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Optimal Capacitor Placement in Distribution Feeders

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***Abstract*—**Optimal capacitor allocation in distribution systems has been studied for a long times. It is an optimization problem which has an objective to define the optimal sizes and locations of capacitors to be installed. In this works, an overview of capacitor placement problem in distribution systems is briefly introduced. The objective functions and constraints of the problem are listed and the methodologies for solving the problem are summarized.

***Keywords*—**Capacitor Placement, Distribution Systems, Optimization Techniques

I. INTRODUCTION

THE application of shunt capacitor in distribution feeders has always been an important research area [1]. It is because a portion of power loss in distribution systems could be reduced by adding shunt capacitors to supply a part of the reactive power demands [2]. For this reason, the source of the system does not necessarily to supply all reactive power demands and losses. Consequently, there is a possibility to decrease the losses associated with the reactive power flow through the branches in the distribution systems. It has been realized that the benefits of capacitor placement in distribution systems are power factor correction, bus voltage regulation, power and energy loss reduction, feeder and system capacity release as well as power quality improvement. The extent of the aforementioned advantages of capacitor placement depends on how capacitors are allocated and controlled under possible loading conditions. This means that the optimization problem, namely, capacitor placement problem should be formulated with the desired objective function (such as loss minimization) and various technical constraints (e.g. the limits of voltage levels and power flow). After that, the proper solution techniques should be applied to simultaneously determine the optimal number, location, type, size and control settings at different load levels of the capacitors to be installed.

II. FORMULATION OF CAPACITOR PLACEMENT PROBLEM

Because capacitor sizes and locations for allocation are discrete variables, this makes the capacitor placement problem as a combinatorial nature. The problem is a zero-one decision with discrete steps of standard bank size of capacitor. In some cases, each step of the capacitor bank size has a different installation cost.

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Such zero-one decision and discrete steps make the capacitor placement problem as a nonlinear and non-differentiable mixed integer optimization problem.

The objective function of the capacitor placement problem is usually formulated as follows:

$$Min\ F = \sum_{j=1}^{S} T^j P_L^j \tag{1}$$

$$Min\ F = \sum_{j=1}^{S} k_e^j T^j P_L^j \tag{2}$$

$$Min\ F = \sum_{j=1}^{S} (k_e^j T^j P_L^j) + C_C \tag{3}$$

$$Min\ F = \sum_{j=1}^{S} (k_e^j T^j P_L^j) + C_C + k_P P_L^P \tag{4}$$

where
F = the value of the desired objective function
S = number of load levels
T^j = time duration for the j-th load level
P_L^j = power loss at the j-th load level
k_e^j = per unit cost of energy loss at the j-th load level
C_C = investment cost of capacitor
k_P = per unit cost of peak power loss
P_L^P = power loss at peak load level

The aim of (1) is to minimize the total energy losses in a day whereas the target of (2) is to keep the cost of energy losses as minimum. The objective function in (3) minimizes the sum of energy loss cost and the investment cost required for capacitors allocation. Finally, the desired objective function in (4) is to minimize the total cost due to energy loss cost, peak power loss cost, and the investment cost of capacitors.

In addition, the study of Sallam et al. [3] defines two news objective functions. The first one considers the cost of reliability (ECOST) and investment cost while the second, ECOST, cost of losses and the investment cost are included in the objective function.

For the technical and functional constraints of the capacitor placement problem, the optimal solution should be satisfied power flow equations, bus voltage limits (to maintain the voltage profile within the upper and lower), limitation of capacitor kVAr to be installed at each bus (because there are limited space for placement).

As more and more nonlinear devices and loads appear in distribution systems, the harmonics constraint (to keep the voltage distortion in term of THD value under the maximum limit) should be added as discussed in [4] to prevent undesired occurrence of harmonic parallel resonance from nonlinear devices and loads.

It should be noted that early studies on capacitor placement problem [5]-[6] assume that the systems are balanced distribution feeders under balanced loads. Three-phase unbalanced distribution systems containing feeders with missing phases, unevenly loaded feeders were shunt capacitors on single or double phase feeders are later studied in [7]-[8].

III. Summary of Solution Techniques

A variety of solution techniques have been applied to solve the capacitor placement problem. In the early work, most of the researchers used conventional analytical method in conjunction with some heuristics [9]-[10]. As the system size grows, the solution of the problem will be prohibitively CPU intensive and many studies have considered faster alternative solution procedures.

Several works have described algorithms based on heuristic programming [11]-[12] to solve the problem. The heuristic algorithms are robust and do not require high computational efforts. However, for very large systems, the quality of the solution may be compromised.

Some methodologies for finding the optimal solution of capacitor placement problem are:

A. Graph

A graph is a set of nodes connected by arcs. Each node corresponds to a possible combination of capacitor sizes and locations for a given number of capacitors to be placed. A separate graph is used for each possible number of capacitors to be installed. The search process finds the nodes of a graph in an attempt to determine the optimal solution. Beginning with some minimum number of capacitors to be placed, a search is performed to locate the node in that graph which gives the minimum value of the objective function. If the maximum number of capacitors to be installed has not been reached, the number of capacitors to be placed is incremented and the next graph is searched. At some point, addition of another capacitor will increase the value of the objective function, the process is then terminated [13].

B. Fuzzy Logic

Fuzzy logic allows a computational representation of heuristic knowledge about a specific problem. It has been extensively applied in several areas of knowledge to solve mainly control and optimization problems [14]. To apply fuzzy logic to solve the problem, it is necessary to identify the main variables that have influence on the decisions to be taken and quantify their values in relevance levels. A relationship function establishes the profile of these variables by expressing the compatibility degree of each one of them with previously known information. According to these situations, rules are established and necessary actions to a solution are determined.

In the capacitor allocation problem, rules are set up to determine whether the advantage of having a bank installed in a particular bus. Bus voltage and the value of the objective function are the fuzzy variables. They are a function of the bus which is being assessed to verify the practicability of having capacitors installed. Bus voltage is given in per unit values whose reference is the substation voltage. It is used to find the buses where the voltage drop is higher [15].

C. Tabu Search

Tabu search (TS) [16] is one of the meta-heuristic methods for solving a combinatorial optimization problem. TS is based on the hill-climbing method that evaluates the final solution through repeating the process of creating solution candidates in the neighborhood around the initial solution and selecting the best solution in them. However, TS is an extension of the hill-climbing method in a way that it has the adaptive memory called the tabu list that adjusts some attributes not to change. Once a new attribute enters into the tabu list, it continues to stay in the tabu list for a while. Afterwards, the oldest attribute is released from the tabu list after a new attribute enters into the tabu list. Each time the iteration count is updated, a new attribute is assigned to the tabu list.

In order to obtain optimal solution, TS use intensification and diversification techniques. The former means intensification of the search in the neighborhood of the sub-optimal solution, the latter means diversification of the search to so far unexplored regions of the solution space. If intensification is missing, the search becomes an iterated random sampling; if diversification is missing, the process may be trapped in a sub-optimal region.

The frequency counter in the solution structure is used in the intensification and diversification techniques. The frequency counter denotes the times the solution (or the move) having been visited throughout the solution process.

For example, according to the size of neighborhood to be searched in the capacitor placement problem, a threshold named the frequency counter threshold is set at three, that is to say, if the solution has been visited three or more times, it will be heavily penalized and thus loose its attractiveness. Search will, therefore, be directed to so far unexplored region of the solution space to diversify the search process. When the frequency counter is less than three times, intensifying the search in the neighborhood of the sub-optimal region is possible. In this manner, the tabu search is expected to be able to find the optimal solution to the combinatorial optimization problem [17].

D. Simulated Annealing

Simulated Annealing (SA) comes from analogy of annealing of metal or crystal. SA introduces a parameter called temperature that is controlled by the cooling schedule at each iteration. As temperature cools down, the state converges to a solution. The state freely moves to other states at high temperature while it has limitations to move to others at low temperature [18].

Application of SA to the capacitor placement problem by means of general-purpose heuristic optimization techniques is proposed in [19].

E. Genetic Algorithms

Genetic algorithm (GA) is a statistical method for the optimization. The important property of GA is its robustness which has a flexible balance between efficiency and necessary features for survival in the different environments. One of the main concepts in the genetic algorithm is coding. Genetic algorithm instead of using problem parameters or variables, it encodes them and uses the codes. The number of bits used for encoding procedure depends on solution accuracy, range of parameter changes and the relation between variables. Chromosomes are string of bits in the encoded form of possible solutions (feasible or unfeasible) of the problem. The set of chromosomes is called population. Each step of genetic algorithm deals with the set of chromosomes in the search space. The crossover operation breaks parents' chromosome from one spot and displace the broken parts with each other [20].

For solving the capacitor placement problem, the chromosome consists of n+l bits of binary numbers where n is the number of probable capacitor locations. The first bit is used to indicate the location of capacitors and will be referred to as location selector. The length of the location selector bit is equal to the number of probable capacitor locations and each location is represented by a bit of the string [21].

A '1' in the bit position is used to select a location and a '0' bit indicates that the location is not selected. Each of the remaining ' n' bits is used to indicate the kVAr value at a probable capacitor location. The kVAr bit for a particular location may have a non-zero value when the selection bit for that location in the location selector bit is zero. The kVAr bit in such cases is ignored while determining the fitness function value of a chromosome.

The operators, namely crossover and mutation are applied on each bit irrespective of the value of the location selector bit for the location. The location selector bits thus, act as switches. While capacitors are installed at each probable location, the capacitors of those locations are connected to the system for which the location selector bit is 1 [22].

F. Particle Swarm Optimization

Particle Swarm Optimization (PSO) is a meta heuristic parallel search technique [23]. PSO is derived from simulation of a simplified social model of swarms (e.g. bird flocks or fish schools). The interaction of particles in swarm, using common evolutionary computation algorithm, guides the direction of swarm towards the optimal regions of search space. The main merits of PSO are computationally efficient, simplicity in concept and implementation, less computation time, and inexpensive memory for computer resource. In [24], PSO is employed to determine the optimal solution of capacitor placement problem with two objective functions. The first one is power loss minimization and the second objective function is cost minimization in a specified period of time

G.Ant Colony Optimization

The ant colony optimization (ACO) imitates the behaviors of real ants. Real ants can find the shortest path from food sources to the nest without 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. In addition, the ants can establish the 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. Any trail that is rich of pheromone will thus become the goal path. The application of ACO to solved capacitor placement problem is shown in [25].

H.Harmony Search Algorithm

Harmony search algorithm (HS) is a recently meta-heuristic optimization algorithm inspired by playing music. It is based on meta-heuristic which combine rules and randomness to imitate natural phenomena. HS algorithm is inspired by the operation of orchestra music to find the best harmony between components which are involved in the operation process, for optimal solution. As musical instruments can be played with some discrete musical notes based on player experience or based on random processes in improvisation, optimization design variables can be considered certain discrete values based on computational intelligence and random processes [26]. Music players improve their experience based on aesthetics standards while design variables in computer memory can be improved based on objective function.

The application of the HS for determining the optimal location and size of shunt capacitors in 9-bus radial distribution systems has been presented in [27].

IV. Conclusion

The capacitor placement problem is a quite complex optimization problem due to its combinatorial nature. Many objective functions including technical and functional are formulated. A wide variety of solution techniques has been applied to solve the problem as described in this paper.

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