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Optimal allocation of capacitors in distribution systems using particle swarm optimization

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ABSTRACT

A particle swarm optimization (PSO) approach for finding the optimal size and location of capacitors is reported in this work. The proposed technique finds optimal locations for shunt capacitors from the daily load curve. In addition, it determines the suitable values of fixed and switched capacitors. A dynamic sensitivity analysis method is used to select the candidate installation locations of the capacitors to reduce the search space of this problem. In case of more than one location, the dynamic sensitivity helps in deciding other locations considering the effect of previously decided locations and values of capacitors. A simple iterative method is used to compute the power flow. The results obtained for well studied 70-bus and 135-bus systems are compared with the solutions obtained by Tabu Search (TS), Hybrid and Genetic Algorithm. It is demonstrated that the proposed PSO approach offers the global optimal solution with greater saving.

1. Introduction

Electrical energy supply from generation sites to ultimate consumers reach via the transmission, sub transmission and distribution segments of the overall power system. Such energy transfer is accompanied by network dependent power losses which have the effect of increasing the peak load on the system. It is acknowledged by all that the bulk of the power loss occurs on the distribution system which is 13% of the total power generated [1]. The reactive power accounts for a portion of these losses. Some of these losses due to reactive power can be reduced by application of shunt capacitors on primary distribution feeders to relieve capacity requirement. Hence, optimal capacitor allocation in electrical distribution networks has always been the concern of electric power utilities. Optimal capacitor allocation problem deals with determination of location, size, type and number of capacitors to be installed such that the maximum economic benefits are achieved without violating the operational constraints. Several formulations have been suggested for this problem and they have been solved by available computational techniques. A survey of these techniques by Ng et al. [1] classifies these techniques in four groups of analytical, numerical programming, heuristics, and artificial intelligence.

Analytical method in conjunction with heuristics for capacitor placement was introduced by Neagle and Samson [2] and subsequently by cook [3]. A pioneering work which determines the capacitor sizes as discrete variables using dynamic programming technique was reported by Duran [4]. More rigorous approaches were suggested in 1980's [5–8]. Grainger and Lee [5] formulated this problem as a non-linear programming problem by treating the capacitors locations and sizes as continuous variables. Fawzi et al. [6] incorporated the released substation kva and the voltage rise at light-load level into a model developed by Neagle and Samson [2]. Ponnavaikko and Prakasa Rao [7] proposed a model, which considered the load growth and the discrete nature of capacitor size, apart from those considered in [5] and used a local optimization technique. Kaplan [8] presented a formulation of feeders with multiple laterals and suggested a heuristic solution algorithm. Baran and Wu [9] presented a problem formulation similar to that of Grainger and Lee [5], a non-linear optimization problem, but incorporated the distribution power flow equation, constraints on node voltage magnitudes at different load levels and discrete nature of capacitor sizes, into the model and the resulting formulation represents a mixed-integer programming problem. Maximum saving objective of this problem and its formulation & solution as mixed integer linear problem is reported by Khodr et al. [10]. Two phase solution, formulation as conic problem and its solution by interior point method in phase-I and mixed integer linear programming formulation and solution in phase-II of this problem is suggested in [11]. A heuristic method is proposed by Segura et al. [12] in which a relaxed version of the exact mathematical model of the problem is solved using interior point method. Mixed integer non-linear programming has been

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Nomenclature

S_i^k	velocity of individual constant
$rand()$, $Rand()$	uniform random number between 0 and 1
x_{id}^k	current position of individual i at iteration k
pbest	best value attained by individual i
gbest	global best value i at iteration k
C_1 & C_2	acceleration of the group
w	inertia weight factor
w_{max}	maximum value of inertia weight (0.9 in this study)
w_{min}	minimum value of inertia weight (0.4 in this study)
$iter_{max}$	maximum iteration number (generations)
iter	current iteration number
x	unknown power flow (depend) variables
y	known or specified (independent) variables
V_m	voltage at mth node
V^{min}	minimum acceptable voltage
V_{sys}^{min}	minimum system voltage in an iteration
V^{max}	maximum system voltage (1.0 pu in this study)
K_{ei}	energy cost constant for load level i
K_{cj}	capacitor cost constant depending on type of capacitor placed at jth location
P_{Li}	power loss at ith load level with corresponding time duration T_i
C_j	injected kvar at jth node
T_i	duration of load level i
n	number of load levels
k	number of locations
θ_i	voltage angle at node i
θ_j	voltage angle at node j
P_j	active power at bus j
Q_j	reactive power at bus j
P_L	total power loss in the system
r_{ij}	real part of impedance between nodes i and j

suggested by Leonardo et al. [13] for capacitor placement as well as reconfiguration in order to achieve the objective of minimum energy loss operation of radial distribution network. A direct search method has been used by Ramalinga Raju et al. [14] in which a best suited node for a particular size of capacitor out of all possibilities is identified and then the capacitor is placed.

The analytical methods are very fast but they suffer from inability to escape local optima. The application of search and evolutionary techniques started in early 1990s in order to overcome this problem of analytical techniques. The evolutionary techniques, simulated annealing, Tabu Search and GA have been reported by several authors [15–29]. In this dissection, Chiang et al. [15] presented a general capacitor placement problem formulation by taking practical aspects of capacitors and the operational constraints at different load levels into consideration and solved by simulated annealing. These authors further extended this method by incorporating the cost associated with capacitor placement considering it to be a step-like function and treating the capacitor sizes and control settings as discrete variables [16]. The Tabu Search technique to find an optimal solution has been used by Huang et al. [17]. Gallego et al. [18] presented same problem using Hybrid Approach, a combination of Tabu Search and heuristics.

Genetic algorithm (GA) based method was initially introduced by Ajjarapu and Albama [19] which was further extended by Boone and Chiang [20] and later by Sundharajan and Pahwa [21] with additional features. Miu et al. [22] reported two stages GA for this problem in which the solution obtained by GA in first stage is further improved by sensitivity based heuristics at the second stage. Levitin et al. [23] included system capacity release, peak load reduction and reduction of annual energy loss in a feeder in their formulation of optimal capacitor allocation problem and solved by GA.

Further improved form of GA was applied by Kim et al. [24] for this problem that combines GA with a stochastic variant of the simplex method called elite based simplex GA (ESGA). In order to avoid local minima of GA, normally large population is desired that require high processing time. This can be overcome by use of micro genetic algorithm wherein De Souza et al. [25] applied fuzzy logic to reduce the search space and micro genetic algorithm for solution of capacitor allocation problem. Use of fuzzified multiple objective function: reducing the total cost of energy loss and capacities, increasing the margin loading of feeders and improving voltage profile and solution by GA was proposed by Hsiao et al. [26]. Ants are capable of finding the shortest path from food sources to their nests. Inspired by this behavior of real ant colonies, ant algorithm was developed. However, further improved version of this method, out detection by bird differential evolution (ADHDE) was applied by Chiou et al. [27]. This is achieved by reducing the number of mutations. Similarly, principle of plant growth process was exploited by Srinivasas Rao et al. [28] to make use of plant growth simulation algorithm for the solution of capacitor placement problem. Haghifam and Malik [29] attempted to overcome the problem of uncertainty and time variation in load by fuzzy representation of load. Final solution is obtained by GA. Their implementation of GA uses two row chromosomes to represent the capacitor values of fixed and switchable type. Szuvovivski et al. [30] suggested use of other voltage regulators along with capacitor for such applications. They solved this problem using both GA and optimal power flow.

It can be observed from above review that the initial methods of capacitor placement problem used analytical methods which are basically conventional optimization techniques. These optimization methods work on the basis of search directions generated from derivatives of the function. Therefore, it becomes imperative to express the problem in the form of continual differentiable function; otherwise, these methods loose efficiency. The later methods starting from 90s are evolutionary and AI based. Combinations of more than one method are also reported. But GA has been found to be attractive and has been widely used. However, a more recent method of particle swarm optimization (PSO) has proved to be more capable and had been applied for many optimization problems related to power system such as economic dispatch of generators [31] and reactive power and voltage control [32]. Apart from these its application for capacitor allocation also has been explored. Prakash and Sydulu [33] applied PSO technique for capacitor placement problem but in their formulation the objective function is not very clear. The PSO technique used by AlHajri et al. [34] does not reveal the constraint handling methodology. Yu et al. [35] demonstrated the application of PSO for this problem considering harmonics and demonstrated on a single and small 9 bus system. The constraints are handled using conventional penalty function method. This idea was further extended by Eajal and El-Hawary [36] to account for unbalanced operating conditions also. Demonstration of PSO is further reported by Etemadi and Fotuhi-Firuzabad [37] where in reliability cost is also included along with the cost of losses and investment in the objective function. However, unconstrained problem has been formulated and solved in this approach. Kim et al. [38] proposed non-linear interior