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Probabilistic reactive power procurement in hybrid electricity markets with uncertain loads

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ABSTRACT

This paper presents a novel probabilistic algorithm for optimal reactive power provision in hybrid electricity markets. The proposed algorithm is a six-stage multiobjective nonlinear constrained optimization problem which takes into account load forecasting inaccuracies. Considering a set of probable forecasted loads, a three-component expected total market payment function is suggested being minimized as cost function of the first stage. Besides economic issues, expected voltage security margin, deviation from multilateral and pool based energy transactions, deviation from spinning reserve contracts, having adequate local reactive power reserve in each voltage control area of the system and transmission congestion probability are well thought out in stages 2–5 as technical aspects of the market. Finally, in the last stage, using different weighting factors to compromise between all objects, a probabilistic multiobjective function is presented to find the best reactive power market schedule. The proposed algorithm is applied on IEEE 24-bus test system. As a benchmark, Monte Carlo Simulation method is utilized to simulate the market of given period of time to evaluate results of the proposed algorithm, and satisfactory results are achieved.

1. Introduction

In deregulated power systems, reactive power provision is one of the most important ancillary services which has a significant impact on power system security and reliability [1–5]. Almost in all electricity markets, Independent System Operator (ISO) is responsible for providing adequate reactive power for the market. There is not a unique approach for reactive power market clearing around the globe. Different methods are used in different electricity markets for reactive power procurement [6].

As main philosophy of the electricity markets, the system operator tries to provide reactive power with the lowest possible cost. Also, because of important role of reactive power in network operation and security, many researches have considered technical issues as well as economic issues. Different objective functions such as reactive power cost minimization, transmission loss minimization and system loadability maximization have been used in reactive power market settlement [7–10].

In power systems, transmission network is a key section which transfers electric power from generators to consumers. In most of power markets, transmission owners should be compensated for transferring electric power through the lines [1]. Several approaches have been proposed for transmission charge payment most of which depend on transmission lines power flow [1]. Reactive power schedule influences on power flow in transmission lines and consequently on transmission charge payment and also transmission energy loss. If the system operator schedules reactive power market without taking into account its effect on transmission lines power flow, final schedule may increase transmission charge and transmission loss payment and consequently total market payment. Therefore, as the economic aspect of market, transmission charge and also transmission loss payments should be considered during market settlement in addition to reactive power provision cost.

Furthermore, reactive power has a vital role in system voltage stability and security [2,9]. Insufficient reactive power is known to be one important reason for some major blackouts and voltage collapses around the world [2]. Hence, as a technical issue, if the system operator does not consider impact of reactive power on voltage stability, it may move the system toward voltage instability point.

As it is explained in stage four of Section 3, considering only voltage security margin does not guarantee that voltage profile of all buses will be kept in acceptable range after any contingency and disturbance. Therefore, as another technical issue in reactive power market, sufficient reactive power reserve is necessary to prevent

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unacceptable voltage deviation after any system disturbance or due to load uncertainty. Since the voltage and reactive power problems are local issues, hence, this paper suggests classifying the system into different voltage control areas (VCAs) [11] and then providing adequate local reactive power reserve in each VCA during market scheduling.

In sequential forward ancillary services markets, active power contracts are known when the system operator schedules reactive power market. Because of some restrictions such as generators' capability curve and transmission lines limits, some active power contracts may deviate from their prespecified values in the time of reactive power market scheduling. It causes changing in optimal active power contracts which is not desirable. Subsequently, active power market needs to be rescheduled. This problem is more important in hybrid electricity markets which are a combination of multilateral and pool models. In these kinds of markets, energy contracts can be based on multilateral or pool transactions [1]. In addition, the reactive power market may impact on network spinning reserve contracts. Therefore, as an important technical issue, the system operator should consider energy and spinning reserve contracts during reactive power market clearing.

As previously discussed, reactive power schedule directly influences on active power contracts and transmission lines power flow. Therefore, it may change available transfer capability of transmission lines. On the other hand, due to some problems such as system contingency and load uncertainties, some transmission lines may become congested during system operation. The transmission congestion may cause some undesirable problems in the market such as market power [12,13]. Also, it may impact the system security. Therefore, the system operator should try to decrease the possibility of transmission congestion during market settlement.

One of the most important problems which appear in system programming and planning is load forecasting [1]. There are several approaches to forecast power demand of all nodes of the system [14]. But, almost all of these approaches consist of some uncertainties. This problem is more significant in forward electricity markets that the system operator should find the optimal market operating point with paying attention to hourly power demand of all electric loads [15]. Load forecasting is important not only for system operator but also for all market participants.

Considering load forecasting inaccuracy, this paper proposes a novel probabilistic algorithm to find the optimal reactive power market schedule in forward hybrid electricity markets. The algorithm, which is a six-stage multiobjective nonlinear constrained optimization problem, considers both economic and technical aspects of hybrid electricity markets during market clearing. As economic issues, considering a set of probable forecasted loads, the algorithm seeks to minimize a new three-component expected total market payment function which includes reactive power provision payment, transmission loss cost and also transmission charge payment. This algorithm takes into account the impact of reactive power market on expected system voltage security margin, expected local reactive power reserve in each VCA and transmission congestion probability as some important technical issues in the market. Furthermore, minimization of multilateral and pool based energy transactions as well as network spinning reserve contracts are considered as other goals of the algorithm. As the numerical studies, the proposed algorithm has been applied on an ancillary services market based on IEEE-24 bus test system. Then, to evaluate the results, the market of given period of time is simulated by Monte Carlo Simulation method. Comparing the results prove the capabilities of the proposed probabilistic reactive power market algorithm.

2. The proposed three-component total market payment function

In almost all deregulated electricity markets, the system operator provides reactive power through commercial transactions with market participants. Hence, as the main philosophy of electricity markets, the system operator tries to provide reactive power with the minimum market payment [8].

On the other hand, due to impact of reactive power schedule on transmission lines power flow, reactive power market influences on some other economic aspects of electricity market such as transmission loss and transmission charge payment. If the operator does not consider this issue during market settlement, it may contract with providers which result in increasing transmission loss and also transmission charge payment and consequently increasing total market payment. Therefore, in this paper a three-component payment function is proposed to be used in reactive power market clearing. The following subsections describe these three components.

2.1. Component 1 (cost of reactive power provider by market participants)

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 [16]. Some references deem it is necessary to pay other reactive power providers such as capacitor banks, synchronous condensers and FACTS devices [17,18]. In Australia both synchronous generators and synchronous condensers receive payments for reactive power provision [19].

In this paper, reactive power provided by synchronous generators, condensers and also capacitor banks are assumed as ancillary service which should be compensated by the system operator.

2.1.1. Cost of generator's reactive power

Different reactive power payment structures can be used for synchronous generators [20,21]. In [21] a quadratic reactive power cost curve has been proposed for a typical synchronous generator. This cost curve models investment cost, operational cost and also lost opportunity cost of a synchronous generator accurately. It has been defined as follows:

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

where Q_{gi} is reactive power output of ith generator; and a_q, b_q and c_q are constant coefficients. As it is described in [21], knowing active power cost curve of a generator, its capability curve and maximum amount of active and reactive power of that generator, these constant coefficients can be estimated accurately using a suitable interpolation technique. This equation can provide accurate results in reactive power market while it is very simple for implementation.

2.1.2. Cost of condenser's reactive power

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

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