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Multiobjective clearing of reactive power market in deregulated power systems

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ABSTRACT

This paper presents a day-ahead reactive power market which is cleared in the form of multiobjective context. Total payment function (TPF) of generators, representing the payment paid to the generators for their reactive power compensation, is considered as the main objective function of reactive power market. Besides that, voltage security margin, overload index, and also voltage drop index are the other objective functions of the optimal power flow (OPF) problem to clear the reactive power market. A Multiobjective Mathematical Programming (MMP) formulation is implemented to solve the problem of reactive power market clearing using a fuzzy approach to choose the best compromise solution according to the specific preference among various non-dominated (pareto optimal) solutions. The effectiveness of the proposed method is examined based on the IEEE 24-bus reliability test system (IEEE 24-bus RTS).

1. Introduction

Reactive power is tightly related to bus voltages throughout a power network, and hence it has a significant effect on system security. One of the main reasons for some of recently major blackouts in the power systems around the world such as those occurred in September 23, 2003 in Sweden and Denmark, September 28, 2003 in Italy and also the United State and Canada blackout (August 2003) was reported as insufficient reactive power of system resulting in the voltage collapse [1–3].

This paper proposes a new reactive power market framework. So, the literature review discusses about previous reactive power markets presented in the literature. Moreover, some references about technical and economical aspects of reactive power in the deregulated systems are also discussed in this section.

In recent years, some papers are published in the area of optimal pricing of reactive power, using the well-known marginal price theory to determine optimal prices for reactive power [4–9]. All of these papers assume that the consumer of reactive power should pay for the reactive power service and the producers of reactive power are remunerated. The differences among various works are mainly in the formulation of the optimization. Also, some of more recent research works on designing reactive power market consider technical issues of the power system in addition to the economical aspects [10–14].

Bhattacharya et al. have designed a competitive reactive power market [15–17]. In order to compensate a generator financially for its reactive power support, generator expected payment function (EPF) is defined and formulated so that independent system operator (ISO) can easily call for reactive bids from all parties [15]. The ISO administers transmission tariffs, maintains the system security, coordinates maintenance scheduling, and has a role in coordinating long-term planning. The ISO should function independent of any market participants, such as transmission owners, generators, distribution companies, and end-users, and should provide nondiscriminatory open access to all transmission system users. The ISO has the authority to commit and dispatch some or all system resources and to curtail loads for maintaining the system security (i.e., remove transmission violations, balance supply and demand, and maintain the acceptable system frequency). Also, the ISO ensures that proper economic signals are sent to all market participants, which in turn, should encourage efficient use and motivate investment in resources capable of alleviating constraints. More details about ISO can be found in [18]. Consequently, according to the generator EPF, a two-part reactive bid structure is suggested. In [16], a four-component bidding framework is proposed for synchronous generators. Mitigating market power, a localized reactive power market is proposed in [17]. It is observed that the localized reactive power market restricted the market power of each generator to its area and it no longer affects the reactive power prices of the other zones.

In [19], a pricing mechanism has been proposed for the other compensators of reactive power in the competitive market. In the proposed market, the owners of network devices (e.g. shunt capacitors, SVCs), like generators, bid the price for supplying or absorbing reactive power. Nevertheless, this approach could be applicable

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only if the ISO accepts these devices as the other resources of reactive power ancillary service and compensate them financially.

In the context of deregulated electricity markets, reactive power dispatch corresponds to short-term allocation of reactive power required from suppliers based on current operating conditions [20]. The ISO is concerned with determining the optimal reactive power schedule for all providers based on a given objective that depends on system operating criteria [21]. Different objective functions can be used by the ISO, besides the traditional transmission losses minimization, such as minimization of reactive power cost [22,23], minimization of deviation from contracted transactions [16], minimization of the cost of adjusting reactive power control devices [24], or maximization of the system load ability to minimize the risk of voltage collapse [25–27].

Considering voltage security in the reactive power pricing, in [28] a cost-based reactive power pricing is proposed, which integrates the production cost of reactive power and voltage stability margin requirement of pre- and post-contingencies into the OPF problem. In [29], a two-level framework is proposed for the 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 an essentially 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 [29]. This optimal set should ideally be determined based on demand forecast and system conditions expected over the season [29].

However, seasonal market for reactive power encounters problems. First, the reactive power consumption of system is volatile that its forecasting over a season becomes very hard. Second, in spite of active power, the reactive power requirement of system strongly depends on the loading condition of network. In the heavy load conditions of system, some of transmission lines are loaded more than their surge impedance loading (SIL) and become as sinks of reactive power in the over SIL loading conditions. On the other hand, in the light loading conditions, the transmission lines are usually loaded in the under SIL conditions, and become as sources of reactive power. This further complicates the prediction of reactive power requirement of the power system over a long horizon. Third, the occurrence of different planned/unplanned outages and effects of maintenance scheduling (such as generators and transmission lines entering to circuit after their maintenance period) in a season can change the configuration of the power system, leading to more complexity of 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 contract with them to become available for reactive power compensation and the remaining generators that are not selected at the beginning of the season are no longer participated in the reactive power compensation. In other words, the available sources of reactive power is limited to the selected generators over a long time which is to some extent in contradiction with the local nature of reactive power. Considering the above mentioned problems of the seasonal procurement model for reactive power market, this paper presents a day-ahead reactive power market model, including both economical issues and security aspects.

It is mentioned that, in this paper, adhering to existing FERC (Federal Energy Regulatory Commission) regulation, only reactive power support from generators is considered as one of six ancillary services eligible for financial compensation. However, the proposed market is generic enough to be readily extended to include other reactive power devices such as capacitor banks, reactors, and FACTS devise. Consequently, these devices, like generators, can be considered as independent VAR sources which lead to improving the level of competition and also limiting the exercise of market power from privilege located generators [30]. In [31] a discussion about considering LTC among the reactive power ancillary services has been presented and it has been concluded that LTC transformers should be separated from SVCs, synchronous condensers, and shunt compensators. However, to the best of our knowledge, no research work in the area proposes bidding structure for LTC transformers in order to participate in the reactive power market. Due to the reasons described above, in this paper we only consider generators participating in the reactive power market. However, participation of the other reactive power market compensators will be considered in the future works. Contribution of this work can be summarized as follows:

(a) A day-ahead reactive power market is proposed, which incorporates system security aspects in the clearing of reactive power market. The clearing process of the proposed reactive power market is formulated in the form of a multiobjective optimization problem.
(b) The multiobjective optimization problem of the reactive power market clearing is solved by the ε-constraint method. Besides, a fuzzy decision making technique is proposed to efficiently select the best compromise solution among the pareto optimal solutions based on the ISO preference.

2. Reactive power market

For the clearing of the reactive power market, in the proposed method the following four objective functions are used which will be described in detail in the next subsections:

$$Multiobjective\ functions: \begin{cases} Min(F_1) \\ Max(F_2) \\ Min(F_3) \\ Min(F_4) \end{cases} \quad (1)$$

where F_1: minimization of the TPF, F_2: maximization of voltage security margin, F_3: minimization of overload index, and F_4: minimization of voltage deviation index.

2.1. Minimization of the TPF (F_1)

The reactive power capability curve of a generator is shown in Fig. 1 [16]. Q_{base} is the reactive power required by the generator for its auxiliary equipment. If the operating point lies inside the

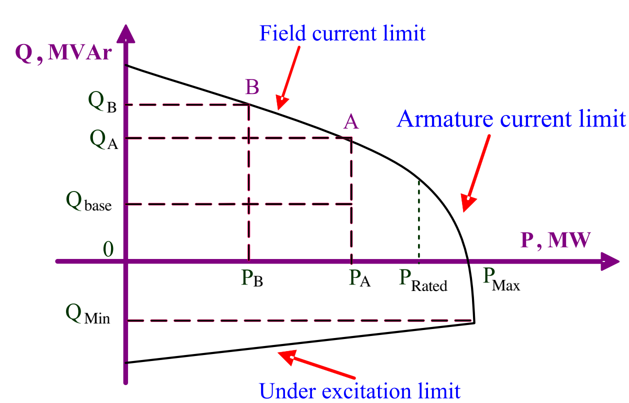

Fig. 1. Synchronous generator capability curve.