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A Survey of Optimal Capacitor Placement Techniques on Distribution Lines to Reduce Losses

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***Abstract-* To reduce the losses in distribution systems, various capacitor placement techniques have been studied so far. This paper focuses on both classical and artificial intelligence methods. This survey helps the researchers to know about all these methods so that further work on optimal capacitor placement can be carried to improve the results.**

***Index Terms-* capacitor placement, capacitor sizing, optimal capacitor allocation, distribution system, power loss reduction, voltage profile.**

I. INTRODUCTION

Electricity distribution is the final stage in the delivery of electricity from transmission system to consumers. Electric distribution systems are becoming large and complex causing the reactive currents to produce losses and result in increased ratings for distribution components. Studies have indicated that as much as 13% of total power generated is wasted in the form of losses at the distribution level [1]. Since reduction of losses is more economical than increasing generation therefore, losses can be reduced by connecting capacitors in shunt to locally supply a considerable portion of the reactive power demanded by the consumers and thereby reducing the reactive component of branch currents [2]. 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. The extent of these advantages depends on the location, size, type and number of the capacitors as well as on their control settings. Since, the optimal capacitor placement is a complicated combinatorial optimization problem, many different optimization techniques and algorithms have been proposed in the past.

II. ANALYTICAL METHODS

Analytical methods used the calculus at the earliest researches for capacitor placements to calculate the minimum losses and maximum savings. These methods were based on impractical assumptions like constant conduction size, uniform loading, non discrete capacitor sizes, equal capacitor sizes and constant capacitor locations. Due to these analytical methods the famous two-thirds rule was established. According to two-thirds rule, a capacitor of rating equal to two-thirds of the peak reactive demand should be installed at a position two-thirds of the distance along the total feeder length for maximum loss reduction. The early analytical methods for capacitor placement are mainly developed by Neagle and Samson [3]. The problem is defined as determining the location and size of a given number of fixed type capacitors to minimize the power loss for a given load level. But the cost of capacitors and the changes in the node voltages were neglected. Further a voltage independent reactive current model was formulated and solved by Cook [4] & Bae [5]. Lee *et al*. [6] used the fixed and switched capacitors which were placed for optimizing the net monetary savings associated with the reduction of power and energy losses. Grainger *et al.* [7] proposed a voltage dependent methodology for shunt capacitor compensation of primary distribution feeders. Kaplan [8] proposed analytical method to optimize number, location and size of capacitors. Grainger *et al.* [9]-[12] formulated equivalent normalized feeders which considered feeder sections of different conductor sizes and non- uniformly distributed loads.

III. NUMERICAL PROGRAMMING METHODS

Numerical programming methods are iterative techniques which are used to maximize or minimize an objective function of decision variables. For optimal capacitor allocation, the losses or the savings function would be the objective function. Bus voltages, current, capacitor available size and number of capacitors may be the decision variables. The values of these decision variables must also satisfy a set of constraints. Duran [13] used discrete capacitors for a feeder with many sections of different wire sizes and concentrated loads and proposed a dynamic programming solution method. Ponnavaiko and Rao [14] considered load growth as well as system capacity release and voltage rise at light load conditions and used a local optimization technique called the method of local variables by treating capacitor sizes as discrete variables. Baran and Wu [15] determine the optimal size of capacitors placed on the nodes of a radial distribution system and minimize the power losses for a given load by nonlinear programming using decomposition technique. Baldick and Wu [16] used integer quadratic programming to coordinate the optimal operation of capacitors and regulators in a distribution system. [17] proposed a mixed integer programming for the optimal location and sizing of static and switched shunt capacitors in radial distribution systems. Grainger and Civanlar [18] combined capacitor placement and voltage regulator problems for a general distribution system and proposed a decoupled solution methodology. Grainger *et al.* [19] formulated the problem as a nonlinear programming problem by treating the capacitor sizes and the locations as continuous variables.

IV. HEURISTIC METHODS

Heuristics methods are developed through experience and judgement. The purpose of developing such heuristic techniques is to decrease the exhaustive search space, while keeping the end result of objective function at an approximate optimal value. The results produced by heuristics algorithms are not guaranteed to be optimal. Salam *et.al* [20] presents a heuristic strategy with varying load to reduce system losses by identifying sensitive nodes at which capacitors should be placed. The capacitor size is the value that yields minimum system real losses without violation of voltage. The process is repeated for the next candidate node until no further losses reduction is achieved. [21] proposes a method of minimizing the loss associated with the reactive component of branch currents by placing optimal capacitors at proper locations. Once the capacitor locations are identified, the optimal capacitor size at each selected location for all capacitors is determined simultaneously, to avoid overcompensation at any location, through optimizing the loss-saving equations. Salam *et al.* [22] adapted this kind of heuristic search to the problem of capacitor placement. According to this method the largest loss section of the primary feeder is determined and then the node with the highest impact on the losses in that section is detected and compensated. The compensation level is determined in such a way that the losses are reduced to a minimum. Chis *et al.* [23] considered the varying load and optimized capacitor sizes based on maximizing the net economic savings from both energy and peak power loss reductions. Hamada *et al.* [24] introduced a new strategy for capacitor allocation handling the reduction in the section losses by adding a new voltage violation constraint. The new constraint has been the sectional ohmic losses in each branch of the feeder.

V ARTIFICIAL INTELLIGENCE METHODS

AI methods include genetic algorithms, artificial neural network, simulation algorithm, fuzzy, PSO, ant algorithm. These methods for capacitor allocation are discussed below:

A. Genetic Algorithm

Genetic programming is based on the Darwinian principle of reproduction and survival of the fittest and analogous of naturally occurring genetic operations such as crossover and mutation [25]. H. Kim and S.K You [26] have used genetic algorithm for obtaining the optimum values of shunt capacitor bank. They have treated the capacitors as constant reactive power loads. S. Sundhararajan and Anil Pahwa [27] proposed an optimization method using genetic algorithm to determine the optimal selection of capacitors. To achieve high performance and high efficiency of the proposed algorithm, an improved adaptive genetic algorithm (IAGA) [28] is developed to optimize capacitor switching, and a simplified branch exchange algorithm is developed to find the optimal network structure for each genetic instance at each iteration of capacitor optimization algorithm. In [29], a nested procedure is proposed to solve the optimal capacitor placement problem for distribution networks. At the outer level, a reduced-size genetic algorithm is adopted aimed at maximizing the net profit associated with the investment on capacitor banks. At the inner level, power losses are minimized for the remaining loading conditions, taking into account the capacitor steps determined at the outer level. [30] proposed genetic algorithm as search method to determine optimum value of injected reactive power while considering the effects of loads harmonic component on network.

B. Artificial Neural Network

A two-stage artificial neural network is used to control the capacitors installed on a distribution system for a non-uniform load profile [31]. Gu *et.al.* [32] control both capacitor banks and voltage regulators using artificial neural network. The regulation of capacitor banks by parallel application of artificial neural network and genetic algorithm is proposed in [33]. The combined use of both methods of the artificial intelligence allows solving the reactive power and voltage control problem with higher level of its reliability and quality.

C. Simulated Annealing

Simulated annealing (SA) is based on annealing of materials which involves heating and controlled cooling of a material to increase the size of its crystals and reduce their defects. The heat causes the atoms to become unstuck from their initial positions (a local minimum of the internal energy) and wander randomly through states of higher energy; the slow cooling gives them more chances of finding configurations with lower internal energy than the initial one. By analogy with this physical process, each step of the SA algorithm attempts to replace the current solution by a random solution. The new solution may then be accepted with a probability that depends both on the difference between the corresponding function values and also on a global parameter T (called the temperature), that is gradually decreased during the process. Chiang *et al.* [34] used the optimization techniques based on simulated annealing (SA) to search the global optimum solution to the capacitor placement problem. This methodology is proposed to determine the locations where capacitors are to be installed, the types and sizes of capacitors to be installed, and the control settings of these capacitors at different load levels. Ananthapadmanabha *et al.* [35] used SA to reduce the cost function which includes the energy and the capacitor installation cost. The practical aspects of capacitors, load constraints and operational constraints at different load levels are considered in [36] which are solved by a powerful simulated annealing approach.

D. Fuzzy Logic Method

This method is based on fuzzy sets theory (FST) was introduced by Zadeh [37] in 1965 dealing with reasoning that is approximate rather than classical logic. A fuzzy variable is modeled by a membership function which assigns a degree of membership to a set. Usually, this degree of membership varies from zero to one. [38] presents a novel approach using approximate reasoning to determine suitable candidate nodes in a distribution system for capacitor placement. Voltages and power loss reduction indices of distribution system nodes are modelled by fuzzy membership functions. [39] developed a fuzzy-based approach for the placement of the shunt capacitor banks in a distribution system with considering harmonic distortions. In [40] voltage and real power loss index of distribution system nodes are modelled by fuzzy membership function. A fuzzy inference system containing a set of heuristic rules is designed to determine candidate nodes suitable for capacitor placement in the distribution system. Capacitors are placed on the nodes with highest sensitivity index. Masoum *et.al.* in [41] proposed a fuzzy-based approach for optimal placement and sizing of fixed capacitor banks in radial distribution networks in the presence of voltage and current harmonics. The objective function includes the cost of power losses, energy losses, and capacitor banks. Using fuzzy set theory, a suitable combination of objective function and constraints is generated as a criterion to select the most suitable bus for capacitor placement. The α-cut process is applied at each iteration to guarantee simultaneous improvements of objective function and satisfying given constraints.

E. Partical Swarm Optimization (PSO)

Particle swarm optimization (PSO) method is a population based evolutionary computation technique developed by Dr. Eberhart and Dr. Kennedy [42] in 1995, inspired by social behaviour of bird flocking or fish schooling. It utilizes a “population” of particles that “fly” through the problem hyperspace with given velocities. At each iteration, the velocities of the individual particles are stochastically adjusted according to the historical best position for the particle itself and the neighbourhood best position. Both the particle best and the neighbourhood best are derived according to user defined fitness function [43]. The movement of each particle naturally evolves to an optimal or near-optimal solution. A discrete version of PSO [44] is combined with a radial distribution power flow algorithm (RDPF) to form a hybrid PSO algorithm (HPSO). The former is employed as a global optimizer to find the global optimal solution, while the latter is used to calculate the objective function and to verify bus voltage limits. To include the presence of harmonics, the developed HPSO was integrated with a harmonic power flow algorithm (HPF). [45] presents a novel approach that determines the optimal location and size of capacitors on radial distribution systems to improve voltage profile and reduce the active power loss. Capacitor placement & sizing are done by loss sensitivity factors and particle swarm optimization respectively. [46] highlights the PSO key features and advantages over other various optimization algorithms and also discusses PSO possible future applications in the area of electric power systems and its potential theoretical studies. Two new objective functions are defined in [47]. The first one is defined as the sum of reliability cost and investment cost. The second is defined by adding the reliability cost, cost of losses and investment cost. This problem is solved using a particle swarm optimisation-based algorithm on a distribution network. [48] provides a comprehensive survey on the power system applications that have benefited from the powerful nature of PSO as an optimization technique.

F. Ant Algorithm

Ant algorithm has been inspired by the behaviour of real ant colonies. Real ants are capable of finding the shortest path from food sources to the nest without using visual cues and bring them back to their colony by the formation of unique trails. Therefore, through a collection of cooperative agents called ants, the near-optimal solution to capacitor placement problems can be effectively achieved. Bouri *et al.* [49] presents an ant colony approach optimization to shunt capacitor placement on distribution systems under capacitor switching constraints. In [50], a method employing the ant colony search algorithm (ACSA) is proposed to solve the capacitor placement problems. [51] aims to minimize the total active losses in electrical distribution systems by means of optimal capacitor bank placement. The proposed methodology to solve this optimization problem is the ant colony optimization (ACO). The gradient method is combined in order to accelerate the convergence of the ACO algorithm.

VI. CONCLUSION

In this paper, various capacitor allocation techniques are discussed. It has been found that the classical methods are simpler but have disadvantages like poor handling of qualitative constraints, weak convergence, and slow computation with large variables. Also they are very expensive for large system. On other hand, AI methods are fast and versatile. These methods are suitable for non linear and large system. This survey article will be useful to the researchers to find the previous work done in the field on capacitor allocation.

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