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Optimal Capacitor Placement For Loss Reduction Of Radial Distribution Systems By Cat Swarm Optimization

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Abstract

Capacitor placement is becoming more important in distribution systems due to the increase in the demands for electrical energy. Capacitor placement plays a vital role in reducing real power losses and in enhancing the voltage stability which is the objective function in this problem. This paper proposes a multi-objective technique for optimally determining the location and sizing of capacitor placement in the distribution network. In this paper, a data structure based load flow method is used to find the total real power losses. Cat swarm algorithm is used to find optimal sizing and location of the capacitor. The proposed method is tested on IEEE-33 bus and 69 bus radial distribution systems. This method is compared with other nature-inspired optimization methods. The simulated results illustrate the good applicability and performance of the proposed method.

Keywords: Cat Swarm optimization, Data Structure, Loss minimization, capacitor placement

Introduction

Power loss is an unavoidable circumstance that badly affects the utility consumers. It is revealed from studies that power losses in distribution networks occur due to Joule effect and it is 13% of the generated energy. This non-negligible amount of losses directly impacts the financial results and the overall efficiency of the power system. The percentage of real power loss in the transmission system is lesser than that of the distribution system. But the voltage level of the transmission system is much higher than distribution system. So a small percentage reduction of loss in the distribution system will be economically beneficial. Therefore, the methods for loss reductions are essential for achieving the financial target of the transmission and distribution companies. The voltage level at the distribution networks reduce, if the buses (nodes) are located far away from the substation busbar. The shortage of reactive power causes the voltage reduction in the buses. Even in certain industrial areas under critical loading, it may lead to voltage collapse and reactive power losses. Hence, in order to improve the voltage profile and to reduce reactive power loss, proper reactive power compensation is required. Network reconfiguration, shunt capacitor placements, etc. are the few methods adopted for reducing the reactive power losses. Such capacitor installation provides indirect reactive power to the grid and reduces the magnitude of reactive branch current. Shunt capacitor installation provides additional benefits like improvement of voltage profile, the power factor and the stability of the Power system.

Damodar *et al.* [6] identified optimal capacitor locations using a fuzzy approach by taking two objectives namely, to minimize the real power loss and to maintain the voltage within the permissible limits. H.Ng *et al.* [7] considered fuzzy approximate reasoning for the capacitor placement problem. Masoum *et al.* [8] solved fixed shunt capacitor placement and sizing under non sinusoidal harmonic distortion conditions by using fuzzy set theory for the discrete optimization problem. Hsiao *et al.* [9] proposed Simulated Annealing (SA) tool for optimal VAR source planning in large-scale power systems. W. Jwo *et al.* [10] reduced the CPU time of SA and retained its main characteristics through a hybrid simulated annealing/genetic algorithm (HSAGA) method and found the near-global optimal solution in a finite time. A Modified Simulated Annealing (MSA) technique has been developed for simultaneous improvement of power quality and optimal placement and sizing of fixed capacitor banks in a modern distribution network [11]. Mohamed *et al.* [15] suggested a binary particle swarm optimization for discrete optimization problem of optimal capacitor placement in nonlinear loads. Majid Davoodi *et al.* [12] adopted a Genetic Algorithm based method considering the majority of the influencing factors in its multi-objective target function for optimal capacitor placement and capacitance computation in the power distribution networks. Srinivasa in [13] presented Plant Growth Simulation Algorithm (PGSA) that employs loss sensitivity factors for capacitor placement in the distribution system. The PGSA has been tested on 9 and 34 bus system to estimate the required level of shunt capacitive compensation at the optimal candidate locations to reduce the active power loss and to enhance the voltage profile. Rama Rao *et al.* [14] used Power Loss Indices (PLI) method that considers initial selection of voltage regulator buses and applied PGSA for optimal location.

In all above literature the intelligent algorithm is used to find size of the capacitor and they are underutilized since the location is found by analytical sensitive analysis method. This drawback is avoided in this paper, the intelligent algorithm Cat Swarm Optimization (CSO) [16] is used to find simultaneous optimization location and sizing of the capacitor. CSO is best suitable for multi objective optimization. In this paper objectives of loss minimization and voltage profile improvement are considered.

Problem formulation

Objective function

The objective of the problem is to minimize the real power loss and improves the voltage profle. The objective also to minimize the annual cost due to capacitor installations. The problem subject to power balance equality constraint and voltage level of inequality constraint [17]. The problem formulation is given below

$$Min.\ F = \sum_{i=1}^{nbus-1} \left(P_{Loss(i,i+1)} \right) * K_p + \left[k^{c}_{fc} * Q_{fc} \right] \quad (1)$$

$$P_{Loss(i,i+1)} = \frac{(P^2{}_i + Q^2{}_i)}{V_i^2} * R_{(i,i+1)} \quad (2)$$

$$Q_{Loss(i,i+1)} = \frac{(P^2{}_i + Q^2{}_i)}{V_i^2} * X_{(i,i+1)}$$

Subjected to:

Equality constraint,

The active and reactive power balance equality constraints can be formulated as follows

$$P_{slack} = \sum_{i=1}^{nl} P_D(i) + \sum_{j=1}^{n} P_L(j) \quad (3)$$

$$Q_{slac}k + \sum_{i=1}^{N_B} Q_c(i) = \sum_{i=1}^{nl} Q_D(i) + \sum_{j=1}^{n} Q_L(j) \quad (4)$$

Inequality constraint,

Voltage limit constraint

The voltage magnitude at each bus must be maintained within its limits and is expressed as,

$$V_{min} \le V_i \le V_{max} \quad (5)$$

Maximum total compensation

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

$$Q_{C,i} \le Q_{C,max} \quad (6)$$

Where,

$P_{Loss(i,i+1)}$ = Loss between bus i and i+1

K_p=annual cost disbursed (cost/kW)

k^{c}_{fc} =capacitor cost spent for one unit of kVAr (cost /kVAr)

Q_{fc} =fixed capacitor bank rating (kVAr)

P_i = Real power at bus i
Q_i = Reactive power at bus i
$Q_{C,i}$ = Capacitor compensation at bus i
$Q_{C,max}$ = Maximum size of capacitor
V_i = Voltage magnitude at bus i
$R_{(i,i+1)}$ = Resistance between bus i and i+1
$X_{(i,i+1)}$ = Reactance between bus i and i+1
P_{Root} = Total real power at root node
$P_{T,Load}$ = Total real power Demand or Load
$P_{T,Loss}$ = Total real power loss in the system
V_{min}, V_{max} = Minimum and Maximum voltage limit

Equation (1) is a multi objective problem of minimizing real power loss and voltage improvement. Equation (2) gives formula to find real power loss using i^{th} bus and consecutive line resistance. Equation (3) and (4) are equality constraints that supplied real and reactive power which is equal to total demand and losses in the system. Equation (5) gives inequality constraint of voltage limit of bus. Size of the capacitor has maximum limit and hence connected capacitor should be less than the maximum value as given in equation (6). Power flow and voltage in all nodes are calculated from its previous node power and voltage, to understand it the simple one line diagram is given in figure 2. Real and reactive power of i+1 bus is calculated from bus i as given in equation (7) and (8). Equation (9) is used to find i+1 bus voltage from i^{th} bus voltage magnitude.

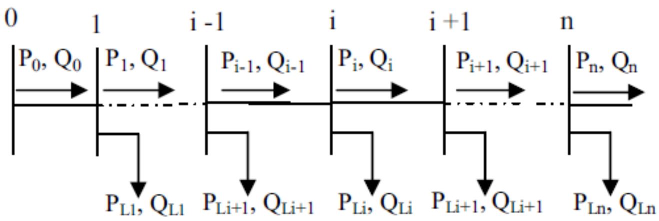

Fig. 2. One line diagram of distribution line

$$P_{i+1} = P_i - P_{Li+1} - R_{i,i+1} * (\frac{P_i^2 + Q_i^2}{|V_i|^2}) \quad (7)$$

$$Q_{i+1} = Q_i - Q_{Li+1} - X_{i,i+1} * (\frac{P_i^2 + Q_i^2}{|V_i|^2}) \quad (8)$$

$$|V_{i+1}|^2 = |V_i|^2 - 2*(R_{i,i+1} * P_i + X_{i,i+1} * Q_i) + (R^2_{i,i+1} + X^2_{i,i+1}) * (\frac{P_i^2 + Q_i^2}{|V_i|^2}) \quad (9)$$

Where,
P_i = Real power available at bus i
P_{i+1} = Real power available at next bus of i (i.e. i+1)
P_{Li+1} = Local real power load at next bus of i (i.e. i+1)
Q_i = Reactive power available at bus i
Q_{i+1} = Reactive power available at next bus of i
Q_{Li+1} = Local reactive power load at next bus of i

OVERVIEW OF CAT SWARM OPTIMIZATION ALGORITHMS

Basic Principle

CSO algorithm is based on the behavior of cats with exceptionally vigorous vitality of curiosity toward moving objects and possessing good hunting skills. Chu and Tsai [16] proposed a new optimization algorithm that imitates the natural behavior of cats. Even though cats spend most of their time resting, they always remain alert and move very slowly. Cats have a very high level of alertness; this alertness does not desert them when they are resting. Hence, what appears to be a cat lazing around upon closer examination will show large wide eyes observing their surroundings. Cats appear to be lazy, when they are actually very smart and deliberate creatures. When the presence of prey is sensed, they chase it very quickly, spending a large amount of energy. These two characteristics of resting with slow movement and chasing with high speed are represented by seeking and tracing, respectively. In CSO, these two modes of operations are mathematically modeled for solving complex optimization problems. These modes are termed the “seeking mode” and the “tracing mode.” A combination of these two modes allows CSO better performance.

CSO algorithm is divided into two sub models based on two of major behavioural of traits of cats. These are termed as “Seeking mode” and “Tracing mode”. Seeking mode has four essential factors such as:

Seeking Memory Pool (SMP) :	It is used to define the size of seeking memory of each cat, indicating any points sorted by cat.
Seeking Range of Selected Dimensions (SRD) :	It is used to declare mutative ratio for selected dimensions. While in seeking mode; if a dimension is selected for mutation, the difference between old and new ones may not be out of range, the range is defined by SRD.
Counts of Dimensions to Change (CDC) :	It is used tell how many dimensions to will be varied. All these factors play important roles in seeking mode.
Self Position Consideration (SPC) :	It is a boolean valued variable, and indicates whether the point at which the cat is already standing will be one of the candidate point to move to.SPC cannot influence SMP.

3.1 Seeking Mode: Resting and Observing

The seeking mode of the CSO algorithm models the behaviour of the cats during the

period of resting but staying alert observing its environment for its next move. The steps involved in Seeking mode of the CSO algorithm can be described as follows:
Step1. Make j copies of the present position of each cat_k , where j=SMP. If the value of SPC is true. Let j= (SMP=1), then retain present position as one of the candidates.
Step2. For each copy according to CDC add or subtract SRD percent values and replace the old ones.
Step3. Calculate the fitness values (FS) of all candidate points.
Step4. If all the FS are not exactly equal calculate the selecting probability of each candidate point .otherwise set all the selecting probability of each candidate point to 1. If the global of the fitness is to find the minimum solution .$FS_b=FS_{max}$, otherwise $FS_b = FS_{min}$.
Step5. Randomly pick the point to move to form the candidate points, and replace the position of cat_k.

3.2 Tracing Mode: - Running after a target:
Step1. Update the velocities for every dimension (V_{id}) according to below equation,
Step2. Check if the velocities are in the range of maximum velocity is over-range, it is set equal to the equal.
Step3. Update the position of cat_k according to the below equation,

$$V_{id} = W*V_{id} + C*r*(P_{gd}-X_{id}) \quad (10)$$

Where, W is inertia weight, P_{gd} is position of cat, who has the best fitness value. X_{id} is the position of cat_k, C is constant, r is a random value in the range of [0, 1].

$$X_{id} = X_{id}+V_{id} \quad (11)$$

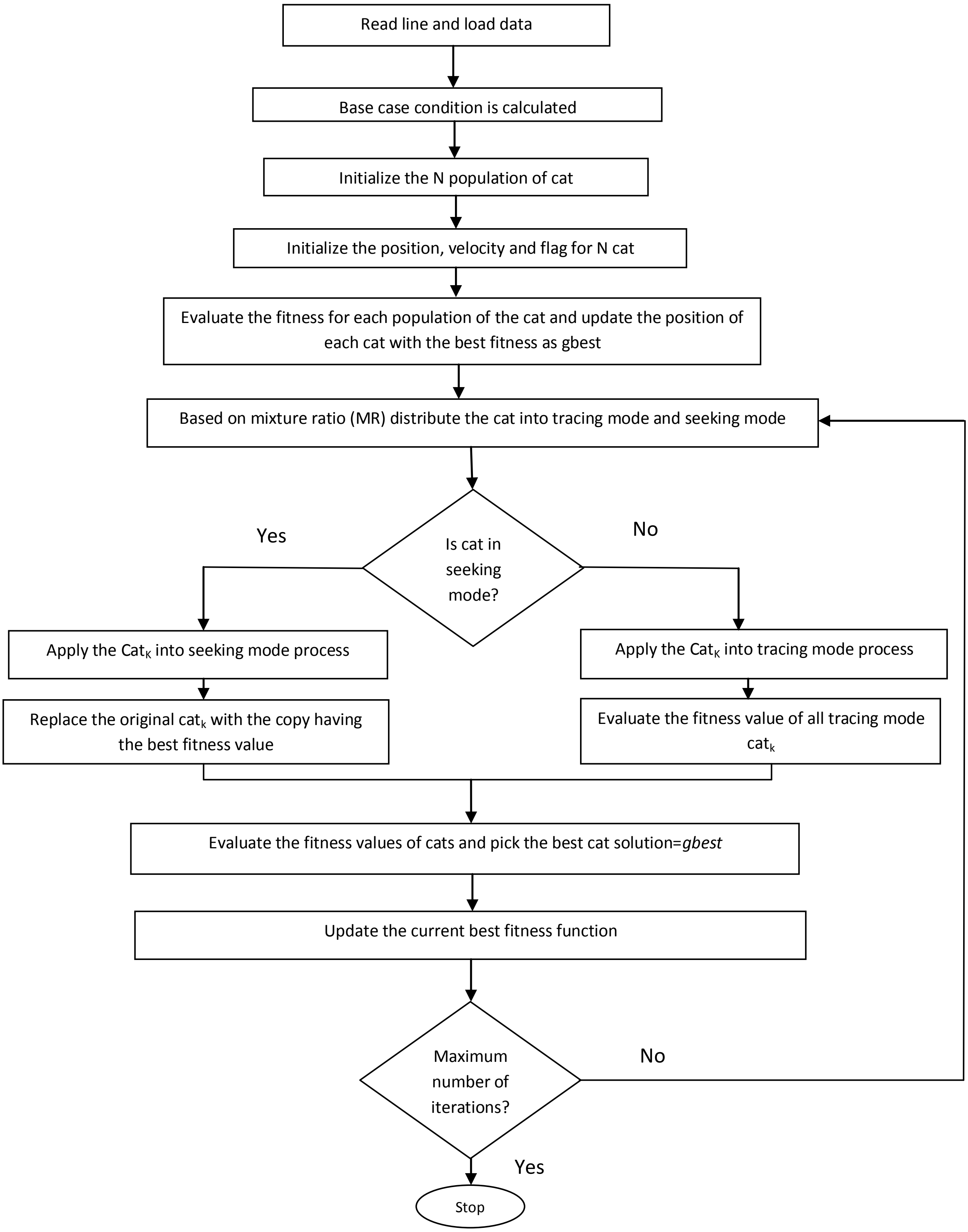

FIG 1. Flowchart of computational procedure for proposed algorithm.

Implementation results and discussions

The performance and effectiveness of the proposed algorithms have been tested on 33-bus and 69-bus radial distribution systems for real power loss minimization and maximization of network savings. In this approach, optimal locations for connection of capacitors and optimal size of capacitors have been treated as a single problem, unlike other approaches quoted in the literature. The potential locations for capacitor placement are decided by algorithm itself along with optimal sizes of capacitors. In 33 bus radial system has 33 buses and 32 distribution lines, the cumulative real and reactive power demands are 3715 kw and 2300 kvar respectively [17]. This radial system has low voltages at end buses due to heavy inductive loads. This low voltage may improve by connecting capacitor to the buses which supplies part of reactive power demand. Further, this capacitor reduces the current flow and thereby losses are reduced. Single line diagram of this 33 bus is given figure 2.

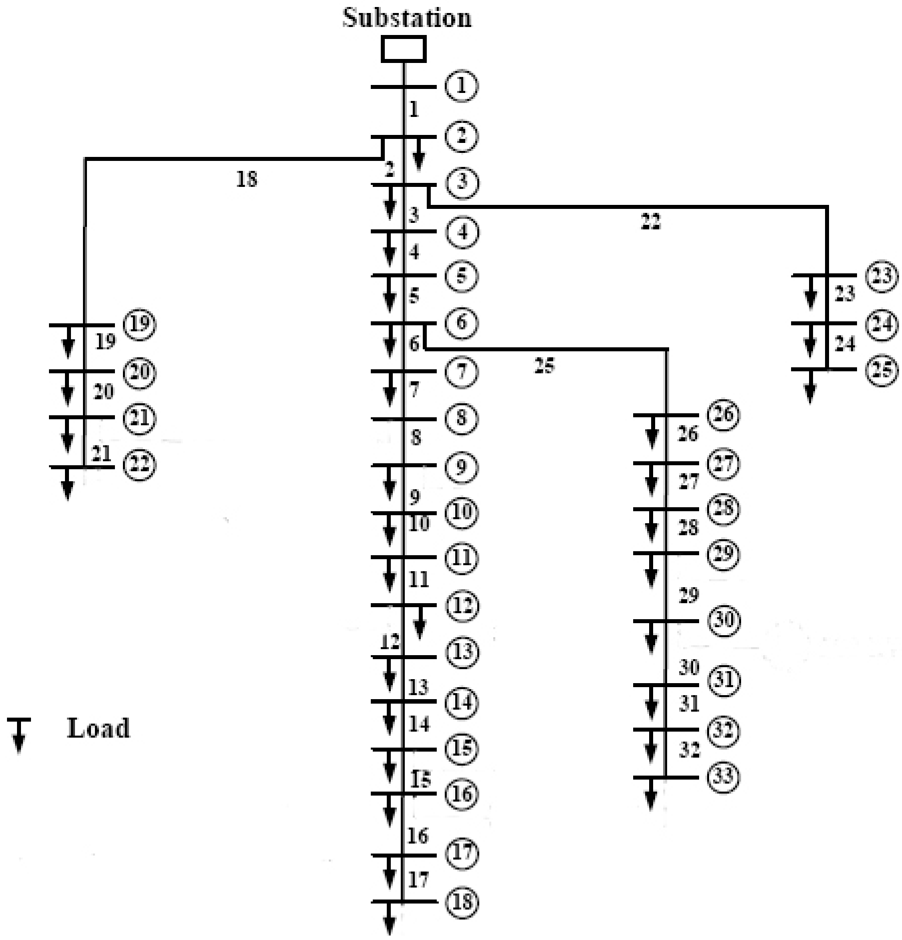

Fig. 2. IEEE 33 bus single line diagram

Considered 69 bus single line diagram [17] is given in figure 3. It has 69 buses and 68 distribution lines. Cumulative real and reactive power demand of the system is

3801.89 kw and 2694.1 kvar respectively. The first bus is the substation and has no local load all other buses have their own local load connected to the bus. Bus 3 has three branches and bus 4, 7, 9, 11 and 12 has two branches, other buses have only one branch connected to its next bus. In this simulation studies for energy cost optimization load demand pattern under nominal load(5260h) are considered to show the effectiveness of the Cat Swarm Algorithm. Here the energy cost is assumed as US $0.06 per kWh and capacitor cost as US $ 3.0 per kVAr [4].

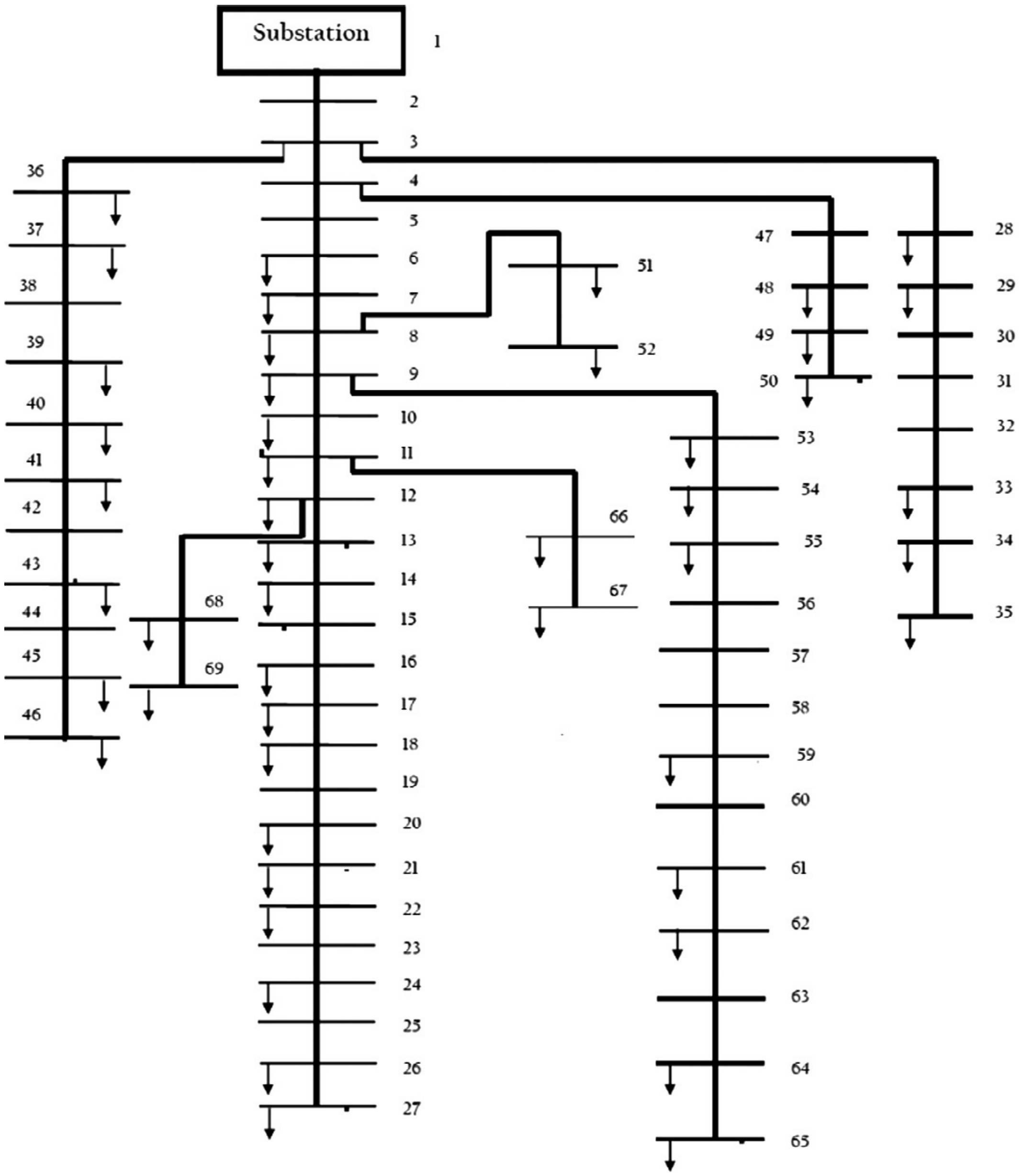

Fig. 3. IEEE 69 bus single line diagram

33 Bus Radial Distribution Systems

The 33 bus RDS with a value of 10 MVA and 12.66 KV having 33 bus and 32 branches as shown in fig. 2. The parameters SMP, SPC, CDC flags are set as 6, 1, and 4 respectively. From the proposed CSO algorithm the capacitor rating as shown in table 1 are placed at the optimal location respectively. Before the capacitor placement, minimum voltage level and power loss of the system for nominal load are 0.9131 p.u., 202.68 kW. After the capacitor placement, minimum voltage level and power loss of the system for nominal are 0.9385 p.u., 133.12 kW. Table 1 shows the comparison of the results with and without considering capacitor placements. The total cost for the system without capacitor is found to be US $63965.80. After placing capacitor, the total cost is US $47412.67. From the results, it is seen that the annual saving is US $16553.13.

Table.1 optimal location and sizing using CSO for 33 bus radial distribution system

	Techniques							
	Heuristic based [15]		FES based[15]		PSO [15]		CSO Proposed	
	Location	Size (kVAr)	Location	Size (kVAr)	Location	Size (kVAr)	Location	Size (kVAr)
Optimal location and size of capacitor	26 11 17 4	1400 750 300 250	24 17 7	1500 750 450	19 22 20	781 803 479	30 6 14	900 500 400
Total kvar		2700		2700		2063		1800
V_{min} (p.u)	-		-		-		0.9385	
Power loss(kw)	168.47		168.98		168.8		133.12	
Cost of kw loss ($)	53169.13		53330.08		53273.28		42012.67	
Cost of capacitor ($/kvar)	8100		8100		6189		5400	
Total Cost ($)	61269.13		61430.08		59462.28		47412.67	
Net Savings ($)	2696.67		2535.72		4503.52		16553.13	

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

Convergence curve of cost of 33-bus system using CSO for the objective function is given in the below figure 4.

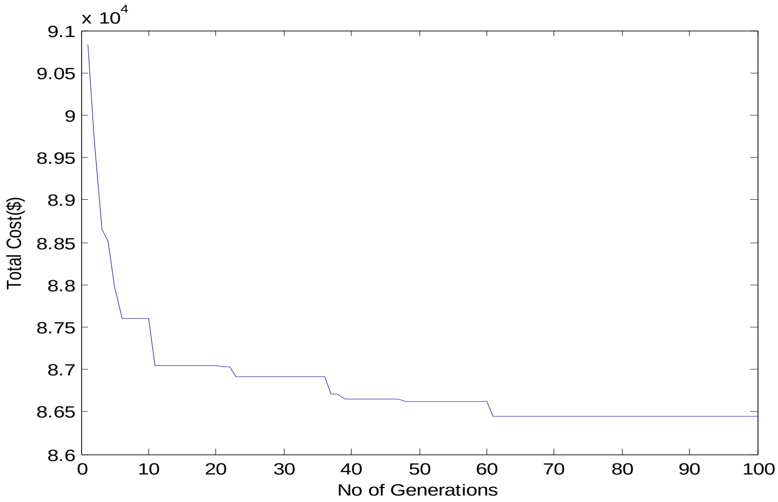

Fig. 4. Convergence characteristics of cost using CSO for 33 bus RDS

Table 2. Voltage comparison before and after capacitor placement for 33 Bus systems

Bus_No	Without Capacitance Voltage in P.u	With Capacitance Voltage in P.u
1	1	1
2	0.997	0.9976
3	0.9829	0.9864
4	0.9755	0.981
5	0.9681	0.9758
6	0.9497	0.9651
7	0.9462	0.9639
8	0.9413	0.96
9	0.9351	0.9565
10	0.9292	0.9535
11	0.9284	0.9529
12	0.9269	0.9519
13	0.9208	0.9459
14	0.9185	0.9437
15	0.9171	0.9424
16	0.9157	0.941
17	0.9137	0.9391
18	0.9131	0.9385
19	0.9965	0.9971
20	0.9929	0.9935
21	0.9922	0.9928

22	0.9916	0.9921
23	0.9794	0.9831
24	0.9727	0.9769
25	0.9694	0.9736
26	0.9477	0.9639
27	0.9452	0.9625
28	0.9337	0.9577
29	0.9255	0.9546
30	0.9219	0.9529
31	0.9178	0.9489
32	0.9169	0.948
33	0.9166	0.9478

Table 3. Voltage comparison before and after capacitor placement for 69 Bus systems

	Without Capacitance	With Capacitance		Without Capacitance	With Capacitance
Bus_No	Voltage in P.U	Voltage in P.U	Bus_No	Voltage in P.U	Voltage in P.U
1	1	1	41	0.9988	0.9989
2	1	1	42	0.9986	0.9986
3	0.9999	1	43	0.9985	0.9985
4	0.9998	0.9999	44	0.9985	0.9985
5	0.9991	0.9995	45	0.9984	0.9984
6	0.9906	0.9967	46	0.9984	0.9984
7	0.9818	0.9939	47	0.9998	0.9998
8	0.9797	0.9932	48	0.9985	0.9986
9	0.9787	0.9929	49	0.9947	0.9947
10	0.9746	0.991	50	0.9942	0.9942
11	0.9737	0.9906	51	0.9797	0.9932
12	0.9706	0.99	52	0.9797	0.9932
13	0.9677	0.9909	53	0.9759	0.9924
14	0.9648	0.9918	54	0.9726	0.9918
15	0.9619	0.9928	55	0.9682	0.9911
16	0.9614	0.993	56	0.9638	0.9905
17	0.9605	0.9935	57	0.9414	0.989
18	0.9605	0.9935	58	0.9303	0.9883
19	0.96	0.993	59	0.9261	0.9881
20	0.9597	0.9928	60	0.921	0.9881
21	0.9592	0.9923	61	0.9136	0.9875

22	0.9592	0.9923	62	0.9134	0.9874
23	0.9592	0.9922	63	0.913	0.9872
24	0.959	0.9921	64	0.9111	0.9863
25	0.9588	0.9919	65	0.9105	0.9858
26	0.9588	0.9918	66	0.9737	0.9905
27	0.9587	0.9918	67	0.9737	0.9905
28	0.9999	0.9999	68	0.9702	0.9897
29	0.9999	0.9999	69	0.9702	0.9897
35	0.9989	0.999			
36	0.9999	0.9999			
37	0.9998	0.9998			
38	0.9996	0.9996			
39	0.9995	0.9996			
40	0.9995	0.9996			

69 Bus Radial Distribution System

In CSO, the parameters SMP, SPC, CDC flags are set as 6, 1, and 4 respectively. The optimal capacitor Placement and location for 69 bus RDS for various load levels are found using CSO. The proposed CSO algorithm is further applied on 69-bus test system to determine the optimal size and location of capacitor such that energy cost is minimized. Before the capacitor placement, minimum voltage level and power loss of the system for nominal load are 0.9092 p.u., 225.001 kW. After the capacitor placement, minimum voltage level and power loss of the system for nominal load are improved to 0.9858 p.u., 145.98 kW. Table 4 shows the comparison of the results with and without considering capacitor placements.

Table 4. Optimal Capacitor placement location and size using CSO for 69 bus

	Techniques									
	GA [4]		PSO [4]		DSA [4]		TLBO [4]		CSO	
	Location	Size (kVAr)	Location	Size (kVAr)	Location	Size (kVAr)	Location	Size (kVAr)	Location	Size (kVAr)
Optimal location and size of capacitor	61 64 59	700 800 100	46 47 50	241 365 1015	61 15 60	900 450 450	12 61 64	600 1050 150	62 18 61	250 400 1000
Total kvar		1600		1621		1800		1800		1650
V_{min} (p.u)	-		-		-		0.9313		0.9858	
Power loss(kw)	156.62		152.48		147.00		146.35		145.98	
Cost of kw loss ($)	49429.27		48122.68		46393.2		46188.06		46071.28	

Cost of capacitor ($/kvar)	4800	4863	5400	5400	4950
Total Cost ($)	54229.27	52985.68	51793.2	51588.06	51021.28
Net Savings ($)	16780.73	18024.32	19216.8	19421.94	19988.72

The total cost for the system without capacitor is found to be US $71010. After capacitor placement, the total cost is US $51021.28. From the results, it is seen that the annual saving is US $19988.72. It is found that, after compensation, for all the algorithms, the total cost, the minimum voltage level and power losses are improved significantly.

Convergence curve of cost of 69-bus system using CSO for the objective function is given in the below figure 5.

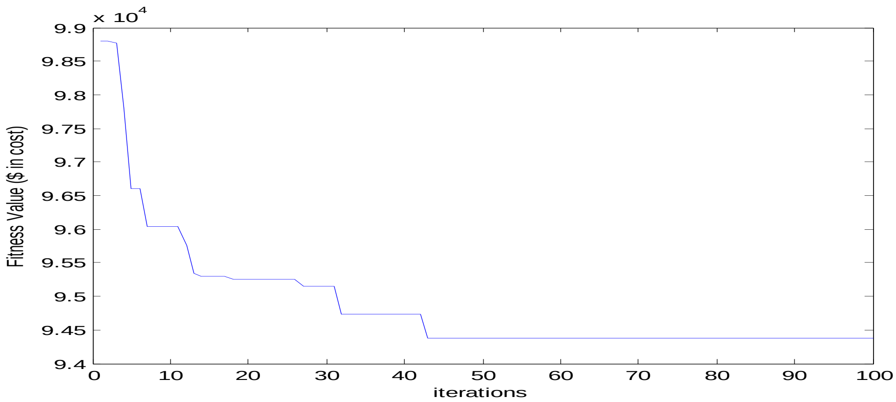

Figure 5 Convergence characteristics of cost using CSO for 69 bus RDS

Conclusions

In this paper, an algorithm that employs Cat Swarm Optimization, for estimation of required allocation of shunt capacitive compensation to improve the voltage profile of the system and reduce active power loss. The main advantage of this proposed method is that it systematically decides the locations and size of capacitors to realize the optimum sizable reduction in active power loss and significant improvement in voltage profile. Test results on 33 and 69 bus systems are presented to show the effectiveness of the proposed algorithm compared with other algorithm. The method places capacitors at less number of locations with optimum sizes and offers much saving in initial investment. The future work can be carried out using Distribution Generation and capacitors, both considered for network reconfiguration to improve voltage profile and system losses.

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