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A PSO-based approach to optimal capacitor placement with harmonic distortion consideration

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Abstract

This paper presents a particle swarm optimization (PSO) based approach to achieve optimal capacitor placement in radial distribution systems. Harmonic distortion effects, discrete nature of capacitors, and different load levels are all taken into consideration in the problem formulation. Mathematically, the capacitor placement problem is a non-linear and non-differentiable mixed integer optimization problem with a set of equality and inequality operating constraints. Most conventional optimization techniques are incapable to solve this hard combinatorial problem, whereas PSO algorithm is very suitable. The proposed solution method employs PSO to search for optimal locations, types, and sizes of capacitors to be placed and optimal numbers of switched capacitor banks at different load levels. Computation procedures of applying the method to the capacitor placement problem are given in detail. The proposed approach has been implemented and tested on a distorted IEEE 9-bus test system with promising results.

Keywords: Capacitor placement; Harmonic distortion; Harmonic power flow; Particle swarm optimization (PSO)

1. Introduction

Capacitor placement plays an important role in distribution system planning and operation. Optimal capacitor placement can result in system loss reduction, power factor correction, voltage profile improvement, and feeder capacity release. To achieve these benefits to the utmost extent under various operating constraints, distribution engineers are required to determine the optimal locations, types, and sizes of capacitors to be placed and control settings of switched capacitors at different load levels.

The capacitor placement problem is a well-researched topic. Different formulations of the problem have been presented [1–4]. Unfortunately, most proposed formulation in published literature assume that all system loads are linear and neglect the presence of increased levels of voltage and current harmonics in distribution systems. In effect, without harmonic distortion concern, the proposed solution may not be optimal due to the additional costs of harmonic power losses; or in the worst case, neglecting the effects of harmonics may generate solution that lead to undesirable harmonic amplification or resonance conditions. Hence, consideration of harmonic effects is very essential while formulating the capacitor placement problem. In addition, a realistic formulation of the problem should also take into account the discrete nature of capacitor banks and load variations over a period of time. With all these considerations in mind, optimal capacitor placement is formulated as a mixed integer optimization problem featuring non-linearity and non-differentiability.

A variety of solution techniques have been employed to solve the capacitor placement problem. Ng et al. classify these techniques into four categories in [5]: analytical methods [6,7], numerical programming methods [8], heuristic search methods [3,9], and artificial intelligence (AI) based methods [10–12]. When a realistic problem formulation with all considerations as mentioned above is to be solved, however, most analytical, numerical programming or heuristic methods are unable to work well. In recent years, AI-based methods such as genetic algorithms (GA) have been applied to the capacitor placement problem with promising results [10,13,14]. Meanwhile, some new AI-based methods are introduced and developed. Although these AI-based methods do not always guarantee the globally optimal solution,

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they will provide suboptimal (near globally optimal) solutions in a short CPU time.

This paper employs a modern AI-based method, particle swarm optimization (PSO) [16–18], to solve the capacitor placement problem with the consideration of harmonic effects. PSO is a population-based search algorithm characterized as conceptually simple, easy to implement, and computationally efficient. As it is reported in [17], this optimization technique can be used to solve many of the same kinds of problems as GA, and does not suffer from some of GA's difficulties. PSO has also been found to be robust in solving problems featuring non-linearity, non-differentiability, and high dimensionality.

In this paper, a PSO-based approach to the capacitor placement problem is presented. The problem is reformulated as a non-linear and non-differentiable mixed integer optimization problem in Section 2. PSO algorithm is described in Section 3. Then the proposed PSO-based approach for solving the capacitor placement problem is presented by detailed computation procedures in Section 4. The results of test on a distorted IEEE 9-bus system and a conclusion are given in Sections 5 and 6.

2. Mathematical formulation

In this section, the capacitor placement problem is reformulated by a comprehensive objective function and a set of equality and inequality constraints. Based on the previous formulation proposed by many researchers, the formulation in this paper is an extension, or a broader one for a realistic distribution system due to full considerations of potential harmonic effects, different load levels, and practical aspects of fixed or switched capacitor banks.

2.1. Objective function

For a realistic distribution system with presence of non-linear loads, the objective of optimal capacitor placement problem is to reduce the power loss and energy loss, and to minimize the cost of capacitor banks, while maintaining bus rms voltages and their corresponding total harmonic distortion (THD) within prescribed values. The objective function can be expressed as:

$$\min f(u^0, u^i) = k_e \sum_{i=1}^{\mathrm{nl}} T_i P_i + k_p P_1 + \sum_{j=1}^{\mathrm{nc}} C_j(u_j^0) \qquad (1)$$

The right-hand side (RHS) of (1) consists of three terms. The first term represents the energy loss cost, the second term is the cost of peak power loss reflecting released system capacity, and the third term represents the total capacitor cost which comprises the purchase cost and the installment cost.

In the above objective function, the representation of harmonic effect is that system loss during load level i consists of fundamental component and harmonic components, i.e.,

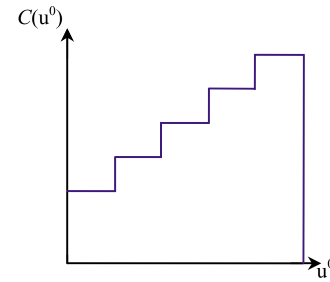

Fig. 1. The cost function of capacitor banks.

$$P_i = P_i^1 + \sum_{h \neq 1}^{\mathrm{Nh}} P_i^h; \quad i = 1, 2, \ldots, \mathrm{nl} \qquad (2)$$

Practically, capacitors are grouped in banks of standard discrete capacities (e.g., a bank of 300 kVAr); therefore, capacitor sizes are regarded as integer multiples of the standard size of one bank. To describe realistic cost of capacitor placement, the cost function of capacitors at node j is formulated as

$$C_j(u_j^0) = k_{\mathrm{inst}} + k_{\mathrm{cj}} \frac{u_j^0}{u_{\mathrm{s}}} \qquad (3)$$

where k_{inst} is a constant representing a fixed installment cost of capacitor banks; k_{cj} is the purchase cost of one capacitor bank: $k_{\mathrm{cj}} = k_{\mathrm{cf}}$ for fixed capacitor banks and $k_{\mathrm{cj}} = k_{\mathrm{cs}}$ for switched capacitor banks with $k_{\mathrm{cf}} < k_{\mathrm{cs}}$. The cost function $C_j(u_j^0)$ is a non-differentiable and piece-wise function as illustrated in Fig. 1. Consequently, the capacitor placement problem is a non-linear mixed integer optimization problem with non-differentiable objective function that cannot be efficiently solved by conventional optimization techniques.

2.2. Operating constraints

The problem of capacitor placement with harmonic consideration is subject to the following equality and inequality constraints:

2.2.1. AC power flow constraints

The overall power flow equations at fundamental frequency can be written in compact form as expressed below:

$$G^i(x^i, u^i) = 0; \quad i = 1, 2, \ldots, \mathrm{nl} \qquad (4)$$

where x^i are state variables, and u^i are control variables. If the capacitor at node j is of fixed type, then $u_j^1 = \cdots = u_j^i = \cdots = u_j^{\mathrm{nl}} = u_j^0$; if the capacitor at node j is of switched type, then $0 \leq u_j^i \leq u_j^0$.