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OPTIMAL CAPACITOR PLACEMENT AND SIZING WITH CONSIDERATION OF COSTS AND LOSSES IN RADIAL DISTRIBUTION SYSTEMS USING ANT COLONY ALGORITHM

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Abstract- The optimal capacitor placement problem involves determination of the location, number, type and sizes of capacitor to be placed in a distribution system with consideration minimizing the cost of peak power, reducing energy loss and improving voltage profile. A distribution system is an interface between the bulk power system and the consumers. The radial distribution system is popular among these because of its low cost and simple design. Ant Colony Optimization (ACO) technique is employed in order to have the perfect placement of the capacitors. The proposed approach is applied on a test case from a section of Tehran distribution network consisting of 13 buses. The results show that this method provides more economical solution by reducing power losses, energy loss and show a good improvement in nodes voltage.

Keywords: Capacitor Placement, Ant Colony Algorithm, Cost Minimization, Power Loss Reduction, Reducing Energy Loss, Voltage Profile Improvement.

I. INTRODUCTION

Reactive currents in an electrical utility distribution system produce losses and result in increased ratings for distribution components. Shunt capacitors can be installed in a distribution system to reduce energy and peak demand losses, release the KVA capacities of distribution apparatus, and also improve the system voltage profile. Thus, the problem of optimal capacitor placement consists of determining the locations, sizes, and number of capacitors to install in a distribution system such that the maximum benefits are achieved while operational constraints at different loading levels are satisfied.

In a distribution system, the reactive load is always varying and it is not a realistic proposition to determine fixed capacitor size and their respective location for a distribution based on an average of the reactive load as even this number is subjected to change as the load grows. In some cases in overcompensation will reduce more losses in the system. In addition, many of the technique for determining the optimal rating and location of capacitors in distribution systems involve the optimization of a cost function which require parameter such as the cost of capacitors, the cost of energy and the cost of the peak power loss to which only an estimation without exact certainty can be obtained.

With uncertainties in the parameter used in these capacitor sizing and location methods, it is difficult to determine how meaningful the results generated are. Near-global optimization techniques have been suggested as a means for improving the quality of solution of the problem [1-13]. While these methods can easily handle discrete variables, they have several drawbacks. A major drawback of these methods is speed and the fact that they use certain control parameters that may be system dependent and difficult to determine.

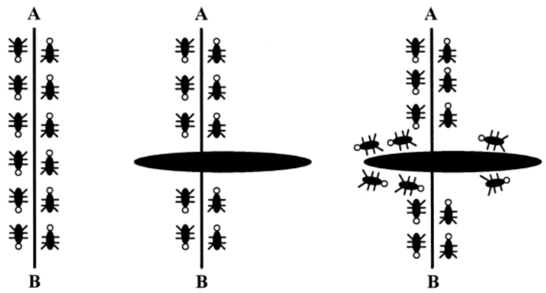
Other search techniques that can be useful in solving the capacitor placement problem have not been fully explored. Ponnavaikko and Rao [14] suggested an approach using the method of local variations. This technique can be considered a graph search technique when used with discrete variables. Shao, Rao, and Zhang have proposed a graph search based on a set of heuristic rules to determine sizes and locations for fixed capacitors [15]. Both of these methods use as decision variables the capacitor sizes at every bus on the feeder. At any step during the search procedure, the current solution, which corresponds to a node on a graph, is defined by these sizes.

In the present paper, Ant colony algorithm based on artificial intelligence is used to optimize the size and place of presented capacitors. The ACO is the most popular technique applied because of its advantages which include simple implementation, small computational load, and fast convergence. ACO is efficient for solving many problems for which it is difficult to find accurate mathematical models in comparison with other optimization techniques such as is used in [19]. The proposed algorithm determines the number, sizes, locations and types for capacitors to be placed on a distribution system in order to minimum cost due to reductions in peak power and energy losses. The solution method treats capacitor sizes as discrete variables and uses standard sizes and exact capacitor costs.

II. ANT COLONY ALGORITHM

The Ant Colony Optimization (ACO) imitate of real ants. As is well known, real ants are capable of finding the shortest path from food sources to the nest using visual cues. Also, they are capable of adapting to changes in the environment, for example, finding a new shortest path once the old one is no longer feasible due to a new obstacle. Moreover, the ants could manage to establish shortest paths through the medium that is called "pheromone". The pheromone is the material deposited by the ants, which serves as critical communication information among ants, thereby guiding the determination of the next movement. Ant trial that is rich of pheromone will thus become the goal path. The process is illustrated in Figure 1(a), the ants are moving from food source *A* to the nest *B* on a straight line. Once an obstacle appears as shown in Figure 1(b), the path is cut off.

The ants will not be able to follow the original trial in their movements. Under this situation, they have the same probability to turn right or left. Figure 1© depicts that the shorter path will collect larger amount of pheromone than the longer path. Hence, more ants will be increasingly guided to move on the shorter path. Due to this autocatalytic process, very soon all ants will choose the shorter path. As illustrated in Figure 1, by the guidance of the pheromone intensity, the ants select preferable path.



(a) (b) (c)

Figure 1. Behavior of ants to find optimal path [16]

Finally, the favorite path rich of pheromone become the best tour, the solution to the problem. At first, each ant is placed on a starting state. Each will build a full path, from the beginning to the end state, through the repetitive application of state transition rule. While constructing its tour, an ant also modifies the amount of pheromone on the visited path by applying the local updating rule. Once all ants have terminated their amount of pheromone on edge is modified again through the global updating rule. In other words, the pheromone-updating rules are designed so that they tend to give more pheromone to paths which should be visited by ants. In the following, the state transition rule, the local updating rule, and the global updating rule are briefly introduced [16].

A. State Transition Rule

The state rule used by the ants system, called a random-proportional rule, is given in Equation (1) [16], which gives the probability with which ant *k* in node *i* chooses to move to node *j*.

$$P_{ij}^{k}(t)=\begin{cases}\dfrac{\tau_{ij}^{\alpha}(t).\eta_{ij}^{\beta}}{\sum\limits_{s\in j_k(i)}\tau_{is}^{\alpha}(t).\eta_{is}^{\beta}} & \text{if} \quad j\in j_k(i)\\ 0 & \text{otherwise}\end{cases} \tag{1}$$

where τ is the pheromone which deposited on the edge between nodes *i* and *j*, η the inverse of the edge distance, $j_k(i)$ the set of nodes that remain to be visited by ant *k* positioned on node *i*, α is the weight of the pheromone concentration and β is a parameter that determines the relative importance of pheromone versus distance. Equation (1) indicates that the state transition rule favors transition toward nodes connected by shorter edges and with greater large amount of pheromone.

B. Updating Rule

While constructing its tour, each ant modifies the pheromone by the local updating rule. This can be written below:

$$\tau(i,j)=(1-\rho)\tau(i,j)+\rho\tau_0 \tag{2}$$

where τ_0 the initial pheromone has a value and ρ is a heuristically defined parameter; the local updating rule is intended to shuffle the search process. Hence, the desirability of paths can be dynamically changed. The nodes visited earlier by a certain ant can be also explored later by other ants. The search space can be therefore extended. Furthermore, in so doing, ants will make a better use of pheromone information. Without local updating, all ants would search in a narrow neighborhood of the best previous tour.

C. Global Updating Rule

When tours are completed, the global updating rule is applied to edges belonging to the best ant tour. This rule is intended to provide a greater amount of pheromone to shorter tour, which can be expressed below:

$$\tau(i,j)=(1-\delta)\tau(i,j)+\sigma\delta^{-1} \tag{3}$$

That δ is the distance of the globally best tour from the beginning of the trial and $\sigma\in[0,1]$ is the pheromone decay parameter. This rule is intended to make the search more directed; therefore the capability of finding the optimal solution can be enhanced through this rule in the problem solving process [16].

D. Problem Description

The capacitor placement problem is the determination of the location, number and sizes of capacitors to be placed on a radial distribution system with consideration minimizing the cost of peak power, reducing energy loss and improving voltage profile.

The objective function, F which will be minimized by this capacitor allocation algorithm, is:

$$\min\ F=\min(Cost) \tag{4}$$

$$Cost=C_p P_{Loss}^{Peak}+C_e E_{Loss}+\sum_{i=1}^{N}K_{c,i}Q_{c,i} \tag{5}$$

where P_{Loss}^{Peak}, E_{Loss} are the peak power and energy loss, $C_{p,e}$ and K_c are the cost coefficients of peak power, energy demand and capacitors per KVAr respectively, and Q_c is the size of capacitor in KVAr. The supposed values for the coefficients in (5) are K_p = 168 \$/kW, K_e = 0.07 \$/kWh. Capacitors available commercial sizes that use in this work with their costs in \$/kVAr from [17] are shown in Table 1.

Energy loss reduction is an important factor for the capacitor placement problem and release network capacity, energy loss is calculated as follows:

$$E_{Loss} = \sum_{i=1}^{3} T_i \times P_{Loss,\, i} \tag{6}$$

where i is the total number of load levels in a year, T_i is the time interval the system operates with load level i and $P_{loss,i}$ is active power loss in the load level i.

Table 1. Possible of capacitor size and their costs [17]

Capacity (KVAr)	Capital cost (\$/kVAr)
300	0.35
600	0.22
900	0.183
1200	0.17

At first, the colonies of ant are randomly selected and the initial fitness in different permutations was estimated. The initial pheromone value τ_0 of is also given at this step. Then, the fitness of ants, which is defined as objective function, is estimated and the pheromone can be added to the particular direction in which the ants have chosen. In this time, by roulette selection method, fitness with higher amount of pheromone will be easy to find.

The ants of capacitor is based on level of pheromone and distance. A greater $\tau(i,j)$ means that there has been a lot of traffic on this edge; hence it is proportional to cost inversion and a greater $\eta(i,j)$ indicates that the closer node should be chosen with a higher probability. In placement of capacitor, this can be seen as the difference between the initial total cost and the new total cost.

$$\eta(i, j) = Cost_{initial}(i, j) - Cost_{new}(i, j) \tag{7}$$

$$\tau(i, j) = \frac{1}{Cost_{new}(i, j)} \tag{8}$$

While constructing a solution of placement of capacitor problem, ants visit edge and change their pheromone level by local updating rule of Equation (2). After n iteration, all ants have completed a tour, the pheromone level is updated by applying the global updating rule of Equation (3) for the trial that belongs to the best selected path. Therefore, according to this rule, the shortest path found by the ants is allowed to update its pheromone.

Also, this shortest path will be saved as a record for the later comparison with the succeeding iteration. Then, if all ants have selected the same tour, the process is satisfactory and acceptable; otherwise, repeat the outer loop.

III. CASE STUDY

A test case is selected from a section of Tehran distribution system. The single line diagram of the system is illustrated in Figure 2. This is a MV feeder with 13 buses from 63/20 KV Khoda-Bande-Loo substation. Tables 2 and 3 provide the data of lines and buses. It is assumed in this paper that the load level is in peak condition (10536 + j 5992) kVA [18].

In this case study different loading levels of the system are modeled as percentage of the peak load and are listed in Table 4. The advantage of using this network should be its practicality.

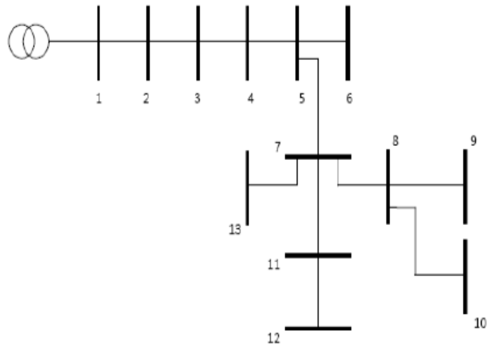


Figure 2. Single line diagram of feeder [18]

Table 2. Line information [18]

From	To	R (ohm)	X (ohm)
1	2	0.176	0.138
2	3	0.176	0.138
3	4	0.045	0.035
4	5	0.089	0.069
5	6	0.045	0.035
5	7	0.116	0.091
7	8	0.073	0.073
8	9	0.074	0.058
8	10	0.093	0.093
7	11	0.063	0.050
11	12	0.068	0.053
7	13	0.062	0.053

Table 3. Bus information [18]

Bus number	P (KW)	Q (KVAR)
1	0	0
2	890	468
3	628	470
4	1112	764
5	636	378
6	474	344
7	1342	1078
8	920	292
9	766	498
10	662	480
11	690	186
12	1292	554
13	1124	480

Table 4. Load level

Level	Network situation	Percentage of Peak Load	Time Duration (hour)
1	Peak load	100	3137
2	Medium load	70	2579
3	Light load	50	3044

IV. NUMERICAL RESULTS

In this section, the proposed location and capacity of the capacitors at different levels are shown in Table 5. For reactive power compensation, the maximum capacitor size should not exceed the total reactive power of the loads.

As can be seen, at maximum load, reactive power due to high network loads and severe voltage drop at the load level, more than other levels of navigation is the number of capacitors. Table 6 has been resulted from simulation before and after capacitor placement at different levels. Information table is not unexpected. It can be seen that with increasing load, the power loss and voltage drop in the bus network was expanded and consequently increases the total cost of the system. So that the cost function value before compensation is 137100 $, but after compensation, the amount is reduced to 106284 $, that makes a 30816 $ benefit. Also cost of peak power loss and cost of energy from 29500 and 107600 is reduced to 22682 and 82792, respectively.

Figure 3 shows the voltage profile of buses in the peak load before and after capacitor installation in the system. It can be observed that the voltage profile has been improved significantly by installing the capacitors in total buses.

Table 5. Location and sizing of capacitors in load levels

Capacity of capacitors (KVAr)			Bus number
Peak load	Medium load	Light load	
300	-	-	4
600	-	-	6
-	1200	-	7
1200	1200	1200	8
1200	-	-	11
-	900	-	12
900	-	-	13

Table 6. Results for the proposed method

After capacitor placement	Before capacitor placement		
106284	137100	Total cost ($)	
22682	29500	cost of peak power loss ($)	
82792	107600	cost of energy ($)	
809.7	0	cost of capacitor ($)	
0.9841	0.9790	Min voltage (pu)	Peak load
135.02	175.60	Power loss (KW)	
0.9879	0.9835	Min voltage (pu)	Medium load
69.24	106.60	Power loss (KW)	
0.9880	0.9864	Min voltage (pu)	Light load
57.40	74.42	Power loss (KW)	

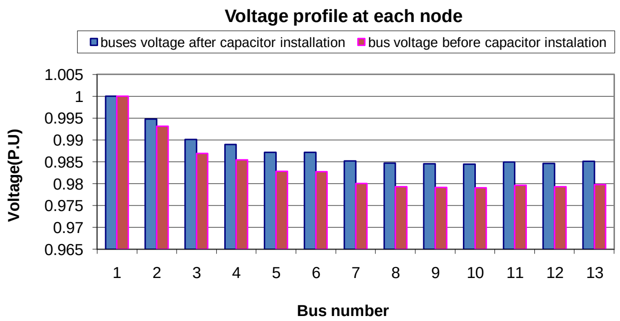


Table 6. Voltage profile after and before installation of capacitors in 13-bus system

V. CONCLUSIONS

Ant colony algorithm is applied in this paper to determine the optimal capacitor placement in distribution systems. An objective function has been considered for the total cost improvement with considering energy loss and peak power loss cost and capacitor's installation cost.

A distribution feeder with 13 buses from Khoda-Bande-Loo of Tehran city is considered and the optimum size and location of capacitors are determined.

The obtained results show that by using capacitor installation with optimum size in optimum location has considerable effects on the reduction of total costs in addition to the power loss reduction and voltage improvement in the test system.

NOMENCLATURES

P_{ij}^{k} : The probability with which ant k in node i chooses to move to node j.

τ_{ij} : The pheromone which deposited on the edge between nodes i and j.

η_{ij} : The inverse of the edge distance between nodes i and j.

α : The weight of the pheromone concentration.

β : The relative importance of pheromone versus distance.

ρ : Evaporation rate

σ : Pheromone decay

P_{Loss} : Power loss

$Cost$: Total cost of system

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