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Optimal Capacitor Placement in Radial Distribution Systems using Artificial Bee Colony (ABC) Algorithm

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Abstract

This paper presents a new method which applies an artificial bee colony algorithm (ABC) for capacitor placement in distribution systems with an objective of improving the voltage profile and reduction of power loss. The solution methodology has two parts: in part one the loss sensitivity factors are used to select the candidate locations for the capacitor placement and in part two a new algorithm called Artificial Bee Colony Algorithm(ABC) is used to estimate the optimal size of capacitors at the optimal buses determined in part one. The ABC algorithm is a new population based meta heuristic approach inspired by intelligent foraging behavior of honeybee swarm. The advantage of ABC algorithm is that it does not require external parameters such as cross over rate and mutation rate as in case of genetic algorithm and differential evolution and it is hard to determine these parameters in prior. The other advantage is that the global search ability in the algorithm is implemented by introducing neighborhood source production mechanism which is a similar to mutation process. To demonstrate the validity of the proposed algorithm, computer simulations are carried out on 34-bus system and compared the results with the other approach available in the literature. The proposed method has outperformed the other methods in terms of the quality of solution and computational efficiency.

Keywords: Distribution systems, Loss Sensitivity Factors, Capacitor placement, Artificial Bee Colony Algorithm.

1. Introduction

The loss minimization in distribution systems has assumed greater significance recently since the trend towards distribution automation will require the most efficient operating scenario for economic viability variations. The power losses in distribution systems correspond to about 70% of total losses in electric power systems (2005).To reduce these losses, shunt capacitor banks are installed on distribution primary feeders. The advantages with the addition of shunt capacitors banks are to improve the power factor, feeder voltage profile, Power loss reduction and increases available capacity of feeders. Therefore it is important to find optimal location and sizes of capacitors in the system to achieve the above mentioned objectives.

Since, the optimal capacitor placement is a complicated combinatorial optimization problem, many different optimization techniques and algorithms have been proposed in the past. H. Ng et al (2000) proposed the capacitor placement problem by using fuzzy approximate reasoning. Sundharajan and Pahwa (1994) proposed the genetic algorithm approach to determine the optimal placement of capacitors based on the mechanism of natural selection. Ji-Pyng Chiou et al (2006) proposed the variable scale hybrid differential evolution algorithm for the capacitor placement in distribution system. Both Grainger et al (1981) and Baghzouz and Ertem (1990) proposed the concept that the size of capacitor banks was considered as a continuous variable. Bala et al (1995) presented a sensitivity-based method to solve the optimal capacitor placement problem.

In this paper, a new algorithm called artificial bee colony (ABC) algorithm is proposed to place the capacitors at candidate locations with an objective of reducing the power losses in the distribution system. The artificial bee colony algorithm is a new meta heuristic approach, proposed by Karaboga [9]-[11]. It is inspired by the intelligent foraging behavior of honey bee swarm. The proposed method is tested on 34 bus radial distribution systems and results obtained are effective and encouraging.

2. Problem Formulation

The objective of capacitor placement in the distribution system is to minimize the annual cost of the system, subjected to certain operating constraints and load pattern. For simplicity, the operation and maintenance cost of the capacitor placed in the distribution system is not taken into consideration. The three-phase system is considered as balanced and loads are assumed as time invariant. Mathematically, the objective function of the problem is described as:

$$\min f = \min (COST) \text{ or } \min f = \min (P_{Loss}) \qquad (1)$$

where COST is the objective function which includes the cost of power loss and the capacitor placement.

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

$$V_{min} \leq |V_i| \leq V_{max} \qquad (2)$$

where $|V_i|$ is the voltage magnitude of bus i, Vmin and Vmax are bus minimum and maximum voltage limits, respectively.

The power flows are computed by the following set of simplified recursive equations derived from the single-line diagram depicted in Fig. 1.

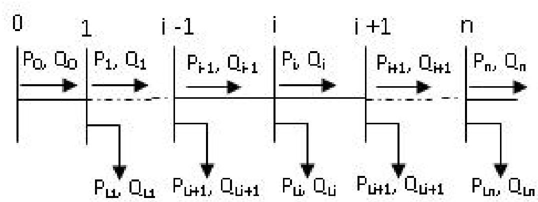

Figure 1. Single line diagram of main feeder

$$P_{i+1} = P_i - P_{Li+1} - R_{i,j+1} \frac{P_i^2+Q_i^2}{|V_i|^2} \qquad (3)$$

$$Q_{i+1} = Q_i - Q_{Li+1} - X_{i,j+1} \frac{P_i^2+Q_i^2}{|V_i|^2} \qquad (4)$$

$$|V_i|^2 = |V_i|^2 - 2(R_{i,j+1} P_i + X_{i,j+1} Q_i) + (R_{i,j+1}^2 + X_{i,j+1}^2) \frac{P_i^2+Q_i^2}{|V_i|^2} \qquad (5)$$

where P_i and Q_i are the real and reactive powers flowing out of bus i, and P_{Li} and Q_{Li} are the real and reactive load powers at bus i. The resistance and reactance of the line section between buses i and i+1 are denoted by $R_{i,i+1}$ and $X_{i,i+1}$ respectively.

The power loss of the line section connecting buses i and i+1 may be computed as

$$P_{Loss}(i,i+1) = R_{i,j+1} \frac{P_i^2+Q_i^2}{|V_i|^2} \qquad (6)$$

The total power loss of the feeder, $P_{T,Loss}$, may then be determined by summing up the losses of all line sections of the feeder, which is given as

$$P_{F,Loss} = \sum_{i=0}^{N-1} P_{Loss}(i, i+1) \qquad (7)$$

Considering the practical capacitors, there exists a finite number of standard sizes which are integer multiples of the smallest size Q_0^c. Besides, the cost per kVAr varies from one size to another.

In general, capacitors of larger size have lower unit prices. The available capacitor size is usually limited to

$$Q_{max}^c = LQ_0^c \quad (8)$$

where L is an integer. Therefore, for each installation location, there are L capacitor sizes$\{Q_0^c, 2Q_0^c \ldots\ldots LQ_0^c\}$ available. Given the annual installation cost for each compensated bus, the total cost due to capacitor placement and power loss change is written as

$$COST = K_p P_{T,Loss} \sum_{i=1}^{n}(k_{cf} + K_i^c Q_i^c) \quad (9)$$

where n is number of candidate locations for capacitor placement, Kp is the equivalent annual cost per unit of power loss in \$/(kW-year); K_{cf} is the fixed cost for the capacitor placement. The constant k_c^i is the annual capacitor installation cost, and, i = 1, 2. . , n are the indices of the buses selected for compensation. The bus reactive compensation power is limited to

$$Q_c^i \leq \sum_{i=1}^{n} Q_{Li} \quad (10)$$

where Q_c^i and Q_{Li} are the reactive power compensated at bus i and the reactive load power at bus i, respectively.

3. Sensitivity Analysis and Loss Sensitivity Factors

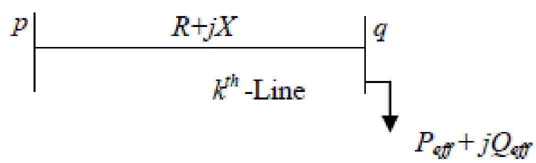

Figure 2. Feeder

The candidate nodes for the placement of capacitors are determined using the loss sensitivity factors. The estimation of these candidate nodes basically helps in reduction of the search space for the optimization procedure.

Consider a distribution line with an impedance R+jX and a load of $P_{eff} + jQ_{eff}$ connected between 'p' and 'q' buses as given above in fig.2.

Active power loss in the k[th] line is given by, $[I_k^2]$ * R[k] which can be expressed as,

$$P_{lineloss}[q] = \frac{(P_{eff}^2[q]+Q_{eff}^2[q])\ R[k]}{(V[q])^2} \quad (11)$$

Similarly the reactive power loss in the k[th] line is given by

$$Q_{lineloss}[q] = \frac{(P_{eff}^2[q]+Q_{eff}^2[q])\ X[k]}{(V[q])^2} \quad (12)$$

Where, $P_{eff}[q]$ = Total effective active power supplied beyond the node 'q'.

$Q_{eff}[q]$ = Total effective reactive power supplied beyond the node 'q'.

Now both the loss sensitivity factors can be obtained as shown below:

$$\frac{\partial P_{lineloss}}{\partial Q_{eff}} = \frac{(2*Q_{eff}[q]*R[k])}{(V[q])^2} \quad (13)$$

$$\frac{\partial Q_{lineloss}}{\partial Q_{eff}} = \frac{(2*Q_{eff}[q]*X[k])}{(V[q])^2} \quad (14)$$

3.1 Candidate node selection using Loss sensitivity factors

The Loss Sensitivity Factors ($\partial P_{lineloss} / \partial Q_{eff}$) are calculated from the base case load flows and the values are arranged in descending order for all the lines of the given system. A vector bus position 'bpos[i]' is used to store the respective 'end' buses of the lines arranged in descending order of the values ($\partial P_{lineloss} / \partial Q_{eff}$).The descending order of elements of "bpos[i]' vector will decide the sequence in which the buses are to be considered for compensation. This sequence is purely governed by the ($\partial P_{lineloss} / \partial Q_{eff}$) and hence the proposed 'Loss Sensitive Coefficient' factors become very powerful and useful in capacitor allocation or Placement. At these buses of 'bpos[i]' vector, normalized voltage magnitudes are calculated by considering the base case voltage magnitudes given by (norm[i]=V[i]/0.95). Now for the buses whose norm[i] value is less than 1.01 are considered as the candidate buses requiring the Capacitor Placement. These candidate buses are stored in 'rank bus' vector. It is worth note that the 'Loss Sensitivity factors' decide the sequence in which buses are to be considered for compensation placement and the 'norm[i]' decides whether the buses needs Q-Compensation or not. If the voltage at a bus in the sequence list is healthy (i.e., norm[i]>1.01) such bus needs no compensation and that bus will not be listed in the 'rank bus' vector. The 'rank bus' vector offers the information about the possible potential or candidate buses for capacitor placement. The sizing of Capacitors at buses listed in the 'rank bus' vector is done by using Plant Growth Simulation Algorithm.

4. Artificial Bee Colony Algorithm (ABC)

In the ABC algorithm, the colony of artificial bees contains three groups of bees: employed bees, onlookers and scouts. A bee waiting on the dance area for making decision to choose a food source is called an onlooker and a bee going to the food source visited by it previously is named an employed bee. A bee carrying out random search is called a scout. In the ABC algorithm, first half of the colony consists of employed artificial bees and the second half constitutes the onlookers. For every food source, there is only one employed bee. In other words, the number of employed bees is equal to the number of food sources around the hive. The employed bee whose food source is exhausted by the employed and onlooker bees becomes a scout. In the ABC algorithm, each cycle of the search consists of three steps: sending the employed bees onto the food sources and then measuring their nectar amounts; selecting of the food sources by the onlookers after sharing the information of employed bees and determining the nectar amount of the foods; determining the scout bees and then sending them onto possible food sources. At the initialization stage, a set of food source positions are randomly selected by the bees and their nectar amounts are determined. Then, these bees come into the hive and share the nectar information of the sources with the bees waiting on the dance area within the hive. At the second stage, after sharing the information, every employed bee goes to the food source area visited by her at the previous cycle since that food source exists in her memory, and then chooses a new food source by means of visual information in the neighborhood of the present one. At the third stage, an onlooker prefers a food source area depending on the nectar information distributed by the employed bees on the dance area. As the nectar amount of a food source increases, the probability with which that food source is chosen by an onlooker increases, too. Hence, the dance of employed bees carrying higher nectar recruits the onlookers for the food source areas with higher nectar amount. After arriving at the selected area, she chooses a new food source in the neighborhood of the one in the memory depending on visual information. Visual information is based on the comparison of food source positions. When the nectar of a food source is abandoned by the bees, a new food source is randomly determined by a scout bee and replaced with the abandoned one. In our model, at each cycle at most one scout goes outside for searching a new food source and the number of employed and onlooker bees were equal.

The probability P_i of selecting a food source i is determined using the following expression:

$$P_i = \frac{fit_i}{\sum_{n=1}^{S_N} fit_n} \qquad (15)$$

Formally, suppose each solution consists of d parameters and let $x_i = (x_{i1}, x_{i2}... x_{id})$ be a solution with parameter values $x_{i1}, x_{i2}... x_{id}$. In order to determine a solution v_i in the neighborhood of xi, a solution parameter j and another solution $x_k = (x_{k1}, x_{k2}... x_{kd})$ are selected randomly. Except for the value of the selected parameter j, all other parameter values of v_i are same as x_i i.e.,$v_i = (x_{i1}, x_{i2}, ..., x_{i(j-1)}, x_{ij}, x_{i(j+1)}, ...x_{id})$. The value v_i of the selected parameter j in vi is determined using the following formula:

$$v_{ij} = x_{ij} + u(x_{ij} - x_{kj}) \quad (16)$$

where u is an uniform variate in [-1, 1]. If the resulting value falls outside the acceptable range for parameter j, it is set to the corresponding extreme value in that range.

The proposed artificial bee colony algorithm is summarized as follows:

1. Read input data and Initialize MIC(maximum iteration count)
2. Initialize the population, $x_{ij} = (Q_{i1},Q_{i2}, ...,Q_{ij})$
3. Evaluate fitness value for each employed bee by using the following formula

$$\text{Fitness} = \frac{1}{1+\text{power loss}}$$

4. Initialize cycle=1;
5. Generate new population(solution) v_{ij} in the neighborhood of x_{ij} for employed bees using equation 16 and evaluate them
6. Apply the greedy selection process between x_i and v_i.
7. Calculate the probability values P_i for the solutions x_i by means of their fitness values using the equation 15.
8. Produce the new populations v_i for the onlookers from the populations x_i, selected based on P_i by applying roulette wheel selection process, and evaluate them.
9. Apply the greedy selection process for the onlookers between x_i and v_i.
10. Determine the abandoned solution, if exists, and replace it with a new randomly produced solution x_i for scout bees using the equation: $x_{ij} = \min_j + \text{rand}(0, 1) * (\max_j - \min_j)$.
11. Memorize the best solution achieved so far
12. cycle=cycle+1
13. if cycle<*MIC*, go to step 5, otherwise go to step 14;
14. Stop.

5. Test Results

The proposed method was tested on 34-bus radial distribution system and results have been obtained to evaluate its effectiveness. The algorithm of this method was programmed in MATLAB environment and run on a Pentium IV, 3-GHz personal computer with 0.99 GB RAM. The results obtained in these methods are explained in the following sections.

5.1 34 Bus system

The single line diagram is shown in fig. 3. The base values of the system are taken as 12.66 kV and 100MVA.

The sensitive analysis method is used to select the candidate installation locations of the capacitor to reduce the search space. The buses are ordered according to their sensitivity values as {19, 22,20,21,23,24,25,26 and 27}. In this case capacitor value has been taken as a continuous variable. The capacitor allowable range is from 100 kVAr to 1000 kVAr with step of 2kVAr. Top three nodes are selected as candidate locations (i.e. nodes 19, 22 and 20) to reduce the search space and then the amount to be injected in the selected nodes is optimized by ABC. The amount of kVAr injected are 900, 986 and 150 kVAr respectively.

The power loss before and after capacitor placement are 221.67 and 168.8 kW. The minimum and maximum voltages before capacitor placement are 0.9417 p.u (bus 27) and 0.9941 p.u (bus 2) and are improved to 0.9504 pu and 0.995 p.u after capacitor placement respectively. The detailed pu voltages of all the nodes of the 34 bus system before and after capacitor placement are shown in the Table 2.The graph showing the comparison of voltages of the 34 bus system before and after capacitor placement is shown in the figure 4. The *Nmax* value is tried from 2 to 80. All of the results converge to the same optimal solution with *Nmax* greater than 8. The results of the proposed method are compared with the results of PSO method [13] and GA method [16] and are shown in Table 1. From the results shown in Table 1, it is observed that the optimal candidate installation locations are three for the proposed and PSO methods [13], but it is five for the GA method [16]. The CPU time needed by the proposed method is 3.07 sec.

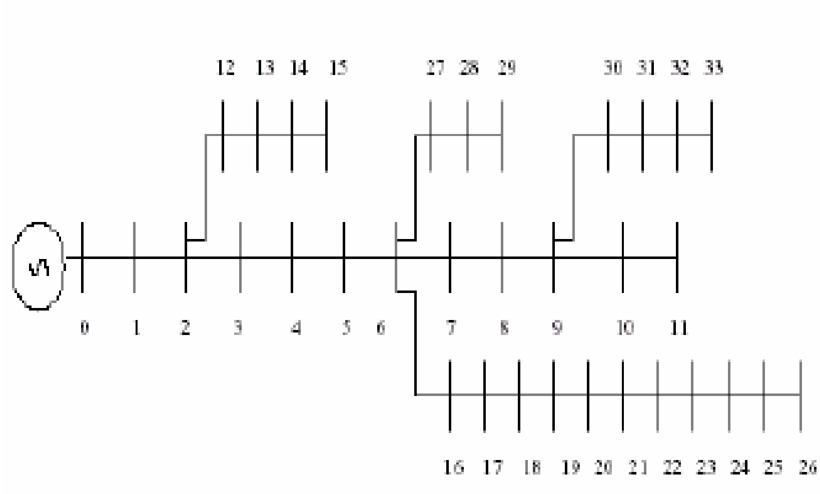

Figure 3. 34 bus distribution system

Table 1. Summary of results for 34 bus system

Items	Uncompensated	Compensated			
		PSO Prakash&Sydulu(2007)	Proposed	GA Swarup(2005)	FES based Ng&Salama(2000)
Total Losses(kW)	221.67	168.8	168.8	170	168.98
Optimal locations and size in kVAR	-	19 781 22 803 20 479	19 900 22 986 20 150	5 300 9 300 12 300 22 600 26 300	24 1500 17 750 7 450
Total kVAR	-	2063	2036	1800	2700

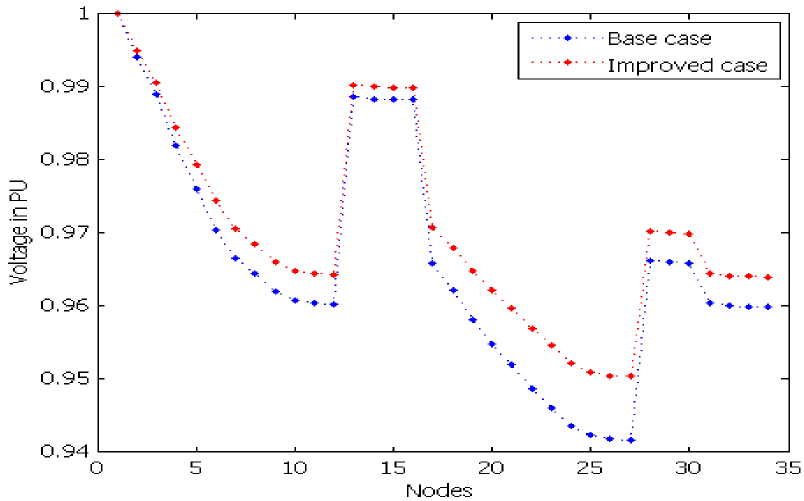

Figure 4. Voltage profile of 34 bus system before and after compensation.

Table 2: PU Voltages of all the nodes of a 34 bus distribution system

Bus No.	Voltage before capacitor placement (pu)	Voltage after capacitor placement (pu)	Bus No.	Voltage before capacitor placement (pu)	Voltage after capacitor placement (pu)
1	1	1	18	0.9622	0.968
2	**0.9941**	**0.995**	19	0.9582	0.9647
3	0.989	0.9907	20	0.9549	0.9622
4	0.9821	0.9846	21	0.952	0.9598
5	0.9761	0.9793	22	0.9487	0.957
6	0.9704	0.9744	23	0.946	0.9547
7	0.9666	0.9706	24	0.9435	0.9522
8	0.9645	0.9685	25	0.9423	0.951
9	0.962	0.9661	26	0.9418	0.9505
10	0.9608	0.9649	27	**0.9417**	**0.9504**
11	0.9604	0.9644	28	0.9663	0.9703
12	0.9602	0.9643	29	0.966	0.9701
13	0.9887	0.9903	30	0.9659	0.9699
14	0.9884	0.99	31	0.9605	0.9645
15	0.9883	0.99	32	0.9602	0.9642
16	0.9883	0.99	33	0.96	0.964
17	0.966	0.9709	34	0.9599	0.964

5. Conclusion

In the present work, a new population based artificial bee colony algorithm (ABC) has been proposed to solve capacitor placement problem in distribution system. Simulations are carried on 34 -bus system and results are compared with the other population based method PSO. The results obtained by the proposed method outperform the other methods in terms of quality of the solution and computation efficiency. The main advantage of ABC algorithm is that it does not require external parameters such as cross over rate and mutation rate etc, as in case of genetic algorithms, differential evolution and other evolutionary algorithms and these are hard to determine in prior. The other advantage is that the global search ability in the algorithm is implemented by introducing neighborhood source production mechanism which is a similar to mutation process.

Appendix

Line and Load data of 34 bus system

Branch No.(i)	Sending end IS(i)	Receiving end IR(i)	R(Ω)	X(Ω)	P_L(kW)	Q_L(kW)
1	1	2	0.117	0.048	230	142.5
2	2	3	0.10725	0.044	0	0
3	3	4	0.16445	0.04565	230	142.5
4	4	5	0.1495	0.0415	230	142.5
5	5	6	0.1495	0.0415	0	0
6	6	7	0.3144	0.054	0	0
7	7	8	0.2096	0.036	230	142.5
8	8	9	0.3144	0.054	230	142.5
9	9	10	0.2096	0.036	0	0
10	10	11	0.131	0.0225	230	142.5
11	11	12	0.1048	0.018	137	84
12	3	13	0.1572	0.027	72	45
13	13	14	0.2096	0.036	72	45
14	14	15	0.1048	0.018	72	45
15	15	16	0.0524	0.009	13.5	7.5
16	6	17	0.1794	0.0498	230	142.5
17	17	18	0.16445	0.04565	230	142.5
18	18	19	0.2079	0.0473	230	142.5
19	19	20	0.189	0.043	230	142.5
20	20	21	0.189	0.043	230	142.5
21	21	22	0.262	0.045	230	142.5
22	22	23	0.262	0.045	230	142.5
23	23	24	0.3144	0.054	230	142.5
24	24	25	0.2096	0.036	230	142.5
25	25	26	0.131	0.0225	230	142.5
26	26	27	0.1048	0.018	137	85
27	7	28	0.1572	0.027	75	48
28	28	29	0.1572	0.027	75	48
29	29	30	0.1572	0.027	75	48
30	10	31	0.1572	0.027	57	34.5
31	31	32	0.2096	0.036	57	34.5
32	32	33	0.1572	0.027	57	34.5
33	33	34	0.1048	0.018	57	34.5

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