is the total energy loss cost plus the cost of capacitors.

Step 10: GEN = GEN + 1.

Step 11: Select the solutions in pool from initial population.

Step 12: Perform crossover on the solutions selected randomly and generate two offspring.

Step 13: Perform mutation on the offspring generated by the crossover operation.

Step 14: Check offspring satisfying the voltage constraints and calculate energy loss cost and capacitors cost. Also evaluate objective function and fitness function of each offspring.

Step 15: Combine the solutions of the pool and the offspring's and refer them as new population.

Step 16: Replace new population with initial population for next generation.

Step 17: Go to step 10, till reaching the maximum number of generations.

Step 18: Stop.

The proposed solution methodology has been implemented by MATLAB 7.7. The solution algorithms are based on Fuzzy Logic and GA, and tested on 33-bus and IEEE 69-bus radial systems that shown in Fig. 7 and Fig. 8 respectively.

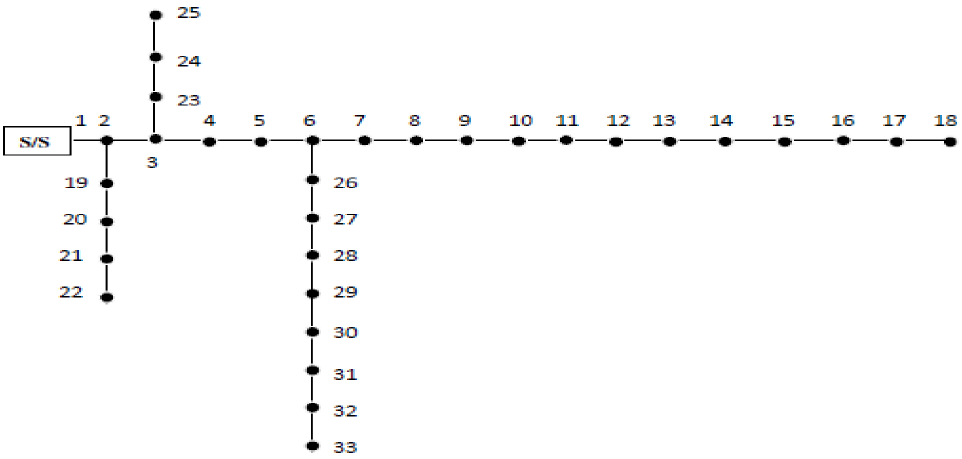

Fig. 7: 33-bus radial distribution system

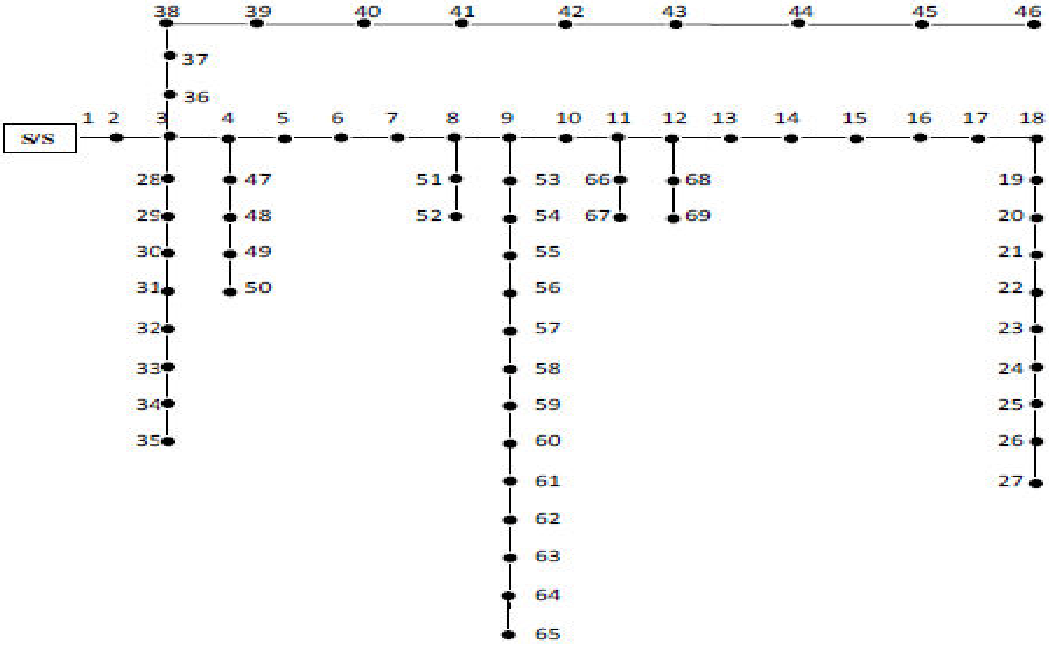

Fig. 8: IEEE 69-bus radial distribution system

Prior to capacitor installation, a power flow program is run to obtain the present system conditions. The second columns of Tables (2, 3) present system conditions. In detail, the minimum per-unit bus voltage at full load, maximum per-unit bus voltage at no load, real power losses in kW and the cost of energy losses, are presented. It is clear from the tables that the minimum bus voltages during the simulation are less than the pre-specified minimum allowable bus voltage. Therefore, capacitors shall be installed to provide the required voltage correction and to reduce the overall power losses in the system.

The capacitor allowable range is between 100 kVAR and 3600 kVAR, and increased with discrete step of 50 kVAR [12]. The installed capacitors are assumed to be fixed type. The loads are assumed to be linear and constant. The parameters are defined as shown below:
Population size = 50
Mutation rate = 0.01
Crossover rate = 0.7
Maximum number of generations = 50
The parameters are set empirically by trial and error procedure. Parameters that have resulted in the best solution were chosen.
The costs are set as following:
Ce = 0.06 \$/kWh, Ccv = 3 \$/kVAR, Cci = 1000 \$/location [13].

After implementing the proposed solution methodology, the optimal solution for this work was obtained and the results were written in the third columns of Tables (2, 3). Fig. 7 and Fig. 8 show comparisons between voltage profiles before and after adding capacitors.

The results revealed that:

1. The distribution network is operated under the safe condition. The voltage magnitude is between its permissible limits at full load and no load operation.
2. The power loss is reduced by sufficient amount to insure economical and high efficient operation.

Table 2: System conditions without and with capacitors for 33-bus system

Case	Without capacitors	With capacitors
Minimum bus voltage at full-load (per-unit)	0.904	0.943
Voltage regulation (%)	9.6	5.7
Improvement of voltage regulation (%)	-------	3.9
Maximum bus voltage at no-load (per-unit)	1	1.033
Real power loss (kW)	210	146
Size of capacitors in kVAR at optimal locations	------- ------- -------	600 kVAR at bus 15 450 kVAR at bus 30 450 kVAR at bus 32
Total reactive power placed (kVAR)	-------	1500
Reactive power required from source (kVAR)	2289	789
Savings due to reduction in power loss ($/year)	-------	33638.4
Total cost of the capacitors ($/year)	-------	7500
Net savings ($/Year)	-------	26138.4
Loss reduction %	-------	30.5 %

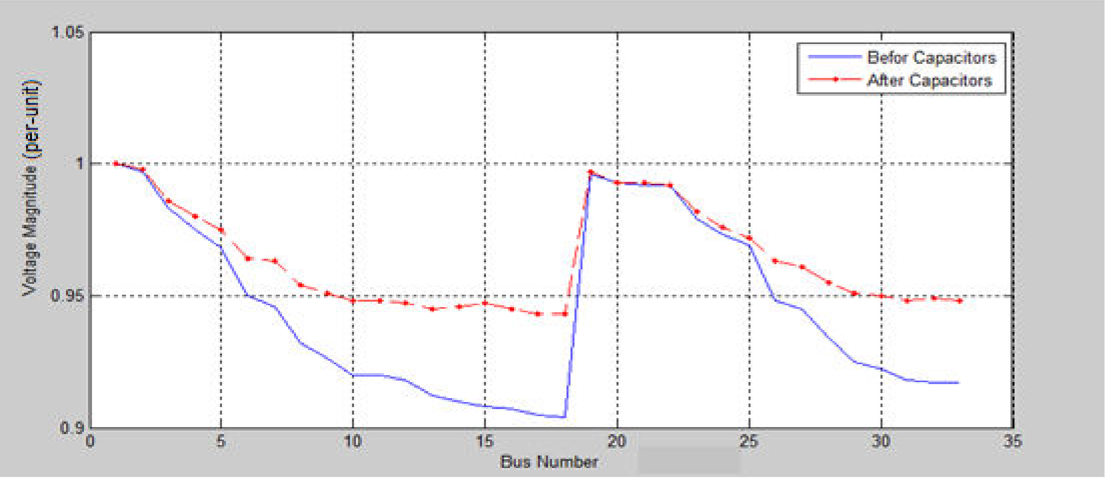

Fig. 7: Comparison of voltage profiles without and with capacitors for 33-bus system

Table 3: System conditions without and with capacitors for 69-bus system

Case	Without capacitors	With capacitors
Minimum bus voltage at full-load (p. u.)	0.909	0.94
Voltage regulation (%)	9.1	6
Improvement of voltage regulation (%)	--------	3.1
Maximum bus voltage at no-load	1	1.025
Real power loss (kW)	224	163
Size of capacitors in kVAR at optimal buses	------- ------- -------	600 kVAR at bus 59 750 kVAR at bus 61 600 kVAR at bus 64
Total reactive power (kVAR) placed	-------	1950
Reactive power (kVAR) required from source	2667	717
Savings due to reduction in power loss ($/year)	-------	32061.6
Total cost of the capacitors ($/year)	-------	8850
Net savings ($/Year)	-------	23211.6
Loss reduction %	-------	27.2 %

Conclusions

The simulation has been carried out to find the optimal locations and sizes (kVAR) of capacitors to be placed in pair of radial distribution systems. The problem has been solved by two-step methodology. Firstly the candidate locations for compensation have been found using Fuzzy Logic. Secondly the sizing has been determined using Genetic Algorithm. From the study, the following conclusions are deduced:

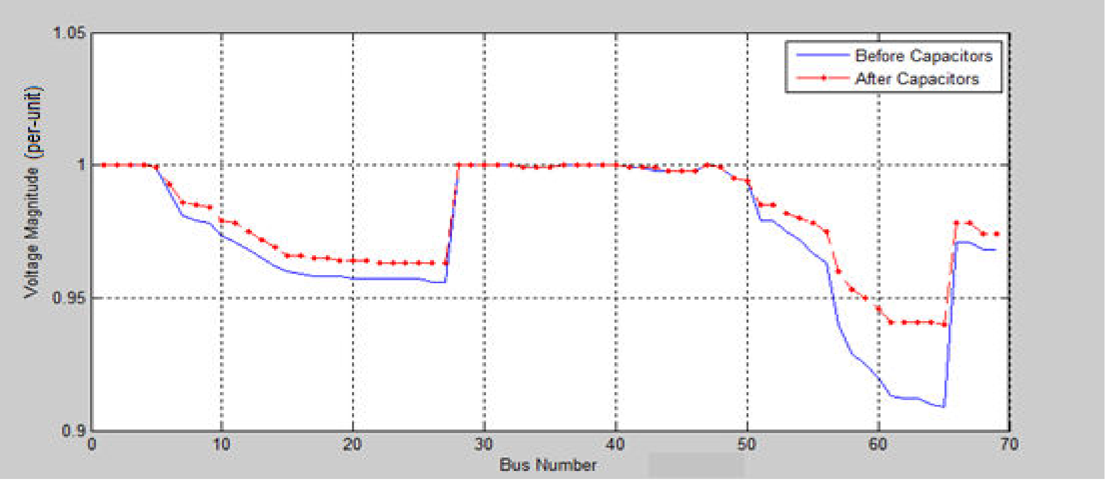

Fig. 8: Comparison of voltage profiles without and with capacitors for 69-bus system

- The compensation yields into increase in voltage profile and reduction in losses.
- The method developed in this paper is simpler and more effective than some methods, where it divides the complicated problem to two smaller sections (placements a section and sizing other one). Each section has independent procedure and this lead to obtain fasted solutions with high accuracy by lesser computational burden. There was not a need to use neither large population size nor large generation number in the Genetic Algorithm operation.

References

[1] Turan Gonen, "Electric Power Distribution System Engineering", California State University, Sacramento, 1986.
[2] Mohamed E. El-Hawary, "Electric Power Applications of Fuzzy Systems", Dalhousie University, 1998.
[3] Leonid Reznik, "Fuzzy Controllers," Victoria University of Technology, Melbourne, Australia, 1997.
[4] Andries, P. Engelbrecht, "Computational Intelligence", University of Pretoria, South Africa, 2002.
[5] www.mathworks.com/access/helpdesk/help/toolbox/fuzzy/fuzzyin3.html
[6] www.mathworks.com/access/helpdesk/help/toolbox/fuzzy/fuzzytn3.html
[7] A. Charette, J. Xu, A. Ba-Razzouk, P. Pillay, V. Rajagopalan," The Use of the Genetic Algorithm for in-situ Efficiency Measurement of an Induction Motor", IEEE Power Engineering Society Winter Meeting, 1(1), 2000, 392-397.
[8] Z.Y Dong, D.J.HILLAND, V.Y.MAKAROV, "Power System VAR Planning with Genetic Algorithm", Technical Report: EE-98015, Department Of Electrical Engineering, University of Sydney, Australia, 1998.
[9] J. H. Holland, "Adoption in Natural and Artificial Systems", Massachusetts, Cambridge, MIT Press, 1975.
[10] D. E. Goldberg, "Genetic Algorithm in Search Optimization and Machine Learning", Massachusetts, Addison-Wesley, 1989.
[11] M. Damodar Reddy and N. V. Vijaya Kumar, "Optimal Capacitor Placement for Loss Reduction in Distribution System using Fuzzy and Harmony Search Algorithm" ARPN Journal of Engineering and Applied Sciences, VOL. 7, NO. 1, January 2012
[12] T. A. Short, "Electric Power Distribution Equipment and Systems", Montana State University, 2006.
[13] Amritpal Singh, "Loss Minimization in High Voltage Distribution System by Capacitor Placement using Genetic Algorithm", M.Sc. thesis, Thapar University, Patiala, 2010.
[14] Ahmed M. Agwa, "New Control Methods of the Nonlinear and Time-Varying Systems," M.Sc. thesis, Department of Electrical Engineering, Faculty of Engineering Al-Azhar University, 2008.