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Capacitor placement in large-scale distribution systems using variable scaling hybrid differential evolution

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Abstract

This paper presents an effective method, variable scaling hybrid differential evolution (VSHDE), with integer programming for solving large capacitor placement problems in distribution systems. The variable scaling factor is used in VSHDE to overcome the drawback of the fixed and random scaling factor in the hybrid differential evolution (HDE). And, the use of variable scaling factor can also alleviate the problem of selection of mutation operator of the hybrid differential evolution. The rule of updating scaling factor is based on 1/5 success rule of evolution strategies (ESs). Various-scale application systems are used to compare the performance of the proposed method with the HDE, simulated annealing (SA), and ant system (AS). Numerical results show that the performance of the proposed VSHDE method is better than the other methods. Also, the VSHDE method is superior to some other methods in terms of solution power loss and costs.

Keywords: VSHDE; Evolution strategies; Capacitor placement

1. Introduction

Capacitors are widely installed in distribution systems for reactive power compensation to achieve power and energy reduction, voltage regulation and system capacity release. And, the installation of shunt capacitors in primary distribution systems can also effectively reduce peak power and energy losses. The extent of these benefits depends greatly on how the capacitors are placed on the system, namely on the location and size of the added capacitors [1,2]. The objective in the capacitor placement problem is to minimize the annual cost of the system, subject to operating constraints under a certain load pattern.

Grainger et al. [3–5] proposed the concept that the size of capacitor banks was considered as a continuous variable. Bala et al. [6] presented a sensitivity-based method to solve the optimal capacitor placement problem. Using genetic algorithm (GA) to select capacitors for radial distribution systems was proposed in [7]. In the above-mentioned methods, the capacitors were often assumed as continuous variables, in which cost is proportionate to the capacitor size. However, commercially available capacitors are discrete. Selecting integer capacitor sizes closest to the optimal values found by the continuous variable approach may not guarantee an optimal solution [8]. Therefore the optimal capacitor placement should be viewed as an integer-programming problem, and discrete capacitors will be considered in this paper. As a result, there is a total of $(L+1)^J$ possible solutions, where J is the bus number and L is the number of variable capacitor sizes. The $(L+1)^J$ will become a very large number even for a medium-sized distribution system. Accordingly, the huge number of combinations in the solution space makes the solution searching process become a heavy burden.

Hybrid differential evolution (HDE) [9,10] is a stochastic search and optimization method. The fittest of an offspring

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competes one-to-one with that of the corresponding parent, which is different from the other evolutionary algorithms (EAs). This one-to-one competition gives rise to a faster convergence rate. However, this faster convergence also leads to a higher probability of obtaining a local optimum because the diversity of the population descends faster during the solution process. To overcome this drawback, migrating operator and accelerated operator act as a trade-off operator for the diversity of population and convergence property in the HDE. Migrating operator maintains the diversity of population, which guarantees a high probability of obtaining the global optimum. And, accelerated operator is used to accelerate convergence. However, a fixed scaling factor is used in the HDE. Using a smaller scaling factor, the HDE becomes increasingly robust. However, much computational time should be expanded to evaluate the objective function. The HDE with a larger scaling factor generally falls into local solutions or misconvergence. Lin et al. [11] used a random number that its value is between zero and one as a scaling factor. However, a random scaling factor could not guarantee the fast convergence. The selection of mutation operator is also a very important issue in the HDE. The proper mutation operator can accelerate to search out the global solution [9]. However, the selection of mutation operator is problem-dependence. In the HDE, the proper mutation operator is not easy to select.

In this study, a variable scaling hybrid differential evolution (VSHDE) with integer programming for solving the optimal capacitor placement of distribution systems is proposed. Here, the 1/5 success rule of evolution strategy (ESs) [12,13] is used in the VSHDE to adjust the scaling factor to accelerate searching out the global solution. Optimal capacitor placement is a combinatorial optimization problem that is commonly solved by employing mathematical programming techniques. However, in those methods, the capacitors are often assumed as continuous variables in which cost is proportionate to the capacitor size. Selecting integer capacitor sizes closet to the optimal values found by the continuous variable approach does not guarantee an optimal solution. Therefore, the optimal capacitor placement should be viewed as an integer-variable problem. The VSHDE method can be used to solve the integer-variable problems effectively. Various-scale application examples are solved respectively by the proposed method, HDE, SA, and AS. From the computational results, it is observed that the convergence property of the VSHDE method is better than that of the other methods.

2. Problem formulation

The mathematical model of the optimal capacitor placement of distribution systems can be expressed as follows:

$$\min \text{COST} \tag{1}$$

subject to

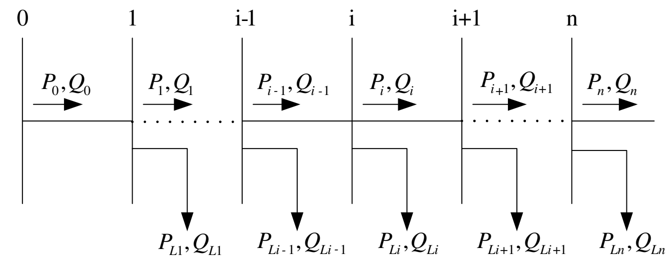

Fig. 1. Single-line diagram of a main feeder.

$$V_{\min} \leqslant |V_i| \leqslant V_{\max} \tag{2}$$

where $|V_i|$ is the voltage magnitude of bus i, $V_{\min}$ and $V_{\max}$ are the minimum and maximum voltage limits, respectively.

The objective function COST in (1) is an overall cost relating to power loss and capacitor placement. The voltage magnitude at each bus must be maintained between its minimum and maximum voltage limits. To avoid the complex iteration process for power flow analysis, a set of simplified feeder-line flow formulations is applied. Considering the single-line diagram depicted in Fig. 1, the following set of recursive equations is used for power flow computation [14,15].

$$P_{i+1} = P_i - P_{\mathrm{L}i+1} - R_{i,i+1} \cdot (P_i^2 + Q_i^2)/|V_i|^2 \tag{3}$$

$$Q_{i+1} = Q_i - Q_{\mathrm{L}i+1} - X_{i,i+1} \cdot (P_i^2 + Q_i^2)/|V_i|^2 \tag{4}$$

$$|V_{i+1}|^2 = |V_i|^2 - 2(R_{i,i+1} \cdot P_i + X_{i,i+1} \cdot Q_i) + (R_{i,i+1}^2 + X_{i,i+1}^2)\frac{(P_i^2 + Q_i^2)}{|V_i|^2} \tag{5}$$

where P_i and Q_i are the real and reactive powers flowing out of bus i, and $P_{\mathrm{L}i}$ and $Q_{\mathrm{L}i}$ are the real and reactive load powers at bus i. The resistance and reactance of the line section between buses i and $i+1$ are denoted by $R_{i,i+1}$ and $X_{i,i+1}$, respectively.

The power loss of the line section connecting buses i and $i+1$ may be computed as

$$P_{\mathrm{Loss}}(i, i+1) = R_{i,i+1} \cdot \frac{P_i^2 + Q_i^2}{|V_i|^2} \tag{6}$$

The total power loss of the feeder, $P_{\mathrm{T,Loss}}$, may then be determined by summing up the losses of all line sections of the feeder. Which is given by

$$P_{\mathrm{T,Loss}} = \sum_{i=0}^{n-1} P_{\mathrm{Loss}}(i, i+1) \tag{7}$$

Considering the real-world capacitors, there exists a finite number of standard sizes which are integer multiples of the smallest size Q_0^{C}. Besides, the cost per kV Ar varies from one size to another.

In general, capacitors of larger size have lower unit prices. The available capacitor size is usually limited to

$$Q_{\max}^{\mathrm{C}} = LQ_0^{\mathrm{C}} \tag{8}$$

where L is an integer. Therefore, for each installation location, there are L capacitor sizes $\{Q_0^{\mathrm{C}}, 2Q_0^{\mathrm{C}}, \ldots, LQ_0^{\mathrm{C}}\}$