Optimal Placement of capacitor in the Radial Distribution System using Multi Objective BA/CS Algorithm

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Abstract:

A distribution system is an interface between the bulk power system and the consumers. Among these systems, radial distribution systems are popular because of low cost and simple design. In distribution systems, the voltages at buses reduces when moved away from the substation, also the losses are high. The reason for decrease in voltage and high losses is the insufficient amount of reactive power, which can be provided by the shunt capacitors. In this paper, two new algorithms are proposed to determine the optimal sizes of fixed capacitors together with their optimal locations in a radial distribution system so that total real power loss is minimized, net savings is maximized and voltage profile improvement is achieved. The two new algorithms Bat Algorithm (BA) and Cuckoo Search (CS): search for all possible locations in the system along with the different sizes of capacitors, in which the optimal sizes of capacitor are chosen to be standard sizes that are available in the market. To check the feasibility, the proposed algorithms are applied on standard 34 and 85 bus radial distribution systems. And the results are compared with results of other methods like artificial bee colony (ABC) and Direct search algorithm which are available in the literature. The proposed approaches are capable of producing high-quality solutions with good performance of convergence. The entire simulation is developed in MATLAB R2010a software.

INTRODUCTION

1.1 Electrical Power System

Electrical power is transmitted by high voltage transmission lines from sending end substation to receiving end substation. At the receiving end substation the voltage is stepped down to a lower value (say 66kV or 33kV or 11kV). The secondary transmission system transfer power from this receiving end substation to secondary substation. A secondary substation consists of two or more step down power transformers together with voltage regulating equipments, buses and switchgear. At the secondary substation voltage is stepped down to 11kV. The portion of the power network between a secondary substation and consumers is known as distribution system. The distribution system can be classified into primary and secondary system. Some large consumers are given high voltage supply from the receiving end substations or secondary substation.

The area served by a secondary substation can be subdivided into a number of sub- areas. Each sub area has its primary and secondary distribution system. The primary distribution system consists of main feeders and laterals. The main feeder runs from the low voltage bus of the secondary substation and acts as the main source of supply to sub- feeders, laterals or direct connected distribution transformers. The lateral is supplied by the main feeder and extends through the load area with connection to distribution transformers. The distribution transformers are located at convenient places in the load area. They may be located in specially constructed enclosures or may be pole mounted. The distribution transformers for a large multi storied building may be located within the building itself. At the distribution transformer the voltage is stepped down to 400V and power is fed into the secondary distribution systems. The secondary distribution system consists of distributors which are laid along the road sides. The service connections to consumers are tapped off from the distributors. The main feeders, laterals and distributors may consist of overhead lines or cables or both. The distributors are 3 phase, 4 wire circuits, the neutral wire being necessary to supply the single phase loads. Most of the residential and commercial consumers are given single phase supply. Some large residential and commercial consumers get 3 phase supply. The service connections of consumers are known as service mains. The consumer receives power from the distribution system. The main part of distribution system includes:

1. Receiving substation
2. Sub- transmission lines
3. Distribution substation located nearer to the load centre
4. Secondary circuits on the LV side of the distribution transformer.
5. Service mains

Unlike main EHV-AC transmission systems, the distribution systems have several service lines, several distribution transformers and associated primary and secondary circuitry and one or two receiving substations. Unlike transmission systems distribution systems are more complicated and have to face more problems like voltage drop during peak load time and voltage rise during off peak load. In addition to above problems distribution transformer is overloaded during most period.

1.2 Distribution System

The part of power system which distributes electric power for local use is known as distribution system. In general, the distribution system is the electrical system between the substation fed by the transmission system and the consumer's meters.

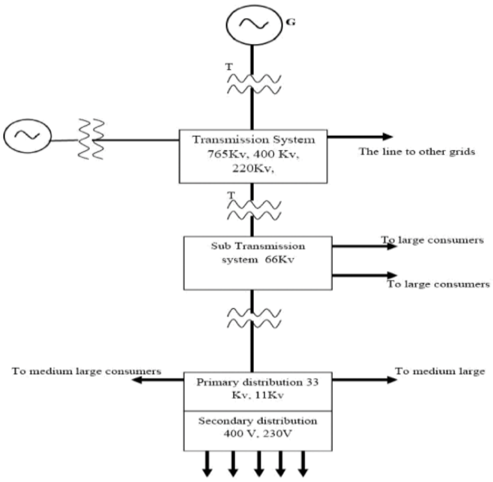

Figure 1.1 Single Line Power System Network

It generally consists of feeders, distributors and the service mains. Figure 1.2 shows the single line diagram of a typical low tension distribution system.

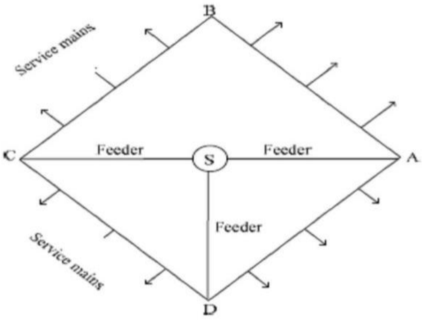

Figure 1.2 Single line diagram of a typical low-tension distribution system.

(i) Feeders: A feeder is a conductor, which connects the sub-station (or localized generating station) to the area where power is to be distributed. Generally, no tappings are taken from the feeder so that the current in it remains the same throughout. The main consideration in the design of a feeder is the current carrying capacity.

(ii) Distributor: A distributor is a conductor from which tapping's are taken for supply to the consumers. In Figure1.2, AB, BC, CD, and DA are the distributors. The current through a distributor is not constant because tapping are taken at various places along its length. While designing a distributor, voltage drop along its length is the main consideration since the statutory limit of voltage variations is ± 10% of rated value at the consumer's terminals.

(iii) Service mains: A service mains is generally a small cable which connects the distributor to the consumer terminals.

1.3 Shunt capacitors and their types

One of the simplest sources for providing the reactive power locally is shunt capacitors. In our study the shunt capacitors are used, so this type of capacitors will be discussed here. The application of capacitors to electric power systems can be used for the control of power flow, stability improvement, voltage profile management, power factor correction and power and energy loss reduction. Capacitors are simple devices, where the insulating dielectric is placed between two metal plates. The capacitor unit is considered as the basic building block of SCB (shunt capacitor bank). Capacitor units are connected in paralleled-series combinations and form a single-phase capacitor bank, within a steel enclosure. The series combination reduces the cost of dielectric while parallel combination increase the total capacitance of SCB. As a general rule, the minimum number of units connected in parallel is such that isolation of one capacitor unit in a group should not cause a voltage unbalance more than 110% of rated voltage on the remaining capacitors of the group. Equally, the minimum number of series connected groups is that in which the complete bypass of the group does not subject the others remaining in service to a permanent overvoltage of more than 110%. The amount of reactive power (Q_c) from capacitor depends on applied voltage (V) and capacitive reactance (X_c), given by Eq. (1).

$$Q_C=V^2/X_C \quad (1.1)$$

In our case, when the capacitors are used in AC systems the capacitors store the energy just only for one half cycle. During the first half cycle capacitor charges and in next half cycle discharges back to the system. In this way capacitors are providing the reactive power when it's needed and the capacitors and reactive power loads are exchanging the reactive power back and forth.

Prior to 1950s the shunt capacitor banks (SCB) were placed nearer to the main substation for capacitive reactive power compensation, it helps in improving the power factor, reduces power losses and improving the voltage profile. SCB changes the power losses up to the point of coupling, however to get the maximum benefits it must be placed as nearer to the load as possible. With the availability of pole mounted equipment including SCB, the trend has changed. The capacitor banks are now placed on primary distribution lines as well. So they can be installed in distribution systems or in substations on different voltage levels. Distribution capacitors can be pole mounted or pad mounted. Other configuration of distribution system capacitors can also exist. Example of pole mounted capacitor by ABB is taken from [15] and is shown on fig. 1.6. below:

Fig.1.6. Pole mounted capacitor from ABB. Image courtesy of ABB Power Capacitors

1.9 Literature Review

Numerous methods for solution to the optimal placement of capacitor with a view to minimizing losses have been suggested in the literature based on both traditional mathematical methods and more recent heuristic approaches. Schmill [2] presented a 2/3 rule for the placement of a single capacitor assuming both load and distribution feeder are uniform. Grainger and Lee [3] developed a nonlinear programming-based method in which capacitor location and capacity were expressed as continues variables. Prakash and Sydulu used PSO [4] approach for finding the optimal sizes of capacitors at fixed locations obtained from the loss sensitivity factors in radial distribution system to minimize power loss. A mixed integer non-linear programming (MINLP) [5] approach for the reconfiguration of capacitor allocation to minimize energy losses on radial electrical networks was proposed by Oliveira et al. Wu et al. developed loop analysis based method [6] to find the optimal size of capacitor to minimize the power loss in distribution systems for daily operation. Rao et al. [7] presented plant growth simulation algorithm (PGSA) for capacitor placement in radial distribution systems which determine the optimal locations and size of capacitor to improve the voltage profile and reduction of power losses.

Capacitors placement causes the investment cost, operating cost and power loss reduction reduces the total cost of power to be purchased leads to economic aspects like minimization of total annual cost, maximization of net savings per year, minimization of energy cost was done by some authors by considering above economic aspects as their objective functions. A multi-objective fuzzy based GA [8] for simultaneous minimization of energy cost and improvement of voltage profile was proposed by Das. Direct search algorithm (DSA) [9] to find the optimal sizes and locations of fixed and switched capacitors for constant & time varying load models in a radial distribution system to maximize the savings and minimize the power loss was presented by Raju et al. Sneha Sultana et al.[10] proposed TLBO algorithm for the optimal placement of fixed capacitor banks along with their locations with an objective function of minimizing power losses. Iman Ziari et al. [11] proposed Modified Discrete Particle Swarm Optimization (MPSO) for optimal allocation and sizing of capacitors and setting of LTC for minimizing line loss using estimation of the load duration curve to multiple levels. Attia A. EI_Fergancy ea al. [12] proposed artificial colony based approach (ABC) for net saving maximization and system stability enhancement in distribution networks where locations are determined by voltage stability indexes and loss sensitivity factors and sizing of capacitors by the algorithm. A comprehensive survey on the various heuristic optimization techniques applied to determine the optimal capacitor placement and size is presented in [13].

Implementation of Optimal Capacitor Problem Using Cuckoo Search Algorithm

3.1 Introduction

Optimal sitting and sizing of shunt capacitor banks at the distribution networks for the purpose of net savings maximization and real power loss minimization is drawing much attention to increase the efficiency of distribution system. In the chapter 2 different approaches for the optimal placement of capacitor are determined by various authors have been discussed briefly. In this chapter a meta-heuristic algorithm, Cuckoo Search Algorithm (CSA) has been attempted and applied to solve the optimum allocation of shunt capacitors problem on radial distribution systems. This optimal allocation of shunt capacitors problem requires

1. Selection of an appropriate number of capacitor units,

2. Allocation of capacitors i.e. finding optimal locations, and

3. Sizing of capacitors i.e. finding optimal sizes of capacitors at locations which are obtained in step 2 to achieve a required result. From the literature different methods for both finding the optimal locations and sizes of capacitors at these locations are tabulated in 4.1 shown below

Table 3.1 Methods for finding optimal locations and capacitor sizes

METHOD	LOCATIONS	CAPACITORS
METHOD 1	Optimal locations are obtained based by using Loss Sensitivity factors	Sizing of continuous size of capacitors at that locations by the algorithm
METHOD 2	Optimal locations are determined by the Algorithm	Determination of Optimal continuous size of capacitors at that locations by the Algorithm
METHOD 3	Optimal locations are determined by the algorithm	Determination of Optimal discrete size capacitors i.e. Shunt capacitor banks at that locations by the algorithm

3.2. Objective Function

Optimal capacitor placement in radial distribution system reduces the active power losses and improves the voltage profile. Reduction in power loss leads to the reduction in energy loss cost. However the capacitor placement increases the installation and investment cost. Therefore the objective of capacitor placement is to maximize the annual net saving by minimizing the total annual cost of system, subjected to specific operational constraints. Mathematically, the objective function

$$\text{Maximize } \{ Ke\,(P_{lb} - P_{la})T - \alpha\,[C_i N_c + Cp \textstyle\sum_{i=1}^{N_c} Q_c(i)] - C_0 N_c \}$$

of the problem is formulated as,

Where S is the annual net savings, P_{lb} & P_{la} are the active power loss before and after compensation respectively, K_e is the energy cost per KWh, α is the depreciation factor, T is the time period in hours, C_i is the installation cost of capacitor per location, N_c is the number of compensated buses where capacitors are to be placed, C_p is the purchase cost of capacitor per KVAR, C_0 is the capacitor operating cost per location and $Q_c(i)$ is the amount of reactive power of installed capacitor at bus i.

The objective function is subjected to following constraints:

- The voltage magnitude must kept within the specified limits at each bus:

$$V_{min} < V < V_{max} \qquad (3.2)$$

Where V_{min}, V_{max} are the lower and upper limits of bus voltage, respectively.

- From practical limitation, maximum compensation by using capacitor bank is limited to the total reactive power demand.

$$\sum_{i=1}^{N_c} Q_C(i) < \sum_{i=1}^{N_c} Q_D(j) \qquad (3.3)$$

Where N_l is the number of load buses and $Q_D(j)$ is the reactive power demand of load at bus j.

- Capacitors are available in discrete sizes so shunt capacitors to be dealt with multiple integers of the smallest capacitor size available and it may be mathematically expressed as

$$Q_C(i) < LQ_S \qquad (3.4)$$

Where, Q_S is the smallest capacitor size available and L is an integer multiple.

3.3 Cuckoo Search (CS)

A new meta-heuristic optimization algorithm, called Cuckoo Search (CS), was developed recently by Yang and Deb in [16]. For simplicity in describing our new Cuckoo Search (Yang and Deb 2009), we now use the following three idealized rules:

- Each cuckoo lays one egg at a time, and dumps it in a randomly chosen nest;
- The best nests with high quality of eggs (solutions) will carry over to the next generations;
- The number of available host nests is fixed, and a host can discover an alien egg with a probability $p \in [0, 1]$. In this case, the host bird can either throw the egg away or abandon the nest so as to build a completely new nest in a new location.

For simplicity, this last assumption can be approximated by a fraction p_a of the n nests being replaced by new nests (with new random solutions at new locations). For a maximization problem, the quality or fitness of a solution can simply be proportional to the objective function. Other forms of fitness can be defined in a similar way to the fitness functions in genetic algorithms.

Table 3.2 Parameter description and assigned values of CSA

Algorithm	Parameters	Description	Values
CSA	Pop	Population of host nests	150
	D	Dimension of a host nest	case dependent
	Pa	Fraction of worst nests (Probability)	0.25
	Maxitr	Maximum number of generations	150

3.5 Simulation results and discussions

The performance and effectiveness of the Cuckoo search algorithm have been tested on 34-bus and 85-bus radial distribution system for power loss minimization and maximization of net savings for all the methods tabulated in 3.1. The locations or buses for method-1 for the 34 bus and 85 bus test system are ordered according to their sensitivity value as {19, 22, 20 & 21} and {8, 58, 7 & 27} respectively given in [17]. The constants used in the calculation of net saving are given [18] in Table 3.3.The entire simulation is developed in MATLAB R2010a software and the simulations are carried on a computer with Intel(R) Core(TM) i5- 2450M CPU @2.50GHz, 4 GB RAM.

Table 3.3 Constants used in computation of net saving for the test cases

S NO.	Parameter description	Value
1	Average energy cost (K_e)	$0.06/kWh
2	Depreciation factor (α)	20%
3	Purchase cost (C_p)	$25/kVAR
4	Installation cost (C_i)	$1600/location
5	Operating cost (C_o)	$300/year/location
6	Hours per year (T)	8760

3.5.1 34-bus test system numerical results

The 34-bus test case consists of a main feeder and 4 sub-feeders (laterals) radial distribution system as shown in Fig. 3.2.The data of the system is obtained from [19]. The total load of the system is 4636.5 kW and 2873.5 kVAR. The rated voltage of the system is 11kV. After an initial load flow run using Backward/Forward Sweep method for an uncompensated system, the active power loss is 221.7235KW and maximum & minimum voltages are 1.0 p.u and 0.9417 p.u.

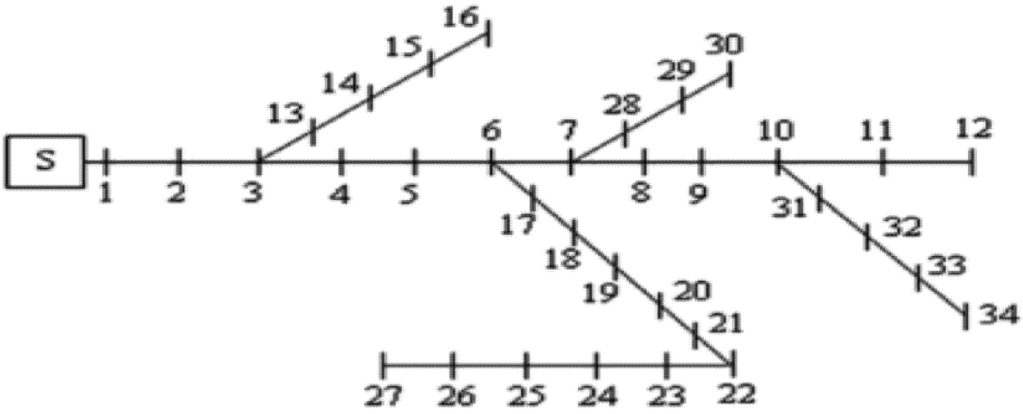

Figure 3.2 IEEE 33-bus radial distribution system

The number of capacitors placed in this case is restricted to three. The sizes of capacitors obtained by Cuckoo Search algorithm for method-1 at locations 19, 22 , 20 are 532.0386, 229.1535, 861.0993 KVAR respectively, with a active power loss of 170.8342 KW, minimum voltage is 0.9482 p.u and annual net savings of $16776. The locations and sizes of capacitors obtained by Cuckoo Search algorithm for method-2 are 9, 20, 25 and 767.0484, 834.5015, 648.4500 KVAR respectively, with a active power loss of 160.6199 KW, minimum voltage is 0.95 p.u and annual net savings of $ 19006. The locations and sizes of capacitors obtained by Cuckoo Search algorithm for method-3 are 9, 20, 25 and 750, 900, 600 kVAR respectively, with a active power loss of 160.6599 KW, minimum voltage is 0.95 p.u and annual net savings of $18985.02. Comparisons of various parameters of three methods are tabulated in 3.4 shown below.

Table 3.4 Comparison of parameters of Methods for 34-bus test case

Parameter/method	Method-1	Method-2	Method-3
Locations and sizes of capacitors in KVAR	19 532.0386 22 229.1535 20 861.0993	9 767.0484 20 834.5015 25 648.4500	9 750 20 900 25 600
Min voltage in p.u	0.9482	0.95	0.95

Active power loss(kW)	170.8342	160.6199	160.6599
Net savings per year	16776	19006	18985.02
Elapsed time(sec)	33.68	33.9666	34.16

By comparing method-1 with method-2 & method-3 the active power loss is high and net savings maximization are very low. So allocation of capacitors through method-1 has not given the optimal global solution. Solutions of method-2 and method-3 are almost same having difference in power loss of 0.4KW and net savings $21. But in method-2 placing capacitors of continues sizes is not practical, so rounding of capacitors to nearest available market sizes to be done may leads to change in the outcomes power loss, net savings per year. Convergence graphs and voltage profile graphs of all the methods are shown in Fig. 3.3

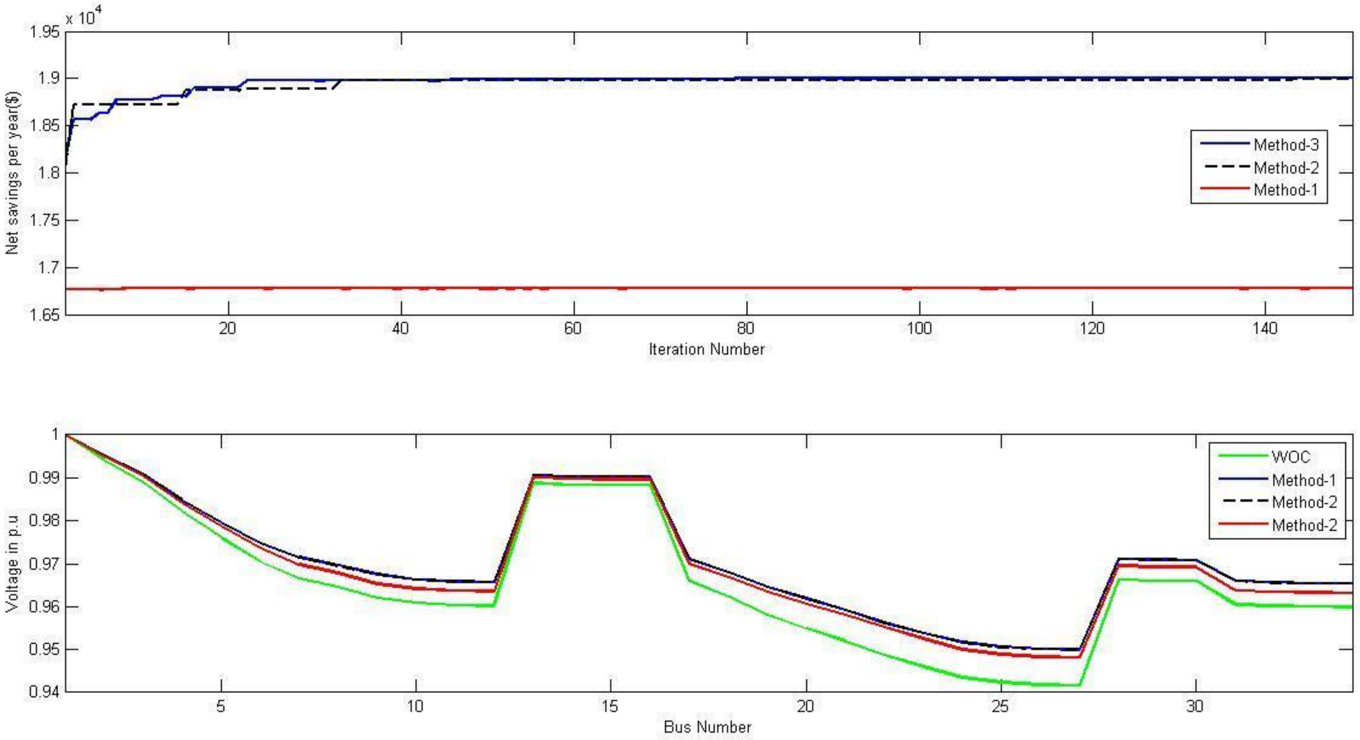

Fig. 3.3 Convergence graphs and voltage profile graphs for 34 bus system test case

3.5.2 85-bus test system numerical results

The 85-bus test case consists of a main feeder, 9 sub-feeders (laterals) and sub-laterals radial distribution system as shown in Fig. 3.4. The data of the system is obtained from [20]. The total load of the system is 2574.3 kW and 2622.6 kVAR. The rated voltage of the system is 11kV. After an initial load flow run using Backward/Forward Sweep method for an uncompensated system, the active power loss is 316.8497 kW and maximum & minimum voltages are 1.0 p.u and 0.8712 p.u.

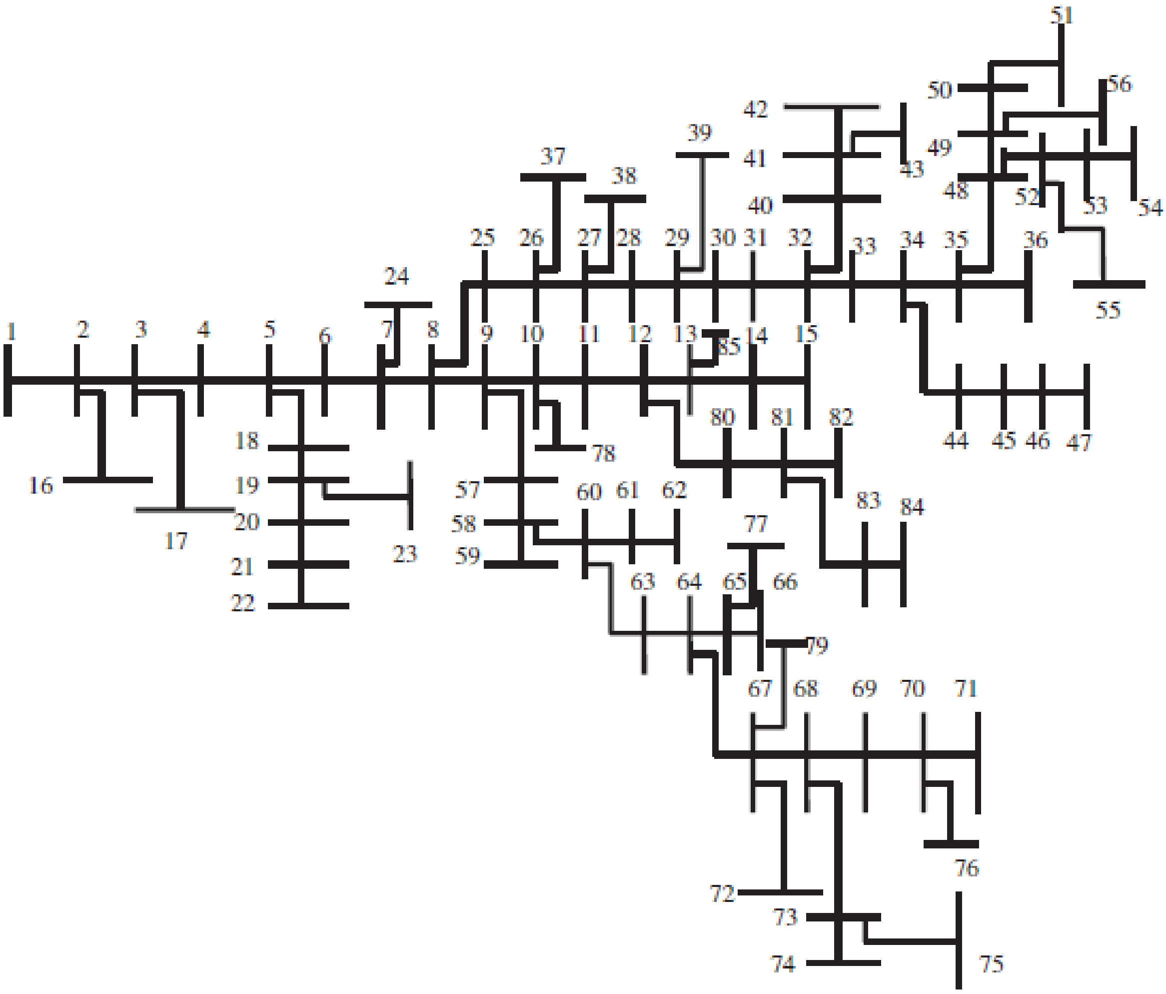

Figure 3.4 IEEE 85-bus radial distribution system

The sizes of capacitors obtained by Cuckoo Search algorithm for method-1 at locations 7, 8, 27, 58 are 150, 434, 885, 714 KVAR respectively, with a active power loss of 164.3820 KW, minimum voltage is 0.9122 p.u and annual net savings of $66742. The location and sizes of capacitors obtained by Cuckoo Search algorithm for method-2 are 8, 68 , 32 , 63, 12 , 44 , 48, 21 and 367, 356, 220, 313, 337,175, 347,134 KVAR respectively, with a active power loss of 145.7435 kW, minimum voltage is 0.9215 p.u and annual net savings of $73700. The location and sizes of capacitors obtained by Cuckoo Search algorithm for method-3 are 18, 27, 29, 42, 48, 60, 69, 80 and 150, 150, 300, 150, 300, 450, 300, 450 KVAR respectively, with a active power loss of 146.6237 kW, minimum voltage is 0.92 p.u and annual net savings of $73260. Comparisons of various parameters of three methods are tabulated in 3.5 shown below

Table 3.5 Comparison of parameters of Methods for 85-bus test case

Parameter/method	Method-1	Method-2	Method-3
Locations and sizes of capacitors in KVAR	7 150 8 434 27 885 58 714	8 367 68 356 32 220 63 313 12 337 44 175 48 347 21 134	18 150 27 150 29 300 42 150 48 300 60 450 69 300 80 450
Min voltage in p.u	0.9122	0.9215	0.92
Active power loss(kW)	164.3820	145.7435	146.6237
Net savings per year	66742	73700	73260
Elapsed time(sec)	180.94	199.321470	174.86

By comparing method-1 with method-2 & method-3 the active power loss is high and net savings maximization are very low. So allocation of capacitors through method-1 has not given the optimal global solution. Solutions of method-2 and method-3 are almost same having difference in power loss of 0.8802KW and net savings $440. But in method-2 placing capacitors of continues sizes is not practical, so rounding of capacitors to nearest available market sizes to be done may leads to change in the outcomes power loss, net savings per year. Convergence graphs and voltage profile graps of all the methods are shown in Fig. 3.5

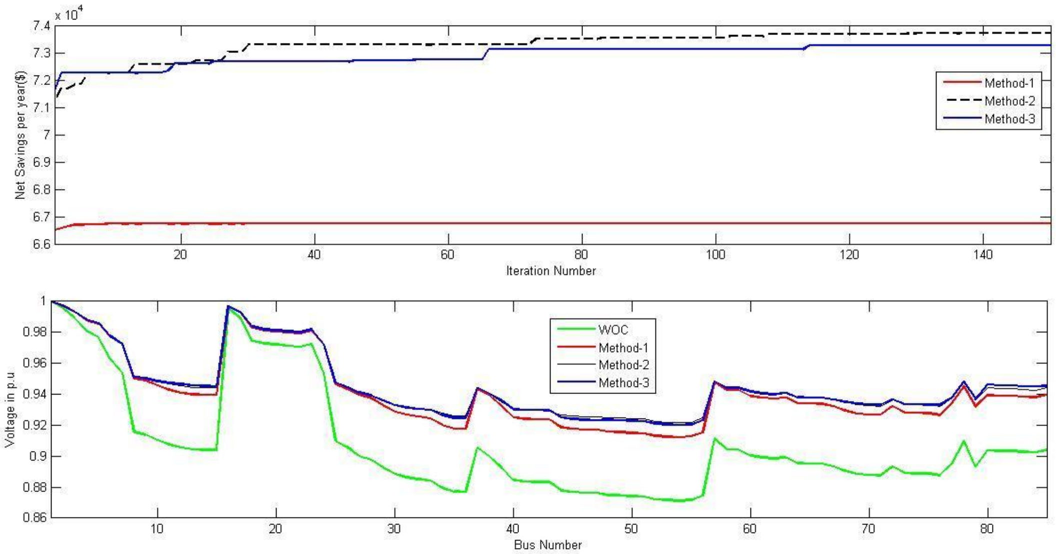

Fig. 3.5 Convergence graphs and voltage profile graphs for 85 bus system test case

Conclusion:

In this paper, application of Bat and CS algorithms to the optimal placement and sizing of capacitors in radial distribution systems has been discussed in two approaches. The practical application and efficiency of these approaches are evaluated using two test systems (34 and 85 bus). From the comparative analysis it is concluded that, CS algorithm gives better results than BAT and other methods, in terms of solution quality. Both CS and BAT generate solutions which satisfy all the constraints. According to convergence BAT converged very quickly due to simple evolution process. However, CS convergence is slower than BAT, the reason is rigorous evolution process in CS. In fact, for any optimization algorithm parameter tuning plays an important role in the performance of the algorithm. From the results; CS and BAT are proved to be promising tools to solve such type of constrained objective optimization problems. So, it may be concluded that the solution given by CS to the specific problem is best so far. Thus the results obtained pave the way for new and promising research area, utilizing CS and BAT algorithms with proper modifications, may give better results with high convergence speed.

References:

1) Ng HN, Salama MA, Chikhani AY. Classification of capacitor allocation techniques. IEEE Trans Power Deliv 2000; 15(1):387–92.

2) J.V.Schmill," optimum size and location of shunt capacitors on distribution feeders",IEEE Trans. On Power Apparatus and System.vol. 84, pp. 825-832, sep. 1965.

3) Grainger JJ, Lee SH. Optimum size and location of shunt capacitors for reduction of losses on distribution feeders. IEEE Trans Power Apparat Syst 1981;100(3):1105–18.

4) Prakash K, Sydulu M. Particle swarm optimization based capacitor placement on radial distribution systems. IEEE power engineering society general meeting; 2007, pp. 1–5.

5) Oliveira LW, Carneiro S, Oliveira EJ, Pereira JLR, Silva I, Costa JS. Optimal reconfiguration and capacitor allocation in radial distribution systems for energy losses minimization. Int J Elect Power Energy Syst 2010;32(8):840–8

6) Wu WC, Zhang BM, Lo KL. Capacitors dispatch for quasi minimum energy loss in distribution systems using a loop analysis based method. Int J Elect Power Energy Syst 2010;32(6):543–50

7) Rao RS, Narasimham SVL, Ramalingaraju M. Optimal capacitor placement in a radial distribution system using Plant Growth Simulation Algorithm. Int. J Elect Power Energy Syst., 2011; 33(5), pp.1133–39.

8) Das D. Optimal placement of capacitors in radial distribution system using Fuzzy-GA method. Int J Elect Power Energy Syst 2008;30(6–7):361–7

9) Raju MR, Murthy KVSR, Avindra KR. Direct search algorithm for capacitive compensation in radial distribution systems. Int J Elect Power Energy Syst., 2012; 42(1), pp.24–30.

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10) Sneha S, Provas Kumar R. Optimal capacitor placement in radial distribution systems using teaching learning based optimization. Int. J Elect Power Energy Syst., 2013, 54, pp. 387–398.

11) Iman Ziari, Gerard Ledwich, Arindam Ghosh. A new technique for optimal allocation and sizing of capacitors and setting of LTC. Electrical Power and Energy Systems 46 (2013) 250–257.

12) Attia A, El-Fergany A, Almoataz Y, Abdelaziz, Capacitor placement for net saving maximization and system stability enhancement in distribution networks using artificial bee colony-based approach. Electrical Power and Energy Systems, 2013, 54, pp. 235–243.

13) Sirjani R, Azah M, Shareef H. Heuristic optimization techniques to determine optimal capacitor placement and sizing in radial distribution networks: a comprehensive review. PRZEGLA˛ D ELEKTROTECHNICZNY (Elect. Rev.), 2012, 88(7a), pp.1–7.

14) Paulo M.D, Oliveira D J. The standard backward/forward sweep power flow