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Application of the ant colony search algorithm to reactive power pricing in an open electricity market

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ABSTRACT

Reactive power management is essential to transfer real energy and support power system security. Developing an accurate and feasible method for reactive power pricing is important in the electricity market. In conventional optimal power flow models the production cost of reactive power was ignored. In this paper, the production cost of reactive power and investment cost of capacitor banks were included into the objective function of the OPF problem. Then, using ant colony search algorithm, the optimal problem was solved. Marginal price theory was used for calculation of the cost of active and reactive power at each bus in competitive electric markets. Application of the proposed method on IEEE 14-bus system confirms its validity and effectiveness. Results from several case studies show clearly the effects of various factors on reactive power price.

1. Introduction

The traditional regulated and monopoly structure of power industry throughout the world is eroding into an open-access and competitive environment. Thus, planning and operation of the utilities are based on the economic principles of open-access markets. In this new environment electric markets are essentially competitive. Until now, effort has been directed primarily toward developing methodologies to determine remuneration for the active power of the generators. Although the investment in electric power generation and the fuel cost, represent the most important costs of power system operation, reactive power is becoming more and more important, especially from the security point of view and the economic effect caused by it [1].

Reactive power compensation and optimization sustains the exchange of electric power greatly as a part of ancillary services. The consumption of the reactive power follows a similar demand against time curve as the active power, especially for motor loads and furnaces. Therefore, the operation and cost allocation of reactive power is very important to the running and management of generation and/or transmission companies [1].

A fixed tariff on the remuneration for reactive power is insufficient to provide a proper signal of reactive power cost [2]. Berg et al. [3] pointed out the limitations of a reactive power price policy based on power factor penalties, and suggested the use of economic principles based on marginal theory [4]. However, these prices represent a small portion of the actual reactive power price [5–7]. Hao and Papalexopoulos [8] note that the reactive power marginal price is typically less than 1% of the active power marginal price and depends strongly on the network constraints. Assessing the cost of reactive power production is difficult, because of differences in reactive power generation equipment and local characteristics of reactive power [9]. Several models for cost of reactive power production have been developed [10–18]. However, despite the complexity, these models lack a precise definition for the cost of reactive power production. Also, the methodology to obtain the cost curves is not described adequately.

In a competitive electric market the generators may provide the necessary reactive power compensation if they are remunerated by the service, provided the loss of opportunity in the commercialization of active power is taken into account [12]. Static compensators (capacitive and inductive) may be remunerated according to their investment costs and depreciation of their useful lives [13].

To address the above mentioned needs, in present paper, both active and reactive power production costs of generators and capital cost of capacitors are considered in the objective function of OPF problem.

Then a new method based on the Ant Colony Optimization (ACO) and advanced sequential quadratic programming, is employed to solve the OPF problem.

Currently, most works are carried out in the direction of applying ACO to the combinatorial optimization problems [19,20]. For most of these applications, the results show that the ACO can outperform other heuristic methods. In power systems, the ACO has

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been applied to solve the optimum generation scheduling problems [21], unit commitment [22], economic dispatch of power systems [23] and the constrained load flow [24]. It is rather difficult to find a single search space, configuration and a parameter set of an ACO that can satisfy every optimization problem. Therefore, there is a need for the development of an improved version of the ACO tailored to solve the reactive power pricing. The ACO proposed in this paper formulates the reactive power pricing problem as a combinatorial optimization problem.

In several case studies, the IEEE 14-bus system was used to verify the validity of the proposed method. Different objective functions are applied in the simulation tests to observe their impacts on reactive power prices.

The paper is organized as follows: in Section 2 the objective function and constraints of reactive power pricing are presented. Section 3 describes the proposed ant colony search algorithm. In Section 4 the simulation results for IEEE 14-bus test system is illustrated.

2. Objective function and constraints of reactive power pricing

Active and reactive marginal prices are normally obtained through solving the optimal power flow in which an objective function subject to a set of equality and inequality constraints is minimized. The objective function is proposed as the summation of active and reactive power production costs, produced by generators and capacitor banks:

$$C = \sum_{i=1}^{N_g}[C_{gpi}(P_{Gi}) + C_{gqi}(Q_{Gi})] + \sum_{j=1}^{N_c} C_{Cj}(Q_{Cj}) \tag{1}$$

where N_g is the number of generators, $N_c$the number of buses which capacitor banks are installed, $C_{gpi}(P_{Gi})$ the active power cost function in ith bus, $C_{gqi}(Q_{Gi})$ the reactive power cost function in ith bus and $C_{Cj}(Q_{Cj})$ is the capital cost function of capacitor bank in jth bus.

Cost function of active power used in (1) is considered as follows:

$$C_{gpi}(P_{Gi}) = a + bP_{Gi} + cP_{Gi}^2 \tag{2}$$

The capacity of generators is limited by the synchronous generator armature current limit, the field current limit, and the under-excitation limits. Because of these limits, the production of reactive power may require a reduction of real power output. Opportunity cost is the lost benefit of this reduction of real power output of the generator.

Opportunity cost depends on demand and supply in market, so it is hard to determine its exact value. In simplest form opportunity cost can be considered as follows:

$$C_{gpi}(Q_{Gi}) = \left[C_{gpi}(S_{Gi,\max}) - C_{gpi}\left(\sqrt{S_{Gi,\max}^2 - Q_{Gi}^2}\right)\right] \cdot k \tag{3}$$

where $S_{Gi,\max}$ is the maximum apparent power in ith bus, Q_{Gi} the reactive power of generator in ith bus and k is the reactive power efficiency rate (usually between 5% and 10%).

Modified triangle method is an alternative strategy for reactive power cost allocation (see Fig. 1).

According to Fig. 1 we can write:

$$P' = P\cos(\theta) = S\cos^2(\theta) \tag{4}$$

$$Q' = Q\sin(\theta) = S\sin^2(\theta) \tag{5}$$

Using (4) and (5) we have:

$$\begin{aligned} &P' + Q' = S \\ &Cost(P') + Cost(Q') = Cost(S) \end{aligned} \tag{6}$$

For expressing active power cost, we replace (4) in (2) as follows:

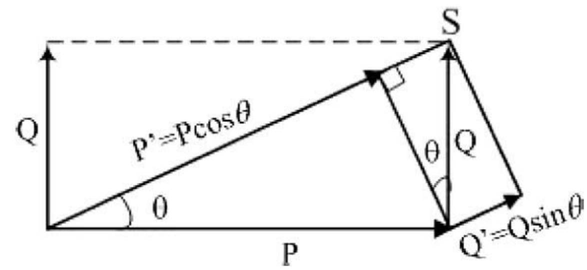

Fig. 1. An illustration of modified triangle method for reactive power cost allocation.

$$Cost(P') = Cost(P\cos(\theta)) = a + b\cos(\theta)P + c\cos^2(\theta)P^2 = a + b'P + c'P^2 \tag{7}$$

Using (2) and (5) the new frame of reactive power pricing can be written as given below:

$$\begin{aligned} Cost(Q') &= Cost(S\sin^2(\theta)) = Cost\left(\frac{P}{\cos(\theta)}\sin^2(\theta)\right) \\ &= a + b\sin(\theta)Q + c\sin^2(\theta)Q^2 = a + b''Q + c''Q^2 \end{aligned} \tag{8}$$

It is assumed that the reactive compensators are owned by private investors and installed at some selected buses. The charge for using capacitors is assumed proportional to the amount of the reactive power output purchased and can be expressed as:

$$C_{Cj}(Q_{Cj}) = r_j Q_{Cj} \tag{9}$$

where r_j and Q_{Cj} are the reactive cost and amount purchased, respectively, at location j. The production cost of the capacitor is assumed as its capital investment return, which can be expressed as its depreciation rate. For example, if the investment cost of a capacitor is \$11600/MVA, and their average working rate and life span are 2/3 and 15 years, respectively, the cost or depreciation rate of the capacitor can be calculated by:

$$r_j = \frac{\text{investment cost}}{\text{operating hours}} = \frac{\$11600}{15 \times 365 \times 24 \times 2/3} = \frac{\$0.1324}{\text{MVA h}} \tag{10}$$

In the reactive power cost optimization, the active power output of generators is specified. The bus voltage, the reactive power output of generators and capacitors are the control variables. The equality and inequality constraints include the load flow equations, active and reactive power output of generators, reactive power output of capacitors, and the bus voltage limits at the normal operating condition, as shown below:

Load flow equations:

$$\begin{aligned} &P_{Gi} - P_{Di} - \sum |\dot{V}_i||\dot{V}_j||Y_{ij}|\cos(\theta_{ij} + \delta_j - \delta_i) = 0 \\ &Q_{Gi} - Q_{Di} + \sum |\dot{V}_i||\dot{V}_j||Y_{ij}|\sin(\theta_{ij} + \delta_j - \delta_i) = 0 \end{aligned} \tag{11}$$

Active and reactive power generation limits:

$$\begin{aligned} &P_{Gi,\min} \leqslant P_{Gi} \leqslant P_{Gi,\max} \\ &Q_{Gi,\min} \leqslant Q_{Gi} \leqslant Q_{Gi,\max} \end{aligned} \tag{12}$$

Capacitor reactive power generation limits:

$$0 \leqslant Q_{Cj} \leqslant Q_{Cj,\max} \tag{13}$$

Transmission line limit:

$$|P_{ij}| \leqslant P_{ij,\max}, P_{ij} = |\dot{V}_i||\dot{V}_j||Y_{ij}|\cos(\theta_{ij} + \delta_j - \delta_i) - |\dot{V}_i|^2|Y_{ij}|\cos\theta_{ij} \tag{14}$$