Electrical Power and Energy Systems 62 (2014) 229–236

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Optimal capacitor placement in radial distribution systems using clustering based optimization

Jovica Vuletić, Mirko Todorovski *

Faculty of Electrical Engineering and Information Technologies, University Ss. Cyril and Methodius, Skopje, Republic of Macedonia

ARTICLE INFO

Article history:
Received 17 January 2014
Received in revised form 15 April 2014
Accepted 1 May 2014
Available online 22 May 2014

Keywords:
Radial distribution systems
Power flow
Losses
Capacitor placement
Voltage improvement

ABSTRACT

A Clustering Based Optimization (CBO) for the discrete optimisation problem of fixed shunt capacitor placement and sizing is presented. We minimize the sum of costs for power/energy losses and capacitor costs. Over-compensation and voltage constraints are also taken into consideration. CBO is based on a simple search which iteratively loops through network buses and places capacitors at locations that yield maximum reduction of losses in the objective function.

The effectiveness of the proposed approach is demonstrated on a 22-bus, 34-bus, 69-bus and 85-bus distribution systems. The CBO results are better than the results from other methods from recent papers which include: Fuzzy Genetic Algorithm (FGA), Direct Search Algorithm (DSA), Teaching Learning Based Optimization (TLBO), Cuckoo Search (CS), Self Adaptive Harmony Search Algorithm (SAHSA) and Artificial Bee Colony (ABC). In addition, for all cases, the proposed method gives repetitive and unique results in significantly shorter computation time.

1. Introduction

Optimal capacitor placement is a procedure that aims towards finding a minimum of certain objective function through solving a combinatorial problem in which the location and sizes of capacitors are to be determined. There are plenty of published papers where different formulations of the problem along with solution methods have been proposed. The goal in general, is to find optimal locations and sizes of shunt capacitors such that the cost of total real power/energy losses and that of shunt capacitors are minimized. At the same time, acceptable voltage levels have to be maintained throughout the whole network.

In one of the seminal papers [1], the problem was divided into master and slave sub-problem and solved in two separate steps. The first step optimizes the capacitor locations, while the second step determines the capacitor sizes. In [2], the optimal capacitor sizing is solved with non-linear programming. This concept of master and slave sub-problems was used for many years and it is still present in nowadays papers in great amount. In [3] the objective function was classified as a non-differentiable adding more challenges to the optimization algorithms and simulating annealing was applied. Later on, more heuristic optimization methods were used: immune system algorithm [4], genetic algorithms [5], fuzzy genetic algorithms [6], ant colony algorithm [7], particle swarm optimization [8] and plant growth algorithm [9]. Very recently, direct search algorithm [10], cuckoo search algorithm [11], self adaptive harmony search algorithm [12], artificial bee colony [13,14] and a new optimization technique known as teaching learning based optimization [15] are also used.

In this paper, we present a simple search based algorithm which iteratively loops through network buses and places capacitors at locations that give maximum reduction in the objective function defined as a sum of costs for power and energy losses, as well as capacitor costs. The proposed algorithm prevents over-compensation in the network and it has a simple procedure for enforcing voltage constraints. In the optimization procedures, load level variation is often introduced [1,5], as it is the case here.

The proposed method is tested on four distribution systems and the results are compared with the results from other methods that include: fuzzy genetic algorithm, direct search algorithm, teaching learning based optimization, cuckoo search algorithm, self adaptive harmony search algorithm and artificial bee colony.

Problem formulation

Objective function

The non-linear integer problem of capacitor placement in distribution system is solved with discrete values of capacitor sizes and

* Corresponding author. Tel.: +389 71254230.
E-mail addresses: jovicav@feit.ukim.edu.mk (J. Vuletić), mirko@feit.ukim.edu.mk (M. Todorovski).

http://dx.doi.org/10.1016/j.ijepes.2014.05.001
0142-0615/

selection of their locations. The objective function, as in [16], comprise of yearly system operation costs including costs for energy, capacitor installation and power losses and it is given with

$$\min F = C_{\mathrm{e}}\Delta W + p\sum_{k\in \boldsymbol{C}}(C_{\mathrm{f}} + C_{\mathrm{v}}Q_{\mathrm{c},k}) + C_{\mathrm{p}}\Delta P^{\max} \tag{1}$$

where C_{e} is electricity cost per kilowatt-hour (\$/kW h), ΔW are yearly electricity losses (kWh), p is fixed annuity payment rate expressed in relative units, C_{f} is fixed costs for capacitors installation (\$/location), C_{v} is capacitors costs per unit size (\$/kvar), $Q_{\mathrm{c},k}$ is capacitor size at location k (discrete values in kvar), $\boldsymbol{C}$ is a set of locations where capacitors are installed, C_{p} are saving per kilowatt for reduction in losses, that is price for peak power (\$/kW) and $\Delta P^{\max}$ are power losses at peak power (kW).

Since we are interested in energy losses for a given period of time (one year), load variation has to be taken into account [1]. We assume that the load variations can be approximated in discrete levels which may be different among the loads, that is the loads may have different variation patterns. Let L_t be Load Duration Curve (LDC) as shown in Fig. 1. A complex load at bus i at time interval t can be represented as

$$\underline{S}_i(t) = L_t \cdot \underline{S}_i^{\max} \tag{2}$$

where $\underline{S}_i^{\max}$ is the peak value of the load. If we let complex values for L_t, then we can model a possible variation of load power factor as well.

Please note that in this paper all complex variables are underlined, otherwise they are either real variables or magnitudes of corresponding complex variables.

If we denote the number of intervals in the LDC as N_{LDC} then for the total energy loss we may write

$$\Delta W = \sum_{i=1}^{N_{\mathrm{LDC}}}\Delta P_i \cdot T_i \tag{3}$$

where ΔP_i is the active power loss in time interval i whose duration is T_i.

Constraints

We impose constraints on bus voltages defined with lower and upper bounds, $V^{\min}$ and $V^{\max}$ respectively, as follows

$$V^{\min} \leqslant V_i \leqslant V^{\max}, \text{ for } i = 1, \ldots, N_{\mathrm{B}} \tag{4}$$

where V_i is the voltage value at bus i and N_{B} is the number of buses in the network. The bounds in (4) are $V^{\min}$ = 0.9 pu and $V^{\max}$ = 1.1 pu.

The total reactive power injection by the installed capacitors should not exceed the total reactive power demand plus the total reactive power losses in the network which may be controlled via the total reactive power of the supply substation Q_{slack}. This is expressed with the following constraint

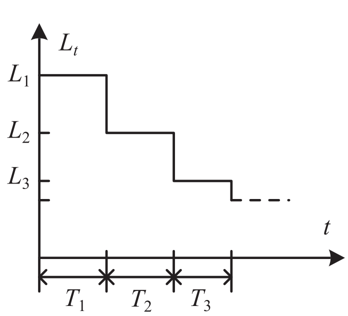

Fig. 1. Load duration curve.

$$Q_{\mathrm{slack}} \geqslant Q_{\mathrm{slack}}^{\min} \tag{5}$$

where $Q_{\mathrm{slack}}^{\min}$ is the minimum value of reactive power taken from the supply substation.

If we set $Q_{\mathrm{slack}}^{\min} = 0$ then we are certain that the reactive power injected by the capacitors is not bigger then the total reactive power demand. By setting values other then zero, different control strategies are possible.

Load flow solution

Distribution systems are different from transmission systems in a number of aspects, such as the X/R branch ratio, magnitudes of X and R and the radial structure. Due to these differences, transmission system power flow algorithms, such as Gauss–Seidel, Newton–Raphson and Fast Decoupled Power Flow, often fail [17] or lose efficiency when applied to distribution systems. A number of power flow solution methods have been developed to account for the specific nature of distribution systems, *backward/forward* sweep methods being the most widely used [18,19].

When using *backward/forward* sweep method for solving radial distribution networks, it is practical to number the branches with numbers that are equal to the receiving bus numbers (Fig. 2a). Furthermore, the oriented branch ordering [20] offers a possibility for fast and efficient backward/forward sweeps. All branches are always oriented from the sending bus to the receiving bus and the only requirement is that the sending bus number should be smaller than the receiving bus number ($i < k$ in Fig. 2a). The indices of the sending nodes of branches are stored in a vector $\boldsymbol{F}$, such that $i = F(k)$, k being the index/node of the branch receiving end.

Usually, the supply bus is enumerated with index 1 meaning that branch indices go from 2 to N_{B} which is the number of buses in the network. In order to fulfil the practical recommendation on enumerating branches with the indices of their corresponding receiving end, we introduce a fictitious branch with index 1 (sending end index 0), which now makes the number of branches N_{L} equal to the number of buses N_{B}. The latter is very convenient for the voltage calculation procedure which is performed in five steps as follows:

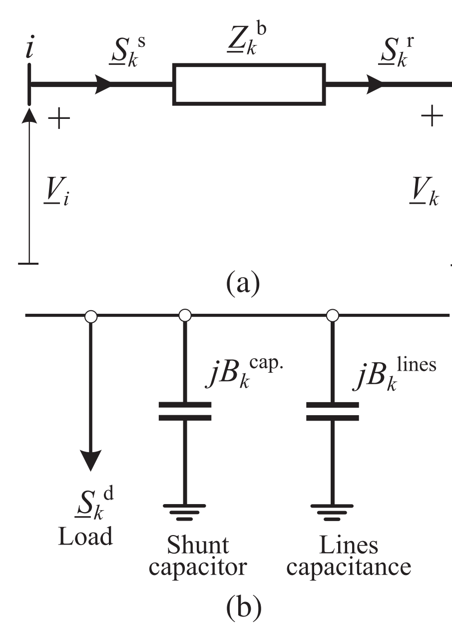

Fig. 2. Network representation: (a) Branch k between buses i (sending) and k (receiving) and (b) load and shunt capacitances at bus k.