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ORIGINAL ARTICLE

Optimal capacitor placement and sizing in radial electric power systems

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Abstract The use of capacitors in power systems has many well-known benefits that include improvement of the system power factor, improvement of the system voltage profile, increasing the maximum flow through cables and transformers and reduction of losses due to the compensation of the reactive component of power flow. By decreasing the flow through cables, the systems' loads can be increased without adding any new cables or overloading the existing cables. These benefits depend greatly on how capacitors are placed in the system. In this paper, the problem of how to optimally determine the locations to install capacitors and the sizes of capacitors to be installed in the buses of radial distribution systems is addressed. The proposed methodology uses loss sensitivity factors to identify the buses requiring compensation and then a discrete particle swarm optimization algorithm (PSO) is used to determine the sizes of the capacitors to be installed. The proposed algorithm deals directly with discrete nature of the design variables. The results obtained are superior to those reported in Prakash and Sydulu (2007).

1. Introduction

The application of shunt capacitor in distribution feeders has always been an important research area. 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. For this reason, the source of the system does not necessarily have 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. 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 [1–2].

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Because capacitor sizes and locations are discrete variables, this makes the capacitor placement problem have a combinatorial nature. The problem is a zero-one decision making problem with discrete steps of standard bank size of capacitors.

Chung and Shaoyun [3] presented a recursive linear programming based approach for minimizing line losses and finding the optimal capacitor allocation in a distribution system. Bouri et al. in [4] presented an ant colony optimization approach to shunt capacitor placement in distribution systems under certain constraints. These constraints were voltage constraints and capacitor switching constraints. The voltage constraints were taken into account by specifying upper and lower limits of voltage variations at the nodes of the distribution system. The capacitor switching constraints prevented high in-rush currents caused by the interaction between the capacitors on the distribution system.

Prakash and Sydulu in [1] presented 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 and sizing were done using loss sensitivity factors and PSO, respectively. The concept of loss sensitivity factors was considered as the contribution in the area of distribution systems. Loss sensitivity factors determined the candidate nodes for the placement of capacitors. The estimation of these candidate nodes basically helps in reduction of the search space for the optimization procedure. These factors are determined using a base case load flow; that is, without any compensation. PSO was used for estimation of required level of shunt capacitive compensation to improve the voltage profile of the system. The method was tested on 10, 15, 34, 69 and 85 bus distribution systems. The main advantage of that method was that it systematically decided the locations and size of capacitors to realize the optimum sizable reduction in active power loss and significant improvement in voltage profile. The method placed capacitors at a fewer number of locations with optimum sizes and offered much saving in initial investment and regular maintenance. The disadvantage of that algorithm was that the capacitor sizes were considered as continuous variables, then the capacitor sizes were rounded off to the nearest available capacitor value. In this paper, an enhancement to that algorithm is proposed.

Azim and Swarup in [5] presented a GA-based approach to determine the optimum locations and sizes of capacitors for a distribution system. The capacitor sizes were assumed as discrete known variables, which were to be placed on the buses such that they reduced the losses of the distribution system to a minimum. A genetic algorithm was used as an optimization tool, which obtained the optimal values and location of capacitors and minimized the objective function, which was the power loss in the distribution network under study. An initial base case load flow was used to calculate power loss and voltage profile of the distribution system. The problem was formulated as a constrained optimization problem. In this constrained problem, the constraint was the voltage limit; i.e. if the voltage magnitude exceeded a specified limit, this increased the value power loss function as a penalty term. Since the addition of a capacitor at any bus in the distribution system resulted in voltage magnitude increase, therefore it became imperative to model voltage magnitude as a constraint in the mathematical equation, which was to be optimized. The line flow limits were taken care of by the load flow program that calculated the losses. The encoding strategy of each individual, which forms a possible solution, is as follows: Each capacitor size value, when converted into binary form is of length 20 and if N is the number of buses in the distribution system including the slack bus, then $N-1$ locations are possible for capacitor placement, hence each individual has length equal to $N-1$. The proposed algorithm was tested on the 33-bus standard radial distribution system and a practical 29-bus radial distribution of Puth-Kalan, North Delhi, India.

In this paper, a new algorithm for solving the problem of optimal capacitor allocation and sizing in a radial power system is proposed. Loss sensitivity factors are used to determine where the capacitors are to be placed and a discrete particle swarm optimization algorithm is used to determine the sizes of the capacitors. The rest of this paper is organized as follows. In the next section, the mathematical formulation of the capacitor placement and sizing problem is provided. Loss sensitivity factors are defined in Section 3. The steps of the proposed algorithm are described in Section 4 and the obtained results are presented in Section 5. Finally, Section 6 concludes the paper.

2. Capacitor placement and sizing problem formulation

The objective of the optimal capacitor placement and sizing problem in this study is to minimize the total annual cost function of capacitor placement and power losses, which is given by

$$K^p P_{\text{loss}} + \sum_{j=1}^{J} K_j^c Q_j^c \tag{1}$$

where P_{loss} is the total power losses, K^p is the annual cost per unit of power losses (\$/KW), K_j^c is the capacitor annual cost (\$/KVAR), Q_j^c is the shunt capacitor size placed at bus j and J is the number of candidate buses for capacitor placement.

The control variables are the shunt capacitors size (Q^C), which are discrete variables. Table 1 shows the available capacitor sizes and the corresponding yearly cost [6].

The constraints that need to be satisfied are listed below.

(i) Shunt capacitors limits

$$Q^C_{\max} \le Q_{\text{total}} \tag{2}$$

where $Q^C_{\max}$ is the largest capacitor size allowed and Q_{total} is the total reactive load

(ii) Bus bar voltage limits

$$V_{\min} < V_i < V_{\max} \tag{3}$$

in radial power systems $V_{\min} = 0.9$ and $V_{\max} = 1.1$

(iii) Line flow limits

$$\text{Flow}_k < \text{Flow}_k^{\max} \tag{4}$$

where Flow_k is the power flow in kth-line and $\text{Flow}_k^{\max}$ is the maximum allowable power flow.

3. Loss sensitivity factors

Consider a distribution line connected between 'p' and 'q' buses, as shown in Fig. 1.