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OPTIMAL CAPACITOR PLACEMENT AND SIZING IN A RADIAL DISTRIBUTION SYSTEM USING CLONAL SELECTION ALGORITHM

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ABSTRACT

This paper presents the Clonal selection algorithmic approach to minimize power loss and energy cost by optimal capacitor placement and sizing in Radial Distribution System (RDS). The clonal selection optimization for optimal capacitor allocation is considering the daily load curve, which is represented by a given number of load levels. As an important branch of the Artificial Immune Systems (AIS), the Clonal Selection Algorithm (CSA) stems from the clonal selection mechanism that describes the basic natural immune response to the stimulation of non-self cells (antigens). To check the feasibility, the proposed method is applied on standard 33 and 69 bus radial distribution systems. Numerical results obtained from the given approach are compared with other methods. The proposed approach results seem to surpass the solution given by other methods.

Keywords: radial distribution system, capacitor placement, CSA, AIS, loss reduction.

1. INTRODUCTION

The analysis of a distribution system is an important area to be considered, as distribution systems provide the vital link between the bulk power system and the consumers. A distribution circuit normally uses primary or main feeders and lateral distributors. A main feeder originates from the substation and passes through the major load centers. Lateral distributors connect the individual transformers at their ends. Many distribution systems used in practice have a single circuit main feeder and are defined as radial distribution systems. Radial distribution systems are popular because of their simple design and generally are of low cost.

It is vividly known that, distribution system losses are significantly higher than transmission system losses. The reactive power flow losses at higher loads can be even more noteworthy. This is in turn results in a higher voltage drop, at certain distribution points in the network. Studies have indicated that as much as 13% of the total power generated is wasted in the form of losses at the distribution level. Many arrangements like network reconfiguration shunt capacitor placements are worked out to reduce these losses. The trend towards distribution automation and control will require the most efficient operating arrangements for economic viability variations. Since major loads are inductive in nature and the shunt capacitors are electrically efficient, cost effective, and static in nature and also happen to be one of the basic equipments, optimal location and sizing of capacitors in electrical distribution network is done to achieve the above mentioned objectives.

The optimal capacitor placement and sizing problem is a constrained non-linear and complicated problem. Many different optimization techniques and algorithms have been developed and proposed in the past. Antunes *et al*. (1) proposed the Non-dominated Sorting Genetic Algorithm (NSGA) to solve optimal capacitor placement problem for reactive power compensation in electric radial distribution network. Jabr *et al*. (2) applied mixed integer linear programming approach for optimal placement of fixed and switched type capacitors in a radial distribution network to minimize the costs associated with capacitor banks, peak power and energy losses while satisfying a specified set of physical and technical constraints. Khodr *et al*. (3) presented mixed integer linear optimization methodology for the optimal location and sizing of static and switched shunt capacitors in radial distribution system.

Kaur *et al*. (4) proposed an ant colony optimization algorithm to solve capacitor allocation problem of radial distribution system. Muthukumar *et al*. (5) implemented harmony search algorithmic to identify optimal location and size of capacitors in unbalanced distribution systems with harmonics consideration to reduce the cost of total real power loss and capacitor installation cost. Oliveira *et al*. (6) proposed the mixed integer non-linear programming approach for the reconfiguration of capacitor allocation to minimize energy losses on radial electrical networks. Prakash *et al*. (7) also used particle swarm optimization approach for finding the optimal size and location of capacitors in radial distribution system. The method was implemented on standard 70-bus and 135-bus systems and its performance was compared with the Tabu Search (TS) and Genetic Algorithm (GA). Rao *et al*. (8) presented plant growth simulation algorithm 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.

Raju *et al*. (9) presented direct search algorithm to find the optimal size and location of fixed and switched capacitors in a radial distribution system to maximize the savings and minimize the power loss. The algorithm was tested on standard 22, 69 and 85 bus systems and the results were compared with the results of PSO. Szuvovivski *et al*. (10) proposed GA to locate optimal position of voltage regulators and capacitor banks to control the voltage, reactive power and power factor of radial distribution system. Sedighizadeh *et al*. (11) presented binary honey bee foraging approach to solve optimal capacitor placement problem of radial distribution systems. To test the effectiveness, the proposed method was implemented on IEEE 9-bus test system and its performance was compared with Binary PSO (BPSO) and GA.

Taher *et al*. (12) introduced hybrid honey bee colony optimization algorithm to place shunt capacitors in IEEE 25-bus and a modified IEEE 37-bus test system to minimize power system losses while maintaining Total Harmonic Distortion (THD) of buses in an acceptable range. Wu *et al*. (13) developed loop analysis based method to find the optimal size of capacitor to minimize the power loss in distribution systems for daily operation. Ziari *et al*. (14) proposed a modified discrete PSO for finding the optimal rating and location of fixed and switched capacitors of radial distribution system in his recent endeavour.

The proposed work focuses on the Clonal selection optimization for optimal capacitor allocation, considering the daily load curve represented by a given number of load levels. Burnet proposed the Clonal Selection Algorithm which is one of the newest evolutionary algorithms and is based on theory of Clonal Selection. The Clonal Selection Algorithm explains the basic natural immune response to the stimulation of non-self cells (antigens). It is also proved to be an efficient optimization technique in other fields of engineering such as Mechanical Engineering and Civil Engineering. However, from the literature review, it is seen that the application of CSA for optimal capacitor placement problem of distribution system has not been explored in previous works. This problem is formulated as a nonlinear constrained mixed discrete-continuous optimization problem. In order to show the effectiveness of the proposed approach, two test systems of standard 33 and 69 bus radial distribution systems are used in this paper.

2. MATHEMATICAL PROBLEM FORMULATION

The objective of capacitor placement in the distribution system is to minimize the energy cost of the system annually, subjected to certain operating constraints and load pattern. The operation and maintenance cost of the capacitor placed in the distribution system is not taken into account. The three-phase system is considered as balanced and loads are assumed as time invariant.

2.1 Real power loss minimization

Mathematically, the real power loss minimization may be defined as

$$Min(P_{rpl}) = \sum_{i=2}^{\eta\eta} (P_{gni} - P_{dni} - V_{mi} V_{ni} Y_{mni} \cos(\delta_{mi} - \delta_{ni} + \theta_{ni}) \quad (1)$$

Where P_{rpl} is the real power loss; P_{gni} is the active power output of the generator at bus ni; P_{dni} is the active power demand at bus ni; V_{mi} is the voltage of bus mi; V_{ni} is the voltage of bus ni; Y_{mni} is the admittance between bus ni and bus mi.

2.1.1 Minimization of total cost

Minimization of total cost is the multiple objective optimization problems. It deals with the minimization of power losses as well as minimizing cost of the total energy loss. Capacitor installation in distribution network can improve the power flow through distribution lines and can also improve the voltage level of different buses. This results in lower power loss and better energy efficiency of the network which ultimately reduces the energy loss cost. However, the installation of capacitor increases the investment cost. Therefore, the objective of optimal capacitor placement problem in this case is to minimize the total cost and is defined as

$$\mathrm{Minimize(S)} = \mathrm{K_e} \sum_{j=1}^{L} \mathrm{T_j P_j} + \sum_{i=1}^{\hat{n}} \mathrm{K_c Q_{ci}} \quad (2)$$

Where K_e is the energy cost per each kWh; T_j is the duration for which jth load level operates; P_j is the active power loss during j^th^ load level; K_c is the purchase cost of capacitor per kVAr; Q_{ci} is the size of the capacitor placed at the i^th^ bus; $\hat{n}$ is the number of capacitor locations.

2.2 Constraints

The optimal capacitor placement problem of radial distribution network is subjected to following inequality constraints:

2.2.1 Bus voltage limits

The voltage must be kept within the specified limits at each bus

$$V_{min} \le V \le V_{max} \quad (3)$$

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

2.2.2 Branch apparent power flow limits

The apparent power flow through each branch must be less than the maximum apparent power admissible for the line and it may be expressed as

$$S_i \le S_{imax} \quad (4)$$

S_i is the apparent power flow of the ith branch. S_{imax} is the maximum apparent power flow limit of the ith branch.

2.2.3 Number and sizes of shunt capacitors

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

$$Q_{ci} \le LQ_s \quad (5)$$

Q_{ci} is the kVAr rating of the capacitor. L is the no of shunt capacitors. Q_s is the smallest discrete rating of the capacitor.

3. CLONAL SELECTION ALGORITHM

The Clonal Selection algorithm is inspired by the Clonal Selection theory of acquired immunity. The Clonal selection theory credited to Burnet was proposed to account for the behaviour and capabilities of antibodies in the acquired immune system inspired itself by the principles of Darwinian natural selection theory of evolution. When a lymphocyte is selected and binds to an antigenic determinant, the cell proliferates making thousands of copies of itself and differentiates into different cell types (plasma and memory cells). Plasma cells have a short lifespan and produce vast quantities of antibody molecules, whereas memory cells live for an extended period in the host anticipating future recognition of the same determinant. The important feature of the theory is that when a cell is selected and proliferates, it is subjected to small copying errors (changes to the genome called somatic hyper mutation) that change the shape of the expressed receptors and subsequent determinant recognition capabilities of both the antibodies bound to the lymphocytes cells surface, and the antibodies that plasma cells produce.

The information processing principles of the clonal selection theory describe a general learning strategy. This strategy involves a population of adaptive information units (each representing a problem-solution or component) subjected to a competitive process for selection, which together with the resultant duplication and variation ultimately improves the adaptive fit of the information units to their environment.

3.1 Philosophy and strategy behind the development of Clonal selection algorithm

Burnet's Clonal Selection theory is used to describe the basic features of an immune response to an antigenic stimulus. The main idea of Clonal Selection theory is that antibodies can selectively react to the antigens, which are the native peptides on the cell surface, is explained in Figure-1. When exposed to antigens, the immune cells that recognize and eliminate, the antigen presenting cells will be selected. These immune cells arouse an effective response against them. This reaction leads to a clonally cell proliferation and the cells in colony have the same antibodies.

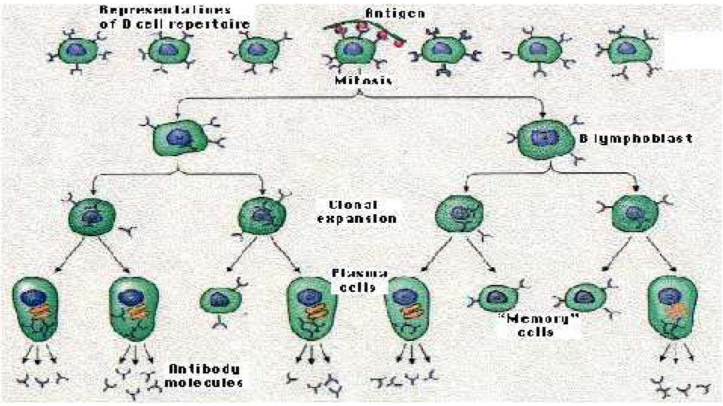

Figure-1. Clonal selection.

Consequently, the process of Clonal Selection actually consists of three main steps:

Clone: descend a group of identical cells from a single common ancestor through asexual propagation. Mutation: gain higher affinity mainly through hyper mutation. Selection: select some excellent individuals from the sub-population generated by Clonal Proliferation. The optimization process includes two steps: first, the antibodies are gained, second, according to the clonal selection theory; the most capable antibodies are produced. The framework of clone selection optimization algorithms is shown in Figure-2.

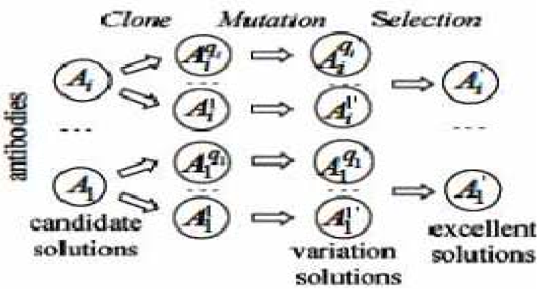

Figure-2. Frame work of CSA.

In this section, the proposed Clonal selection algorithm is presented and analyzed.

3.2 Algorithm of CSA applied to optimal capacitor placement problem

In optimal capacitor placement problem, the size of the capacitors and their positions are considered as decision variables and are used to form objective function. The procedure for implementing the CSA algorithm in solving optimal capacitor placement problem may be summarized by the following steps:

Step-1: Initialize the population size (np), the maximum number of iterations, number of capacitors to be installed, the different load levels and their corresponding duration in hours in the distribution network.

Step-2: Input the system data such as line and load details of the distribution system, constraint limits etc.

Step-3: Depending upon the capacitor numbers, their positions are randomly generated. Initialize randomly the size of the capacitors within their operating limits which are installed in the distribution network.

$$Pi = [loc_{i,1}, loc_{i,2}, ..., loc_{i,nc}, Q_{i,1}, Q_{i,2}, ..., Q_{i,j}, ..., Q_{i,nc}] \quad (6)$$

Depending upon the population size, initial solution P is created which is given by:

$$P = [P_1, P_2, ..., P_i, ..., P_{Np}] \quad (7)$$

Step-4: Run the load flow to find the power losses of the distribution network. Afterward, the objective functions are evaluated.

Step-5: Based on the objective value, sort the values from best to worst and the first 50% of the best solution is selected from the initial population and is referred to as elites.

Step-6: Clone the elites in each elite pool with a rate proportional to its fitness, i.e., the fitter the antibody, the more clones it is likely to produce. The amount of clone generated for these antibodies are given by:

$$Pi = \text{round}\ ((\frac{n - i}{n}) \times Q \quad (8)$$

Q determines the scope of the clone and round (.) is the operator that rounds its argument towards the closest integer.

Step-7: Subject the clones in each pool through either hyper mutation or receiver editing processes. Some of the clones in each elite pool undergo the hyper mutation process.

Step-8: Determine the maximum number of generation and check, if max no of generations to evolve is reached. If it terminates then it would return the best fitness individual. If it doesn't, go to step4.

Step-9: Check whether the calculated kVAr of any of the installed capacitor violates the operating limits or not. If any value is less than the minimum level, it is made equal to minimum value and if it is greater than the maximum value, it is made equal to the maximum level.

Step-10: Stop the iteration process and print the best solution set (optimal locations and optimal size of capacitors) if the stop- ping criterion is satisfied, else go to Step-4.

3.3 Flowchart of CLONALG selection algorithm

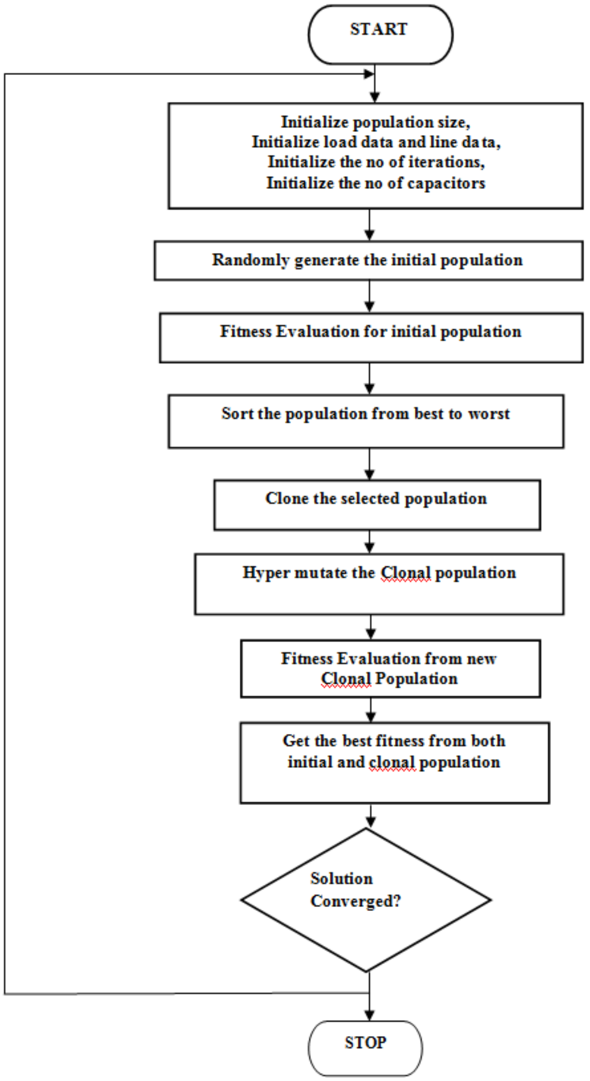

Figure-3. Flowchart of clonal selection algorithm for optimal capacitor placement problem.

4. NUMERICAL RESULTS

The CSA algorithms are programmed using MATLAB software. The proposed method for loss reduction and energy cost minimization by capacitor placement and sizing using CSA algorithm is tested on 33-bus and 69-bus radial distribution system. In all simulations, the following parameters are used:

Table-1. Parameters used for optimal capacitor problem.

Parameters	Values
Population size	30
Maximum no of iterations	100
Energy cost ($K_{e)}$	0.06/KWhr
Purchase cost of capacitor (K_c)	3.0/KVAr
Cloning rate	0.5
Replication rate 'Beta'	0.02

The population size, the no of iterations, cost constants for energy cost and purchase cost of capacitor, Cloning rate and replication rate are given in Table-1. The Capacitor minimum rating is 50KVAr, maximum is 1100 KVAr and their step size is 50 KVAr. To demonstrate the efficiency of the proposed method for cost minimization over objective function, simulation studies are carried out on 33 and 69 bus test systems. In this simulation study, three different load demand patterns of light load (50%), nominal load (100%) and peak load (160%) are considered to show the effectiveness of the proposed method. Duration of time for light load, nominal load and peak load are 2000 h, 5260 h and 1500 h respectively. Here, energy cost is assumed as US $ 0.06 per kWh and purchase cost of capacitor is taken as US $ 3.0 per kVAr.

4.1 Optimal capacitor placement and sizing of capacitors using 33 bus RDS

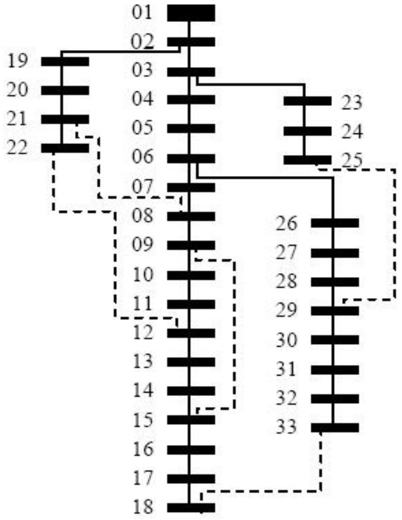

Figure-4. Single line diagram of 33 bsus RDS.

The first test case for the proposed method is a 33-bus radial distribution system. The single line diagram of 33bus RDS is shown in Figure-4. The line and load data of the feeders are given in appendix. The base values of the system are taken as 12.66 kV and 10MVA.

Table-2. Optimal capacitor placement location and size for 33 bus system.

Optimal location	Control setting (kVAr)			Optimal size (kVAr)
	0.50	1.0	1.60	
30	600	900	1050	1050
12	150	400	550	550
24	100	550	100	100

4.1 Simulation results using CSA for loss analysis for 33 bus system

Table-3. Comparison of the results without and with capacitor placement for 33 bus system.

Losses cost, capacitor cost at different load levels		Without capacitors	With capacitors
Total Cost		$121396	$86278
Total losses cost		$121396	$81178
Total capacitor cost		0.0	$5100
Load level 0.50	V_{min} at 18	0.9583	0.9678
	Losses (KW)	47.0709	32.0895
Load level 1.0	V_{min} at 18	0.9131	0.9341
	Losses (KW)	202.6783	132.8677
Load Level 1.60	V_{min} at 18	0.8528	0.8818
	Losses (KW)	575.3682	393.2709

Maximum voltage Vsubstation = 1.0 pu.

The proposed CSA algorithm is further applied on 33-bus test system to determine the optimal size and location of capacitors such that energy cost is minimized. Before the capacitor placement, minimum voltage level and power loss of the system for light, nominal and peak load are 0.9583 p.u., 47.0709 kW; 0.9131 p.u., 202.6783 kW; and 0.8528 p.u., 575.368 kW, respectively. The size of capacitors, their positions of capacitors are given in Table-2. The Table-3 shows the comparison of the results with and without considering capacitor placements in the 33 bus system. Energy loss cost, capacitor cost and total cost of the system for three different load levels are shown in Table-3.

The total cost for the system without any compensation is found to be US $121396. After compensation, the total cost is US $86278. From the results, it is seen that the annual saving is US $35118. It is found that, after compensation, for all the algorithms, the total cost, the minimum voltage level and power losses at different load levels have improved significantly [8]. This demonstrates that the CSA successfully achieves better simulation results satisfying all the system operational constraints.

Convergence curve of cost of 33-bus system using CSA are given in Figure-5.

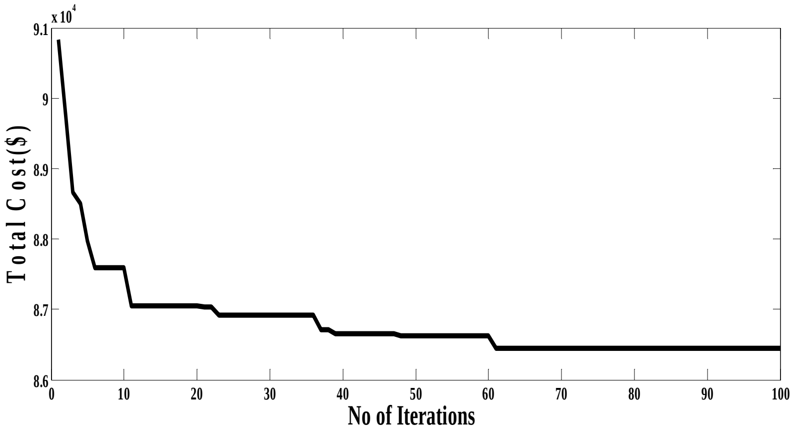

Figure-5. Convergence curve of cost of 33 bus RDS using CSA.

4.2 Optimal capacitor placement and sizing of capacitors using 69 bus RDS

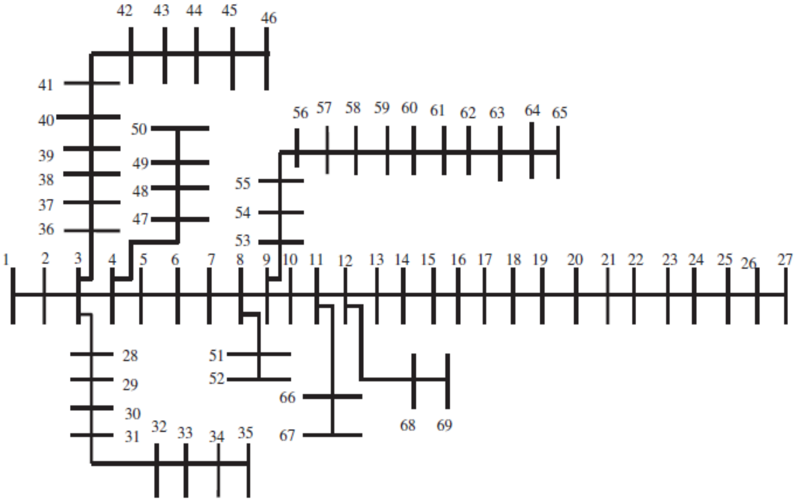

Figure-6. Single line diagram of 69 bus RDS.

The second test case for the proposed method is a 69-bus radial distribution system. The single line diagram of 69 bus RDS is shown in Figure-6. The system data of the feeders are given in (16). The base values of the system are taken as 12.66 kV and 10MVA. The proposed CSA algorithm is further applied on 69-bus test system to determine the optimal size and location of capacitors such that energy cost is minimized. Before the capacitor placement, minimum voltage level and power loss of the system for light, nominal and peak load are 0.9567 p.u., 51.606 kW; 0.9092 p.u., 252.001 kW; and 0.8445 p.u., 652.427 kW, respectively. The size of capacitors, their positions of capacitors are given in Table-4. The Table-5 shows the comparison of the results with and without considering capacitor placements and energy loss cost, capacitor cost and total cost of the system for three different load levels. The total cost for the system without any compensation is found to be US $135, 921. After compensation, the total cost is US $93519. From the results, it is seen that the annual saving is US $42402. It is found that, after compensation, for all the algorithms the total cost, the minimum voltage level and power loss at different load levels are improved significantly [16]. This demonstrates that the CSA successfully achieves better simulation results satisfying all system operational constraints. Convergence curve of cost of 69-bus system using CSA for the objective function are given in Figure-7.

Table-4. Optimal capacitor placement location and size for 69 bus system.

Optimal location	**Control setting** (kVAr)			**Optimal size** (kVAr)
	0.50	**1.0**	**1.60**	
64	200	300	550	550
23	200	300	200	200
61	300	950	1050	1050

4.2.1 Simulation results using CSA for loss analysis for 69 bus system

Table-5. Comparison of the results with and without capacitor placement for 69 bus system:

Losses cost, capacitor cost at different load levels		**Without capacitors**	**With capacitors**
Total cost		$135921	$93519
Total losses cost		$135921	$88119
Total capacitor cost		0.0	$5400
Load level 0.50	V_{min} at 65	0.9567	0.9663
	Losses (KW)	51.606	34.49
Load level 1.0	V_{min} at 65	0.9092	0.931
	Losses (KW)	225.001	146.539
Load level 1.60	V_{min} at 65	0.8445	0.8794
	Losses (KW)	652.427	419.255

Maximum voltage $V_{substation}$ = 1.0 p.u

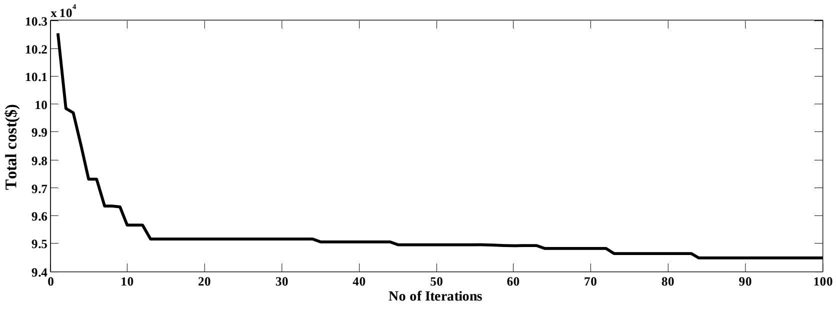

Figure-7. Convergence curve of cost for 69 bus RDS using CSA.

5. CONCLUSIONS

Thus, the paper is based on finding the optimal locations and sizes (kVAr) of capacitors to be placed in radial distribution system to maximize the saving after considering the energy loss cost and capacitor cost. The load flow analysis along with power flow equations comes in handy to get the power loss. The Clonal Selection Algorithm is used for sizing. In CSA, coding scheme is developed to carry out the allocation problem, which involves identification of location and size by one dimensional array. The study is carried out on 33-bus and 69-bus radial distribution systems considering the capacitors discrete sizes of 50kVAr. From the study, the following conclusions are drawn. The compensation is yielding into increase in voltage profile, reduction in losses and reduction in total energy cost. The developed algorithm is effective in deciding the placement and sizing of capacitors for 33-bus and 69-bus systems for different load levels of light, nominal and peak load levels for appropriate duration hours. Future work needs to be carried out considering the following one. The fixed and switched type capacitors should be considered after network reconfiguration to improve voltage profile and system losses.

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Appendix

Table-6. System data for 33-bus radial distribution network.

Branch number	Sending Bus	Receiving Bus	Resistance Ω	Reactance Ω	Nominal load at receiving bus	
					P (kW)	**Q** (kVAr)
1	1	2	0.0922	0.047	100	60
2	2	3	0.493	0.2511	90	40
3	3	4	0.366	0.1864	120	80
4	4	5	0.3811	0.1941	60	30
5	5	6	0.819	0.707	60	20
6	6	7	0.1872	0.6188	200	100
7	7	8	0.7114	0.2351	200	100
8	8	9	1.03	0.74	60	20
9	9	10	1.044	0.74	60	20
10	10	11	0.1966	0.065	45	30
11	11	12	0.3744	0.1298	60	35
12	12	13	1.468	1.155	60	35
13	13	14	0.5416	0.7129	120	80
14	14	15	0.591	0.526	60	10
15	15	16	0.7463	0.545	60	20
16	16	17	1.289	1.721	60	20
17	17	18	0.732	0.574	90	40
18	2	19	0.164	0.1565	90	40
19	19	20	1.5042	1.3554	90	40
20	20	21	0.4095	0.4784	90	40
21	21	22	0.7089	0.9373	90	40
22	3	23	0.4512	0.3083	90	50
23	23	24	0.898	0.7091	420	200
24	24	25	0.896	0.7011	420	200
25	6	26	0.203	0.1034	60	25
26	26	27	0.2842	0.1447	60	25
27	27	28	1.059	0.9337	60	20
28	28	29	0.8042	0.7006	120	70
29	29	30	0.5075	0.2585	200	600
30	30	31	0.9744	0.963	150	70
31	31	32	0.3105	0.3619	210	100
32	32	33	0.341	0.5302	60	40