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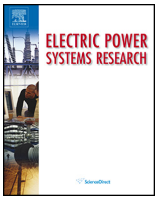

Algorithm of inclusion and interchange of variables for capacitors placement

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ABSTRACT

This work develops the algorithm of inclusion and interchange of variables to obtaining the sizes, the placements and the control schemes of the capacitors banks that minimize the annual total cost while complying with the maximum and minimum voltage constraints. This is a new and very efficient search method that improves the results of the previous contributions. The method considers all the possible locations for capacitors placement as well as the correct interrelation between sizes of all the capacitors of fixed and switched type. Instead of to place the capacitors on candidate nodes that are previously selected by sensitivity factors and then to select their time-controls, the presented method examines the placement of the capacitors in all available positions (node, control) by evaluating directly the effects of the inclusion and the interchange of variables (capacitors) in the value of the objective function. The fact that the optimization of the placements and the time-controls of the capacitors is coordinated with the selection of their sizes, allows the obtaining of a high quality solutions for the optimization problem. The effectiveness of the proposed method is tested by solving various examples and by comparing the obtained results with several previously published solutions for these examples.

1. Introduction

The capacitor placement in distribution circuits has received much attention in the specialized bibliography. The tabu search (TS) method is applied by Huang [1] to determine the size and placement of capacitor banks. The set of candidate nodes is obtained by a sensitivity analysis of losses. Miu [2] uses a genetic algorithm (GA) to obtain initial solutions. These solutions are later refined by a heuristic based in sensitivities of the losses respect to the reactive power. Wang [3,4] employs the integer quadratic programming method to solve the capacitors placement and the real time control of switched banks as two decoupled problems. Ng [5] uses a fuzzy expert system to determine the locations of the capacitors and Mekhamer [6] presents diverse heuristic strategies to capacitor placement.

Das [7] uses a simple GA for capacitors placement that considers fixed banks and the switched banks. Kim [8] uses an elitist implementation of GA to improve voltage profile and minimize power losses in the unbalanced circuits. Souza [9] employs a micro-genetic algorithm that uses a fuzzy heuristic to determine the locations. The non-dominated sorting genetic algorithm (NSGA) is employed by Milosevic [10] to find the optimal locations of capacitor banks to compensate the voltage drop during emergencies and to reduce losses during normal operation. Mendes [11] uses a memetic algorithm which solves placement of fixed capacitor banks with constraints in budget.

Khodr [12] formulates the capacitor placement problem as an integer linear programming problem. Thus, the model must be linearized. Das [13] selects the placement of capacitors by sensitivity analysis and uses a GA for select the capacitors size and control. Another application of GA is presented by Swarnkar in [14]. In [15], Rao presents a two part methodology that uses the losses' sensitivity factors to select the candidate locations for the placement of the capacitors and then employs plant growth simulation algorithm (PGSA) to estimate the optimal size of the capacitors.

Singh [16] uses a particle swarm optimization (PSO) technique locate the capacitors. The locations are selected from a set of candidate nodes obtained by a dynamic analysis of sensitivity. The direct search algorithm (DSA) presented by Raju [17] tests all possible locations for placing a capacitor. The node which gives maximum reduction in active power losses is selected. The sizes of the previously placed capacitors are not recalculated which can degrade effectiveness of the solutions obtained.

A two stage method is presented by Abul'Wafa [18]. The sizes of the capacitors is determined simultaneously by optimizing the

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saving of losses with respect to the currents of the capacitors. However, the candidate locations for placement are determined by sensitivity technique of losses. El-Fergany [19] presents an artificial bee colony-based (ABC) approach that identifies the sizing and placement of the capacitors within the set of candidate nodes. The method ranks the nodes by using the losses' sensitivity factors. Sultana [20] uses the teaching-learning based optimization (TLBO) to minimize losses and cost with capacitors placement. However, the selection of sizes is made independently for the different load levels.

Tavakoli [21] presents an approach based on the ABC metaheuristic, while Yahya [22] uses the technique of ant colony optimization (ACO). Two bio-inspired algorithms: the bat algorithm (BA) and cuckoo search (CS) are used in [23] to search in all possible locations by considering all the different sizes of capacitors. Devabalaji [24] employs the losses sensitivity factors and voltage stability index to determine the optimal location of capacitor banks. The bacterial foraging optimization algorithm (BFOA) is used to find the optimal sizes. Besides, Shuaib [25] uses a sensitivity analysis to reduce the search space of locations and applies the gravitational search algorithm (GSA) to calculate the capacitors sizes.

Recently, Ali [26] uses improved harmony search algorithm (IHA), Abdelaziz [27] the flower pollination algorithm (FPA) and El-Ela [28] the ant colony optimization method (ACO). In these cases the algorithm decides the sizes and locations of the capacitors within the set of nodes previously determined by the magnitude of power losses index. Other presented algorithms are: the crow search algorithm (CSA) in Askarzadeh [29], the improved PSO algorithm (IPSO) in Lotfi [30], fuzzy techniques and the BFOA algorithm in Kishore [31] and the harmony search algorithm (HSA), the algorithm PSO and the algorithm ABC (HSA-PABC) in Muthukumar [32].

Some recent contributions to the simultaneous optimization of capacitors and distributed generators (DG) are presented by: Sudabattula [33] with the FPA method, Kanwar [34] with the IPSO method, Rahiminejad [35] with the TLBO method, Mohammadi [36] with the BFOA method and Kansal [37] with PSO method. Although these procedures can improve the savings, the capacitors placement remains as a subject of interest by himself.

The most of the previous contributions [1,2,5,6,9,11,13,15,16,18,19,24–28,31–34] use the losses sensitivity factors to rank the importance of the nodes with respect the capacitors placement. This ranking is used to reduce the set of candidate nodes to place the capacitors. However, this reduction of the candidate locations can prevent from the obtaining of solutions of interest. Besides, a node with high sensitivity-factor for capacitor placement at one load level could have a low sensitivity factor at another load level. Some heuristic methods [7,17] are based in the consecutive placement of the capacitors, one at one, but the sizes of the previously placed capacitors are not recalculated for obtain maximum saving. Besides, in some of the contributions only consider fixed capacitor banks.

This work develops the algorithm of inclusion and interchange of variables to obtaining the sizes, the placements and the control schemes of the capacitor banks that achieve the maximum saving of annual total cost. This is a new and very efficient search method that improves the results of the previous contributions. The method considers all the possible locations for capacitors placement as well as the correct interrelation between sizes of all the capacitors of fixed and switched type. Besides, the formulation allows the inclusion of maximum and minimum voltage constraints. The effectiveness of the proposed method is tested by solving various examples and by comparing the obtained results with several previously published solutions for these examples.

2. Formulation of the optimization problem

The present work formulates the capacitor placement problem in distribution circuits as the selection, placement and control in time of the needed capacitor banks to obtain the maximum saving in total annual cost. The solution must comply with the constraints of: maximum and minimum voltage.

2.1. Independent variables

The daily variation of load is described by K states that are sorted in ascending order of load. In order to represent the control in time of the capacitor is defined the parameter t which value determines the load state in which is started the connection of the capacitor. Due the load states are sorted in ascending order, the capacitor will be connected in all load states with index $k \geq t$. In that way, if $t = 1$ means that the capacitor is of fixed type (connected at all load states). Otherwise, if $t > 1$ means that the capacitor is of switched type (connected at the load states from t up to the peak load state).

The circuit contains N nodes for capacitors placement and there are K possible values for the control parameter of each capacitor. If the capacitor's position is an structured parameter defined by the node (n) and the control (t) of the capacitor, is declared the *pos* array of length ($N{\cdot}K$) that contains all the possible positions for the capacitors where, $pos(i).n$ and $pos(i).t$ are the node and the control of the capacitor placed on the position i.

Thus, the independent variables of the problem are the vectors x and u of length (Mx1) that represent respectively the sizes and the positions of the M capacitors that will be placed on the circuit. The elements of u are integers limited to the number of elements of the array of possible positions.

2.2. Objective function

As the capacitors placement represents an investment project that pursues to obtain earnings from the saving achieved in the cost of losses, the $F(x,u)$ objective function is expressed as the maximization of the total cost saving.

$$\max F(x,u) = \sum_{k=1}^{K} c_k \left(\Delta P_k(0) - \Delta P_k(x,u)\right) - kc \sum_{i=1}^{M} x_i - kf \cdot M \tag{1}$$

Where c_k($/kW) is calculated as the product of the energy cost ($/kWh) and the duration of load status k (hours/year). Besides, at peak load status, an extra amount of $/kW can be added to c_k to account for the cost of electric capacity. On the other hand, $\Delta P_k(0)$ represents the losses in k load state in the base case (uncompensated) and $\Delta P_k(x,u)$ the obtained losses after the installation of the capacitors of sizes x on the positions u. Finally, kc is the annual cost coefficient ($/kvar) of capacitors, kf represents the fixed cost per capacitor bank ($/bank) and M is the number of capacitors.

The system power losses at the k load state are calculated by:

$$\Delta P_k = {I_{[k]}}^{*} \cdot R \cdot I_{[k]} \tag{2}$$

Where $I_{[k]}$ represents the column vector of the injected currents at load state k (column of index k of the matrix I of size (NxK)) and R is the resistance matrix (real part of the impedance matrix of the network). The matricial operation z^* denotes the transposed conjugate of the matrix z.

Once the capacitors of sizes x are placed on the positions u, is produced a variation on system power losses due to the capacitive current injections.

$$\Delta P_k(x,u) = \left(I_{[k]} + \Delta I_{[k]}\right)^{*} \cdot R \cdot \left(I_{[k]} + \Delta I_{[k]}\right) \tag{3}$$