Optimal Capacitor Placement in a Radial Distribution System using Plant Growth Simulation Algorithm

R. Srinivasa Rao and S. V. L. Narasimham

***Abstract*—**This paper presents a new and efficient approach for capacitor placement in radial distribution systems that determine the optimal locations and size of capacitor 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 that employs Plant growth Simulation Algorithm (PGSA) is used to estimate the optimal size of capacitors at the optimal buses determined in part one. The main advantage of the proposed method is that it does not require any external control parameters. The other advantage is that it handles the objective function and the constraints separately, avoiding the trouble to determine the barrier factors. The proposed method is applied to 9, 34, and 85-bus radial distribution systems. The solutions obtained by the proposed method are compared with other methods. The proposed method has outperformed the other methods in terms of the quality of solution.

***Keywords*—**Distribution systems, Capacitor placement, loss reduction, Loss sensitivity factors, PGSA.

I. 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. Studies have indicated that as much as 13% of total power generated is wasted in the form of losses at the distribution level [1]. 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. Schmill [2] developed a basic theory of optimal capacitor placement. He presented his well known 2/3 rule for the placement of one capacitor assuming a uniform load and a uniform distribution feeder. Duran *et al* [3] considered the capacitor sizes as discrete variables and employed dynamic programming to solve the problem. Grainger and Lee [4] developed a nonlinear programming based method in which capacitor location and capacity were expressed as continuous variables. Grainger *et al* [5] formulated the capacitor placement and voltage regulators problem and proposed decoupled solution methodology for general distribution system. Baran and Wu [6, 7] presented a method with mixed integer programming. Sundharajan and Pahwa [8] proposed the genetic algorithm approach to determine the optimal placement of capacitors based on the mechanism of natural selection. In most of the methods mentioned above, the capacitors are often assumed as continuous variables. However, the commercially available capacitors are discrete. Selecting integer capacitor sizes closest to the optimal values found by the continuous variable approach may not guarantee an optimal solution [16]. Therefore the optimal capacitor placement should be viewed as an integer-programming problem, and discrete capacitors are considered in this paper. As a result, the possible solutions will become a very large number even for a medium-sized distribution system and makes the solution searching process become a heavy burden.

In this paper, Capacitor Placement and Sizing is done by Loss Sensitivity Factors and Plant Growth Simulation Algorithm (PGSA) respectively. The loss sensitivity factor is able to predict which bus will have the biggest loss reduction when a capacitor is placed. Therefore, these sensitive buses can serve as candidate locations for the capacitor placement. PGSA is used for estimation of required level of shunt capacitive compensation to improve the voltage profile of the system. The proposed method is tested on 9, 34 and 85 bus radial distribution systems and results are very promising.

The advantages with the Plant Growth Simulation algorithm (PGSA) is that it treats the objective function and constraints separately, which averts the trouble to determine the barrier factors and makes the increase/decrease of constraints convenient, and that it does not need any external parameters such as crossover rate, mutation rate, etc. It adopts a guiding search direction that changes dynamically as the change of the objective function.

The remaining part of the paper is organized as follows: Section II gives the problem formulation; Section III sensitivity analysis and loss factors; Sections IV gives brief description of the plant growth simulation algorithm; Section

V develops the test results and Section VI gives conclusions.

II. 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:

$$min\ f = min(COST) \tag{1}$$

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:

$$V_{min} \le |V_i| \le V_{max} \tag{2}$$

where $|V_i|$ is the voltage magnitude of bus i, V_{min} and V_{max} 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.

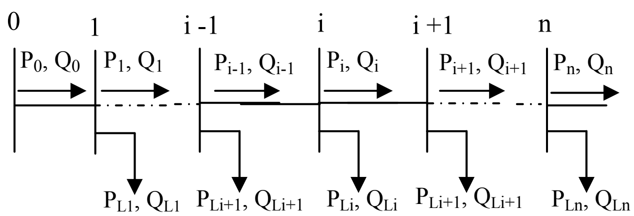

Fig. 1 Single-line diagram of a main feeder

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

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

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

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

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

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

$$P_{T,Loss} = \sum_{i=0}^{n-1} P_{Loss}(i, i+1) \tag{7}$$

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

$$Q_{max}^C = LQ_0^C \tag{8}$$

where L is an integer. Therefore, for each installation location, there are L capacitor sizes $\{Q_0^C, 2Q_0^C, 3Q_0^C, \ldots\ldots, LQ_0^C\}$ available. Given the annual installation cost for each compensated bus, the total cost due to capacitor placement and power loss change is written as

$$COST = K_P P_{T,Loss} + \sum_{i=1}^{n} (K_{cf} + K_i^c Q_i^c) \tag{9}$$

where n is number of candidate locations for capacitor placement, K_p 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_i^c 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

$$Q_i^C \le \sum_{i=1}^{n} Q_{Li} \tag{10}$$

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

III. SENSITIVITY ANALYSIS AND LOSS SENSITIVITY FACTORS

The candidate nodes for the placement of capacitors are