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Pool equilibria including strategic storage

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HIGHLIGHTS

- Energy storage systems (ESSs) are considered as price makers in the energy market.
- A multi-period EPEC is proposed to study strategic behaviors of various generators.
- The impacts of different ESSs on the market equilibrium are thoroughly compared.
- Reformulation technique is used to handle the nonlinear complementarity constraints.

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ABSTRACT

With a rapid increase in capacity, independently-invested energy storage systems (ESSs) might take up a significant share in the generation mix, and would be required to participate in the electricity market. Considering the arbitrage capability of ESSs, their behaviors would be remarkably different from those of conventional generators, impacting the market equilibrium. These impacts would vary with the type of ESSs and the generation mix. Therefore, this paper formulates a multi-period market equilibrium problem with equilibrium constraints (EPEC) to study the strategic behaviors of different types of ESSs and their impacts on the market outcomes, assuming that ESSs behave as price-makers. The EPEC model is established within a general framework, which considers the individual profit-maximization behaviors of different ESSs and generators, including thermal units, hydro units and renewable units. Interactions between different generators and the market operator are also represented. Finally, numerical studies based on a modified IEEE 57-node system with different wind generation curves are performed for illustration and validation.

1. Introduction

At present, energy storage systems (ESSs) play an increasingly important role in supporting the secure and economic operation of power systems, especially in case of large-scale renewable penetration [1,2]. In the foreseeable future, the share of renewables and ESSs, which might belong to different companies, may rapidly increase, making producers based on these technologies major market players. Thus, privately-owned and independently-invested wind farms, solar plants and ESSs would be required to participate in the electricity market just as conventional generators do. In this case, all generators will jointly compete in the market and strategically pursue their respective maximum profits with potential market power. Considering the arbitrage capability of ESSs, their behaviors would be remarkably different from those of conventional generators, impacting differently the market equilibrium. And these impacts would vary with the type of ESSs and the generation mix.

Several papers have studied the participation of ESSs in electricity markets. However, most of these papers simply regard ESSs as price-takers [3], or as a part of a virtual power plant, but not as individual price-makers. Ref. [4] proposes a mixed complementarity model to study the impacts of ESS sizes and locations on a perfectly competitive market. With a forecasted, fixed hourly marginal clearing price (MCP) curve, the bidding strategies for pumped hydroelectric storage (PHS) are analyzed in [5]. Strategies for the integrated self-scheduling of a wind farm and a PHS are proposed in [6]. Robust bidding in combination with ESS is presented in [7], which uses forecast errors of MCPs and wind generation. An optimal bidding mechanism for an independent ESS is proposed in [8], assuming the ESS behavior to be price-taker. Moreover, revenue analysis for ESSs participating in the electricity markets are

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studied in [9–12], but without considering the impacts of ESSs on MCPs.

In fact, in order to perform an equilibrium analysis of a pool-based electricity market with ESSs, it is necessary to extend the market equilibrium model from single-period to multi-period, representing that the ESS intra-day operation state may switch from charging to discharging and vice versa. Available models pay limited attention to the multi-period market equilibrium analysis and to ESS strategic arbitrage behavior. Clearly, extending the analysis to a multi-period framework significantly increases the complexity of the market equilibrium problem, which is an equilibrium problem with equilibrium constraints (EPEC). Most of the related papers concentrate on a single-period EPEC with thermal units [13–20], or use a Nash-Cournot equilibrium model rather than a supply function equilibrium model [21–23], or find a near-equilibrium under locational marginal pricing and minimum profit conditions [24]. Moreover, the differences in technical characteristics of ESSs have significant influences on their bidding strategies, as different types of ESSs with different energy limits, efficiencies and operation costs have different impacts on the market equilibrium. This issue is not carefully considered in the available literature.

In brief, the research on the impacts of ESSs on the electricity market equilibrium and the investigation of the strategic behaviors of various types of ESSs are limited and need further attention. Therefore, this paper focuses on electricity market equilibria considering the strategic behaviors of various types of ESSs, which is also the main contribution of this paper. First, the ESSs are considered as *price makers* strategically choosing their bidding prices and their discharging or charging strategies. Second, a *multi-period EPEC* is established to study the market equilibrium and the strategic interactions among different generators, including ESSs, thermal units, conventional hydro units, wind farms and solar plants. Third, the impacts of *different types* of ESSs, PHS, compressed air energy storage (CAES) and zinc bromine flow battery storage (ZBFBS) are analyzed to accurately compare their different technical characteristics [2]. The changes in market prices, consumer payments and arbitrage profits are comprehensively studied in a modified IEEE 57-node system.

Several cases are compared to analyze the strategic behaviors of different ESSs. A case with only strategic thermal units, a hydro unit, a wind unit and a solar unit is first considered as a benchmark. Then, the strategic cases respectively involving PHS, CAES or ZBFBS are investigated. For comparison, the non-strategic cases where producers offer at true marginal costs are also studied. In order to focus on the strategic behaviors of various generators, the uncertainties of renewable generation are not included in the EPEC model but different wind generation curves are considered in the case studies.

The rest of this paper is organized as follows. The procedures to formulate the EPEC model are described in Section 2. The equilibrium model of the electricity market is described in Section 3. The MPEC of each agent is derived in Section 4 and the joint Karush–Kuhn–Tucker (KKT) conditions are collected together to form an EPEC in Section 5. Numerical examples to illustrate the impacts of the ESSs on the market equilibrium are provided in Section 6. Finally, conclusions are summarized in Section 7.

2. EPEC modeling

In a bid-based electricity market, all participants are leaders and the market operator (MO) that clears the market after receiving all bids is the single-follower, which constitutes a Stackelberg game [18]. Therefore, to formulate the equilibrium problem, a bi-level model per participant is first formulated. This hierarchical formulation includes each generator's individual profit-maximization problem as part of the upper-level model and the market clearing conditions, incorporating the operation constraints of various generators and the power system, as the lower-level problem. The detailed schematic diagram for the bi-level equilibrium model is shown in Fig. 1(a).

To solve such problem, two general methodologies are often used [19]. The first one is the diagonalization methods that iteratively solve each participant's individual profit-maximization problem until a Nash stationary point is obtained. The second one collects the KKT conditions of all the participants' individual profit-maximization problems and solves them together. Considering the lack of versatility of the diagonalization methods [19–26], the KKT method is adopted in this paper.

Specifically, a mathematical program with equilibrium constraints (MPEC) is derived for each generator by considering the KKT conditions of the lower-level model. Then, to formulate the EPEC, the first-order optimal conditions of each MPEC are derived, and then, all these KKT conditions are jointly considered. The principle of this procedure is presented in Fig. 1(b) [20].

3. Model of market equilibrium

We assume that the participants strategically submit their bidding prices to the MO before the gate closure. Then, the MO clears the energy market considering the operational constraints of various generators and the power system to obtain the MCPs and the production levels for each generator.

3.1. Upper-level model

The upper-level models are the individual profit-maximization problems of the different generators. The problem of the ESS Si is, ($\forall Si = 1, 2, \ldots, ES$):

$$\begin{aligned}&\min_{\beta_{Si}} \pi_{Si} = \sum_{t=1}^{T}\left\{b_{Si}\left[q_{Si}^{cha}(t) + q_{Si}^{dis}(t)\right] - \lambda(t)\left[q_{Si}^{dis}(t) - q_{Si}^{cha}(t)\right]\right\}\\ &\begin{cases}\beta_{Si}(t) - \beta_{\min} \geqslant 0\\ \beta_{\max} - \beta_{Si}(t) \geqslant 0\end{cases}\end{aligned} \tag{1-a}$$

where b_{Si} is the variable non-fuel operation and maintenance (O&M) costs of Si, $q_{Si}^{cha}(t)$ and $q_{Si}^{dis}(t)$ are the charging and discharging power which are determined by the MO in period t, $\lambda(t)$ is the uniform MCP in period t, $\beta_{Si}(t)$ is the bidding price of Si strategically submitted to MO, $\beta_{\min}$ and $\beta_{\max}$ are the floor and cap bidding prices, respectively, which are determined by MO. The problem of capital costs or fixed costs recovery is related to the capacity market or pricing mechanism regarding capacity, which is beyond the scope of the paper.

The individual profit-maximization models of a thermal unit ($\forall Ti = 1, 2, \ldots, TP$), hydro unit ($\forall Hi = 1, 2, \ldots, HP$) and renewable unit ($\forall Ri = 1, 2, \ldots, RE$) can be formulated as:

$$\begin{aligned}&\min_{\beta_{Ti}} \pi_{Ti} = \sum_{t=1}^{T}\left[a_{Ti}q_{Ti}^2(t) + b_{Ti}q_{Ti}(t) - \lambda(t)q_{Ti}(t)\right]\\ &\begin{cases}\beta_{Ti}(t) - \beta_{\min} \geqslant 0\\ \beta_{\max} - \beta_{Ti}(t) \geqslant 0\end{cases}\end{aligned} \tag{1-b}$$

$$\begin{aligned}&\min_{\beta_{Hi}} \pi_{Hi} = \sum_{t=1}^{T}\left[b_{Hi} - \lambda(t)\right]q_{Hi}(t)\\ &\begin{cases}\beta_{Hi}(t) - \beta_{\min} \geqslant 0\\ \beta_{\max} - \beta_{Hi}(t) \geqslant 0\end{cases}\end{aligned} \tag{1-c}$$