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Coupled energy and reactive power market clearing considering power system security

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ABSTRACT

In a deregulated environment, when talking about electricity markets, one usually refers to energy market, paying less attention to the reactive power market. Active and reactive powers are, however, coupled through the AC power flow equations and branch loading limits as well as the synchronous generators capability curves. However, the sequential approach for energy and reactive power markets cannot present the optimal solution due to the interactions between these markets. For instance, clearing of the reactive power market can change active power dispatch (e.g. due to a change of transmission system losses and the capability curve limitation), which can lead to degradation of the energy market clearing point. This paper presents a coupled day ahead energy and reactive power market based on the pay-at-MCP settlement mechanism. Besides, the proposed coupled framework considers voltage stability and security issues and branch loading limits. The coupled market is cleared through optimal power flow (OPF). Its objective function includes total payment of generating units for their active power production along with the total payment function (TPF) of units for their reactive power compensation. Moreover, lost opportunity cost (LOC) of the units is also considered. The effectiveness of the proposed framework is examined on the IEEE 24 bus Reliability Test System.

1. Introduction

Recently, there has been a significant interest in reactive power as one of several ancillary services required to ensure system reliability and security. One of the main reasons for some of the recently major blackouts in power systems around the world, such as those that occurred in September 23, 2003 in Sweden and Denmark, September 28, 2003 in Italy and also the United States and Canada blackout (August 2003), was reported as insufficient reactive power of the system, resulting in voltage collapse [1,2].

In recent years, some papers have been published in the area of optimal pricing of reactive power [3–8]. All of these papers assume that the consumer of reactive power should pay for the reactive power service, and the producers of reactive power should be remunerated. With this understanding, the well known marginal price theory has usually been applied to determine the optimal prices for reactive power. Some of the more recent research works on designing reactive power markets also consider technical issues of the power system in addition to the economical aspects [9–12]. In [13], the authors determine the minimum reactive power (Q_{min}) that each generator needs to transfer its own active power through the power system. The Q_{min} is determined only for heavily loaded conditions.

Zhong et al. have designed a competitive reactive power market [14–17]. In order to compensate a generator financially for its reactive power support, a generator expected payment function (EPF) is defined and formulated so that an ISO (independent system operator) can easily call for reactive bids from all parties [14]. Consequently, according to the generator EPF, a two part reactive bid structure is suggested. In [15], the generator EPF as well as generator reactive power capability curve has been used to analyze the reactive power costs and subsequently construct a four component bidding framework for synchronous generators. Mitigating market power, a localized reactive power market is proposed in [16]. It is observed that the localized reactive power market restricted the market power of each generator to its own area, and it no longer affects the reactive power prices of the other zones. In [17], a pricing mechanism for the other compensators of reactive power (e.g. shunt capacitors, SVCs) in a competitive market has been proposed.

The reactive power problem has also been studied in the form of a multi-objective problem in [18,19]. Other research works [20,21] took into account voltage security in reactive power pricing. In [20], a cost based reactive power pricing is proposed, which integrates the production cost of reactive power and the voltage stability margin requirement of pre- and post-contingencies into the

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OPF (optimal power flow) problem. In [21], a two level framework is proposed for operation of a competitive reactive power market taking into account system security aspects. The first level, i.e. procurement, is on a seasonal basis, while the second level, i.e. dispatch, is close to real time operation. In that work, reactive power procurement is considered as essentially a long term issue, i.e. a problem in which the independent system operator or ISO seeks optimal reactive power "allocation" from possible suppliers that would be best suited to its needs and constraints in a given season [21]. This optimal set should ideally be determined based on demand forecast and system conditions expected over the season [21]. One of the main contributions of this paper is to propose a day ahead reactive power market model instead of the seasonal model because the seasonal market for reactive power encounters problems. First, the reactive power consumption of a system is so volatile that its forecasting over a season becomes very hard. Second, in spite of active power, the reactive power requirement of a system strongly depends on the loading condition of the network. In heavy load conditions of the system, some transmission lines are loaded more than their surge impedance loading (SIL) and become sinks of reactive power in the over SIL loading conditions. On the other hand, in light loading conditions, the transmission lines are usually loaded in the under SIL conditions and become sources of reactive power. This further complicates prediction of the reactive power requirement of the power system over a long horizon. Third, the occurrence of different planned/unplanned outages and the effects of maintenance scheduling (such as generators and transmission lines entering the circuit after their maintenance period) in a season can change the configuration of the power system, leading to more complexity in designing a seasonal reactive power market. Fourth, over the long time of a season, the ISO can handle the reactive power requirements of the system only with the selected generators of the network that have contracted with them to become available for reactive power compensation, and the remaining generators that are not selected at the beginning of the season no longer participate in reactive power compensation. In other words, the available sources of reactive power are limited to the selected generators over a long time, which is, to some extent, in contradiction with the local nature of reactive power. Therefore, considering the above mentioned problems of the seasonal procurement model for the reactive power market, this paper proposes a day ahead market model for reactive power rather than a seasonal market model.

In the above mentioned papers, the energy and reactive power markets are decoupled from each other and cleared sequentially. In other words, the active power of generating units obtained in the energy market is considered as input for clearing the reactive power market. Active and reactive powers are, however, coupled through the AC power flow equations and branch loading limits as well as the synchronous generators capability curves. With this concern, some research works pay attention to the interaction of reactive and active powers during clearing of the reactive power market [22–24]. In [22], a coordinated fuzzy constrained optimal power dispatch for bilateral contracts, balancing electricity and ancillary services markets is proposed and solved in the form of two sub-problems. The main objective of [23] is to minimize the total amount of dollars paid by the system operator to the generator for providing the required reactive power. The real power generation is decoupled and assumed fixed during the reactive power dispatch. However, due to the effect of reactive power on the real power, real power is allowed to be re-scheduled within given limits. Two new active/reactive dispatch models are presented in [24] to remarry active and reactive allocation procedures based on a market approach as a way to ensure operation transparency. Its objective function is to minimize the cost paid to the generator for balancing transmission losses plus the adjustment cost of generators and loads.

From a brief review of utility practices, it is clear that there is no fully developed structure for competition or pricing of reactive power services in any system [25]. Moreover, there is no unified framework, universally acceptable, for reactive power management practice in the deregulated environments [25]. In other words, although many papers are published in the literature, the reactive power market has yet to reach the maturity level of the energy market. For this reason, the introduction is devoted to the reactive power market and its related problems rather than the energy market. Additionally, due to the importance of having an efficient market for both active and reactive powers and also the interaction between them, this problem should be studied and analyzed in such a way that the system ends with optimal results in both the energy and reactive power markets. It is worth mentioning that the solution obtained from a coupled model simultaneously dispatching active and reactive powers is theoretically closer to the optimal in comparison with the results of decoupled energy and reactive power markets [21,25]. Accordingly, based on the proposed day ahead reactive power market model, this market is also suggested to be cleared jointly with energy market in a joint energy and reactive power market, considering power system security. Contributions of this paper can be summarized as follows:

(a) A coupled market framework for energy and reactive power is proposed, which results in a solution closer to the optimal in comparison with the results of decoupled energy and reactive power markets.
(b) The security issues of power systems including voltage stability and security and branch loading limits are considered in clearing the coupled market in the form of an OPF problem.
(c) LOC is incorporated in the proposed framework of the coupled market with a new formulation.

The reminder of this paper is organized as In Section 2, two, the proposed framework for the coupled market is described and the clearing of this framework is formulated as an OPF, which is mathematically in the form of a mixed integer non-linear programming (MINLP) problem. In Section 3, the effectiveness of the proposed coupled market is studied based on the IEEE RTS 24 bus test system. The last section includes the conclusions.

2. The proposed method

In this section, the coupled market formulation is presented. For this approach, first the decoupled energy and reactive power markets are discussed briefly. Then the coupled energy and reactive power market is formulated.

2.1. Decoupled energy market

In the energy market, the ISOs generally use an auction mechanism that minimizes the total offer cost to select generating units and their capacity levels for the energy market and then use a market clearing price settlement mechanism (Pay-at-MCP) to determine the corresponding payments for the selected generating units in the market settlement [26–28]. Accordingly, the objective function of the energy market, considering the system demand is given, can be written as follows:

$$\text{Minimize} \sum_{i=1}^{NB} \sum_{u=1}^{NB_i} (\rho_e^{i,u} \cdot \tilde{P}_G^{i,u}) \tag{1}$$

where $\rho_e^{i,u}$ is bid price for the uth unit of the ith bus for energy and $\tilde{P}_G^{i,u}$ is the energy output of the uth unit in the ith bus in the energy market; NU_i is the number of units of the ith bus; NB is the number