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Economic theory and the application of incentive contracts to procure operating reserves

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Abstract

The ancillary services market plays an important role in the operation of an electricity market, especially for achieving a high level of reliability. Among all ancillary services, operating reserve is an important research focus, with the attention mainly on the optional procurement and pricing methods. These methods differ in many aspects, including the objective, allocation of risks, and feasibility. In this paper, a new approach is proposed to analyze the users' reserve procurement problem and a novel reserve trade mechanism is developed between electricity users and the retailer of the market. First, the differences between the procurement of operating reserve in decentralized and centralized ways are analyzed. The comparison of the equilibrium solutions reveals that the centralized procurement that results in a systemic optimal solution is better than the decentralized procurement that results in a Nash equilibrium solution. Furthermore, an incentive contract based on a Principal-agent model, that is able to induce a systemic optimality as well as a Pareto equilibrium and manage risks at the same time is designed. The proposed model is equitable and beneficial to all participants. An example is served to illustrate the features of the model and the methodology.

Keywords: Electricity market; Operating reserve; Pareto equilibrium; Principal-agent model

1. Introduction

The restructuring of the global electric power industry is giving rise to a renascence in this industry and creating an unprecedented competitive environment for users and providers of energy. Of all the deregulated or deregulating electricity markets, a common challenge is the assurance of reliability. If the failure of the California market was a prelude to the problem of reliability [1], the blackout of August 14, 2003 could at least have shown the industry how crucial the problem of reliability had become [2]. There is an urgent need to find a way out of the problem and to develop corresponding mechanisms for high level reliability achievement. The solution finding will influence not only the establishment of a well-ordered electricity market, but also the integrity and progress of the society.

Electricity markets in different countries differ largely in the methods of procuring operating reserve. In Britain, operating reserve is acquired mainly by long-term contracts. No operating reserve market is established. However, capacity not scheduled for energy or redundant in neighborhood areas can be scheduled as operating reserves. In the Nord Pool, power companies are asked to provide specific ancillary services, which is a necessary condition to participate in the market. Services are compensated through electricity charges. In California, an operating reserve market is established apart from the energy market. An independent system operator (ISO) runs both markets. In New England, there is an installed capacity market, as well as an operating capacity market that is similar to an operating reserve market.

Despite the different market forms for operating reserve, a considerable amount of research has been conducted from a wide range of perspectives. A comprehensive theory on the procurement and pricing scheme for operating reserve was proposed in [3]. The theory is based on a capacity-reliability correlation analysis and is compatible with electricity auctions in the context of a deregulation of the electricity supply industry. Taking into consideration various elements, including the available capacity of generators, outage costs, indices of

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reliability, and so on, the capacity-reliability correlation analysis that reflects the equilibrium condition for procuring operating reserve capacity is built based on an optimal pricing model. The value of the capacity and the energy of the reserve can then be derived. Using the correlation analysis a novel mechanism for monitoring the existence of the participant's gaming behavior was also developed. An adaptive strategy was presented in [4] for integrating the direct load control with an interruptible load to provide operating reserve. Insurance theory was applied in [5] to guarantee the availability of reserved capacity. Prada [6] summarized the economic criteria for pricing operating reserve, including cost-effectiveness analysis, cost-benefit analysis, and market-based allocation. Prada also analyzed the implications of alternative structures for the operation of competitive energy and reserve markets. A calculation of the reserve requirement was formulated in [7] as a function of the endogenously determined marginal values of reserves, and was adjusted based on price signals. As we can see, operating reserve researches have been focusing on reserve supply and assignment, trade mechanism between system operator and reserve suppliers, and unit reliability study. There is not much published work on operating reserve procurement from users' view and trade study between users and market administrator. Moreover, most works presume that a market administrator procures operating reserve on consumers' behalf with neither any incentive mechanism nor any remedial mechanism like ex post punishment, to ensure the rationality of the market administrator's behavior.

In this paper, system security is considered a public good, with operating reserve as its key element. With the utility maximization of all the users in a region as the objective, the differences between the procurement of operating reserve in decentralized and centralized ways are analyzed. The comparison of the equilibrium solutions reveals that the centralized procurement that results in a systemic optimal solution is better than the decentralized procurement that results in a Nash equilibrium solution. Furthermore, an incentive contract based on the Principal-agent model, that is able to induce a systemic optimality as well as a Pareto equilibrium and manage risks at the same time is designed (solutions included in the Pareto optimal set are those that cannot be improved along any dimension without simultaneously being deteriorated along other dimension(s)). An example is served to illustrate the features of the model and the methodology. However, the allocation of reserve costs among users and the reserve assignment among generators are beyond the scope of this study.

This paper is organized as follows: The basic concepts of reliability as a public good and operating reserve as its key element are presented in Section 2. In Section 3, decision alternatives for procuring operating reserve are discussed and the results are compared. A framework, using an incentive contract based on the Principal-agent model, is designed to achieve expected optimality and risk-sharing in Section 4. A sensitivity analysis is carried out in Section 5 and the results are interpreted. In Section 6 an example is served to illustrate the propositions described in Section 5 and the application of the method is discussed. Conclusions are detailed in Section 7.

2. Reliability as a public good

Reliability encompasses two attributes in an electrical power system: security and adequacy [8]. Security describes the ability of the system to withstand disturbances, which depends on protection devices, operation standards, constrained dispatch, and ancillary services. Adequacy represents the ability of the system to meet the energy requirements of all consumers at all times.

Economically, security is a public good while adequacy is a private good. Public goods essentially imply that they are non-rival in consumption and their costs and benefits are non-exclusive [9]. "Non-rival" means that the consumption/use by one party has no effect on other parties' consumption/use. "Non-exclusive" means that the consumption/use of the goods cannot be withheld from those who may seek to avoid paying for it, i.e. who attempt to free-ride. Traffic lights, national defence, law, as well security are referred to as public goods [9,10]. For public goods, a major concern is to exterminate the free-rider problem. Similar to other public goods, power system security tends to be over-consumed if there is no intervention, which leads to economic inefficiency from a systemic view. Some users may be reluctant to pay for operating reserves since they think they do not consume it, regardless of the fact that they are provided with extra security paid by other users. This also applies to some power providers. This situation is not only a free-rider problem, but is a potential hazard to the security of the system. The reason is that, technically, security is closely related to adequacy. The more operating reserve a system has, the higher is the system scheduling flexibility. In this study system security is considered a public good, with operating reserve as its key element. The problem is to decide the optimal procurement level for the whole system and derive a method to realize it.

In fact, after the recent large-scale blackouts in the U.S. and Europe, preventing over-consumption of the security as a public good is now one of the major aims of regulation, although which could be achieved through market-based methods.

3. Operating reserve procurement decisions

Considering the procurement of operating reserve as the procurement of a supply for security as a public good, we define a region with n users, in which user $i (i = 1,2\ldots, n)$ consumes q_i units (MWh) of energy and purchases r_i units (MW) of operating reserve within a per unit time. We then have the aggregate reserve procurement $R = \sum_{i=1}^{n} r_i$. Assume that the energy price is P_e, the reserve price is P_r, and this user i has a budget C_i for electricity consumption. The utility function of user$i$, formulated as $U_i = U_i(q_i, R)$ with $(\partial U_i/\partial q_i) > 0$ and $(\partial U_i/\partial R) > 0$, is used to quantify the perceived satisfaction value of the user i and is depicted using consumption variables q_i and R. The major advantage of using utility function is that it could account for the revenue and risk at the same time.

Define user i's marginal rate of substitution $\mathrm{MRS}(q_i, R) = ((\partial U_i/\partial R)/(\partial U_i/\partial q_i))$, which indicates the rate at which user i is willing to give up one good in exchange for another good, given a fixed utility level [10]. Here, MRS shows the marginal rate of substitution of energy for the reserve. User i's