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Reactive power market management considering voltage control area reserve and system security

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ABSTRACT

This paper presents a new algorithm to optimize reactive power procurement through commercial transactions considering system voltage security. The proposed algorithm minimizes reactive power provision and transmission loss costs in addition to maximizing system voltage security margin through a multi-objective function. In order to maintain the voltage profile of power system during sever contingencies or due to load uncertainty, all voltage control areas (VCA) of the system are detected and then optimal reactive power reserve is provided for each VCA during the market settlement. A four-stage multiobjective mathematical programming method is proposed to settle the reactive power market. The proposed algorithm has been applied on IEEE-RTS test system. The simulation results show the effectiveness of the proposed algorithm for reactive power market management.

1. Introduction

In restructured power systems, ancillary services are among significant issues which have essential role in reliable operation of electricity markets [1]. In most competitive electricity markets, one basic responsibility of Independent System Operator (ISO) is to provide ancillary services through commercial contracts with market participants [1,2]. Reactive power provision is one of the most important ancillary services in electricity markets. There are several issues which should be regarded by the system operator in the time of reactive power market settlement [1].

The system operator should compensate market participants for reactive power provision. Therefore, economic issues in the reactive power market are very important. Several methods have been proposed for reactive power payment [3–9]. In [3] a piece-wise linear cost curve has been developed for reactive power pricing in accordance with generator's energy bid curve and its reactive power capability curve. In [4–7] a three-region reactive power cost curve for a synchronous generator has been presented. Ref. [8] proposes a value-based method to allocate the cost of reactive power provision by the generators. In [9] a quadratic polynomial has been fitted to calculate the cost of reactive power provided by a generator. In comparison with other proposed reactive power cost curves, the quadratic polynomial is much simpler to be implemented and analyzed in optimization problems without losing the accuracy. Some references deem it is necessary to compensate not only synchronous generators but also other reactive power sources such as synchronous condensers, capacitor banks and FACTS devices [10].

Because of the important role of reactive power in network operation and security, technical issues have been thought out as well as economic issues in many researches. Different objective functions such as minimization of reactive power cost, transmission loss minimization, and maximization of system loadability, have been used in reactive power market settlement [5,11–14].

Scheduling the reactive power market ignoring total energy loss may lead to increase the network loss and hence market operation cost. Therefore, transmission loss should be considered in the time of reactive power market clearing [3–5].

Reactive power has an essential role in power system voltage security [15,16]. Inadequate reactive power has been known to be one of the most important reasons for some major blackouts in the world [16]. Thus, system voltage security is another important issue which should be regarded in reactive power scheduling. In [17] a cost-based reactive power pricing has been proposed, which integrates reactive power cost minimization and voltage security problem into the optimal power flow problem. Ref. [7] proposes a two-level framework for scheduling reactive power market taking into account system voltage security aspects. In the first level, reactive power procurement has been performed on a seasonal basis while, in the second level, close to real-time reactive power dispatch has been carried out. Because of some difficulties in seasonal reactive power procurement, especially in forecasting the need for reactive power, Ref. [18] proposes a day-ahead reactive power market scheduling.

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As it is shown in Section 3, considering only the voltage security margin does not guarantee that the voltage profile will be kept in acceptable range after any disturbance. Therefore, similar to conventional power systems, in deregulated electricity markets, sufficient reactive power reserve is necessary to prevent unacceptable voltage deviation after any system disturbance or due to load uncertainty. Ref. [19] proposes to provide enough reactive power reserve to improve system voltage security and profile in power systems. Because the voltage and reactive power problems are local issues, it is shown in Section 3 that local reactive power reserve allocation is more efficient in the system. Hence, this paper proposes to provide local reactive power reserve in the stage of reactive power market settlement to achieve a more efficient ancillary market. In [20] an algorithm has been proposed to recognize all voltage control areas (VCA) of the network which is used in this paper to find VCAs in the time of allocating local reactive reserve.

In this paper a new algorithm is proposed for optimal reactive power provision in a day-ahead ancillary market. A full AC constrained OPF problem is developed to find the best schedule of reactive power produced by all synchronous generators and condensers. The proposed algorithm minimizes reactive power provision cost and transmission energy loss payment. Simultaneously, power system voltage security margin and reactive power reserve are maximized through a multiobjective function.

In the proposed algorithm, all voltage control areas of the system (VCA) are detected and optimal reactive power reserve is provided for each VCA separately during the market settlement. A four-stage multiobjective mathematical programming method is used to clear the reactive power market. The proposed algorithm has been applied to IEEE-RTS test system. The simulation results show the effectiveness of the proposed algorithm for reactive power market management.

The rest of the paper is organized as follows: Section 2 describes economical aspects of reactive power market design. In Section 3, voltage security and reactive power reserve have been discussed as two important technical issues of reactive power market clearing. Section 4 presents the proposed multiobjective reactive power market model. Sections 5 and 6 include numerical results and conclusion, respectively.

2. Economic aspects of the reactive power market

In deregulated electricity markets, the system operator should provide reactive power in an optimal manner considering both economic and technical issues. Owing to importance of economic aspects in any activity in the market, the economic issues are reviewed in this section and technical issues are the subject of the next section.

The system operator should compensate market participants for providing reactive power. If the operator seeks to minimize only cost of reactive power provision, it will contract with providers which offer the minimum prices. But, it may result in increasing transmission energy loss and consequently increasing total system payment. Therefore, cost of both reactive power provision and transmission energy loss should be considered in the time of reactive power market clearing.

According to NERC (North American Electric Reliability Council) Operation Policy 10, only reactive power produced by synchronous generators has been considered as ancillary service and is eligible for financial compensation [7].

In this paper, it is assumed that both synchronous generators and synchronous condensers should be compensated due to their contribution in reactive power control. The reactive power pricing algorithms are presented in the following subsections.

2.1. Cost of generator's reactive power

Different reactive power payment structures can be used for synchronous generators [7–9]. In [9] a quadratic reactive power cost curve for a typical synchronous generator has been proposed. This cost curve accurately models the investment cost, operational cost and also lost opportunity cost of a synchronous generator. It is defined as follows:

$$Cost(Q_{gi}) = a_{q,i}Q_{gi}^2 + b_{q,i}Q_{gi}c_{q,i} \tag{1}$$

where Q_{gi} is reactive power output of ith generator and equation coefficients, a_q, b_q and c_q can be calculated based on active power cost curve [9]. This equation can provide accurate results in reactive power market while it is very simple to be implemented.

2.2. Reactive power cost of condensers

Synchronous condenser is a synchronous machine without any prime mover which can provide only reactive power. The reactive power cost curve of a condenser consists of the investment and operating costs. The operating cost contains the cost of energy consumed to overcome the mechanical friction and electrical loss, and the maintenance cost. Consequently, the reactive power cost curve of a synchronous condenser can be formulated by (2):

$$Cost(Q_{ci}) = (\beta_{ci} + \sigma_{ci})Q_{ci} \tag{2}$$

where Q_{ci} is the reactive power output of condenser, σ (\$/Mvar-h) is the operating cost of condenser and β_{ci} (\$/Mvar-h) which is formulated by (3) models the investment cost [21].

$$\beta_{ci} = \frac{\text{capital investment cost}}{8760 \times \text{lifespan} \times \text{average usage rate}} \ (\$/\text{Mvar-h}) \tag{3}$$

3. Technical aspects of the reactive power market

There are some important technical issues such as voltage security, reactive power reserve, bus voltage profiles, generators' capability limits and transmission lines' limits which should be regarded in the time of reactive power market management [5,11–14]. All of the mentioned subjects should be thought out for both normal and post contingency conditions.

After a contingency in the power system, the voltage profile of each bus may become unacceptable and also the system goes toward the voltage instability point. If the system operator thinks only about the system voltage security margin in the time of reactive power market clearing, the system will be strengthened against the voltage instability even after a severe contingency. But, it does not guarantee that the voltage profile will be kept in the acceptable range. Vice versa, if the operator pays only attention to the voltage profile of buses, the system may have good voltage profile but it does not guarantee that the system have adequate voltage security margin. In Fig. 1 two different p–v curves are demonstrated to explain the above discussion. If the voltage magnitude is equal to V_1, which is considered to be acceptable voltage magnitude, the system with p–v curve 1 does not have adequate voltage security margin, while in the case of curve 2, the voltage security margin is sufficient.

Consequently, in this paper, system voltage security margin and reactive power reserve are considered as two important technical problems during reactive power planning.

3.1. Voltage security assessment

The voltage security is defined as an important subject in power systems and should be taken into account in many programming