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A Distributed Scheme for Power Profile Market Clearing under High Battery Penetration ⋆

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Abstract: In this paper, we formulate a problem of power profile market clearing and develop a distributed market clearing scheme with explicit consideration of high battery penetration. The power profile market is a multiperiod electricity market in which each aggregator aims at making the highest profit by transacting a power profile, i.e., a time sequence of energy amounts at several time slots, that is generated by dispatchable power generation as well as the charge and discharge of batteries. It is theoretically shown that the clearing price profile during the time period of interest tends to level off in the high penetration of batteries. This finding enables to develop a distributed market clearing scheme that is implemented as a bidding strategy for the total energy amount during the period followed by a distributed iterative algorithm for profile imbalance minimization. Numerical simulations demonstrate the price leveling-off led by high battery penetration and the efficiency of the proposed distributed scheme.

Keywords: Multiperiod electricity markets, Energy storage, Power profile balancing, Bidding strategy, Convex analysis.

1. INTRODUCTION

The development of a smart grid has been recognized as one of key issues in addressing environmental and social concerns, such as the sustainability of energy resources and the efficiency of energy management [Annaswamy and Amin (2013)]. In particular, towards effective integration of dispatchable and renewable power generation, the potential of energy storage has been attracting international attention in smart grid community. Actually, energy storage techniques can be expected as a fundamental tool for load shifting as well as reducing the fluctuation of renewable energy.

The penetration of energy storage is generally supposed to be spatially distributed due to the limitation of installation capability. Examples of distributed energy storage include electric vehicles, home energy storage systems, batteries in electric devices, and so forth. Even though the impact of these individual materials and components on the grid may be tiny, the aggregation of them has high potential to serve for supply-demand balancing in power system operation. This implies that an aggregator, a manager of available energy resources including energy storage, can be a strong stakeholder in an electricity market.

With this background, we formulate an electricity market mechanism with explicit consideration of battery penetration, which is referred to as a *power profile market mechanism*. A power profile market is a multiperiod electricity market in which each aggregator aims at making the highest profit by transacting the time sequence of energy amounts at several time slots. This energy amount sequence, formulated as a vector having the dimension compatible with the number of time slots, is referred to as a *power profile*. Each aggregator generates a marketable power profile by aggregating available energy resources, such as dispatchable and renewable power generation and the charge and discharge of distributed batteries. As shown in Section 4.3 of [Annaswamy and Amin (2013)], such a multiperiod market is indispensable for making use of the *power shiftability* of batteries and flexible loads. This is because their utility or cost function is not an additively decomposable function of period-specific power consumption and generation.

To establish a mathematically rigorous formulation of the power profile market mechanism, we first derive a regulation cost function of marketable power profiles,

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consisting of load, dispatchable power generation, and battery charge and discharge power profiles. Then, we show that the profile regulation cost function is necessarily convex provided that the aggregator adopts the optimal strategy for managing dispatchable power generators and batteries, whose cost functions are assumed to be both convex. This clarification enables to formulate the power profile market clearing problem as a convex program.

Furthermore, we develop a distributed solution scheme to the power profile market clearing problem, which can be implemented as an indirect communication among aggregators through an independent system operator (ISO). The market clearing scheme is developed by theoretically showing that the clearing price profile, i.e., the multiperiod clearing price vector of the power profile market, tends to level off in high penetration of batteries. Numerical simulations in this paper demonstrate the price leveling-off as well as the efficiency of the proposed distributed scheme, which consists of a bidding strategy for the total energy amount during the period and a distributed iterative algorithm for profile imbalance minimization.

Finally, references related to electricity markets are discussed. As market clearing strategies, a number of bidding and dynamic pricing methods have been developed in different settings; see [Hansen et al. (2015); He et al. (2015); Liu et al. (2016); Shiltz et al. (2016)] and references therein. However, these existing methods are not directly applicable to the power profile market clearing problem. This is due to the fact that a transacted power profile is a high-dimensional vector and the cost function of power profile regulation is not strictly convex because of the power shiftability of batteries; see Section 2.3 for details. Furthermore, even though the efficiency and significance of their methods are demonstrated numerically, the structures and properties of market mechanisms are not theoretically investigated. In contrast to this, by utilizing tools from convex analysis theory, we clarify a particular impact of high battery penetration on multiperiod market mechanisms on the basis of a simple but meaningful mathematical formulation.

The remainder of this paper is structured as follows. In Section 2, we first formulate the power profile market clearing problem, and then discuss the difficulties in addressing it. Next, in Section 3, we develop a distributed market clearing scheme while clarifying that the clearing price profile tends to level off in high battery penetration. Numerical simulations are provided in Section 4 and concluding remarks are provided in Section 5.

Notation: We denote the set of real values by $\mathbb{R}$, the set of nonnegative real values by $\mathbb{R}_+$, the image of a matrix M by $\mathrm{im}\, M$, the all-ones vector by $\mathbf{1}$, the orthogonal projection of a vector v onto a subspace $\mathcal{V}$ by $\mathrm{proj}_{\mathcal{V}}(v)$, and the direct product of sets $S_1, \ldots, S_n$ by

$$S_1 \times \cdots \times S_n = \prod_{i \in \{1,\ldots,n\}} S_i.$$

A function $F : \mathbb{R}^n \to \mathbb{R}$ is said to be convex if

$$F\big((1-\lambda)x + \lambda x'\big) \le (1-\lambda)F(x) + \lambda F(x') \qquad (1)$$

for all $\lambda \in (0,1)$ and for every pair of x and x' in the domain such that the value of F is finite. In particular, F is said to be strictly convex if (1) holds with the strict inequality unless $x = x'$.

2. FORMULATION OF POWER PROFILE MARKETS

2.1 Aggregator Models

In this subsection, we give a model of aggregators, each of whom transacts a power profile, i.e., the time sequence of energy amounts at several time slots. Let $\mathcal{A}$ denote the index set of aggregators and let n denote the number of time slots during the period of interest. The power profile equation of the αth aggregator can be described as

$$x_\alpha = g_\alpha - l_\alpha + \eta_\alpha^{\mathrm{out}} \delta_\alpha^{\mathrm{out}} - \tfrac{1}{\eta_\alpha^{\mathrm{in}}} \delta_\alpha^{\mathrm{in}}, \quad \alpha \in \mathcal{A} \qquad (2)$$

where $x_\alpha \in \mathbb{R}^n$ denotes the resultant power profile to the grid, $g_\alpha \in \mathbb{R}^n_+$ denotes the power generation profile of dispatchable generators, $l_\alpha \in \mathbb{R}^n_+$ denotes the load profile, and $\delta_\alpha^{\mathrm{in}} \in \mathbb{R}^n_+$ and $\delta_\alpha^{\mathrm{out}} \in \mathbb{R}^n_+$ denote the battery charge and discharge power profiles. The positive constants $\eta_\alpha^{\mathrm{in}}$ and $\eta_\alpha^{\mathrm{out}}$ denote the charge and discharge efficiency, respectively, each of which takes a value in $(0,1]$. Note that the sign of x_α is positive for outflow direction to the grid.

In the following, we suppose that the load profile l_α is fixed as a constant vector, whereas the dispatchable power generation profile g_α as well as the battery charge and discharge power profiles $\delta_\alpha^{\mathrm{in}}$ and $\delta_\alpha^{\mathrm{out}}$ are decision variables. To realize a desired power profile x_α, each aggregator determines g_α and $\delta_\alpha := (\delta_\alpha^{\mathrm{in}}, \delta_\alpha^{\mathrm{out}})$ as complying with the constraints of

$$g_\alpha \in \mathcal{G}_\alpha, \quad \delta_\alpha \in \mathcal{D}_\alpha, \qquad (3)$$

where $\mathcal{G}_\alpha$ and $\mathcal{D}_\alpha$ denote some connected spaces including the origin. The left condition in (3) is given to represent the upper and lower bounds for the dispatchable generator outputs, whereas the right is given to represent the limitation of inverter and battery capacities.

With respect to each power profile x_α, we denote the feasible subspace of the dispatchable power generation and the battery charge and discharge profiles as

$$\mathcal{F}_\alpha(x_\alpha) := \big\{ (g_\alpha, \delta_\alpha) \in \mathcal{G}_\alpha \times \mathcal{D}_\alpha : (2) \text{ is satisfied} \big\}, \qquad (4)$$

and denote the set of realizable power profiles as

$$\mathcal{X}_\alpha := \big\{ x_\alpha \in \mathbb{R}^n : \mathcal{F}_\alpha(x_\alpha) \neq \emptyset \big\}. \qquad (5)$$

Furthermore, we denote the generation cost function of dispatchable generators and the battery usage cost function as

$$G_\alpha : \mathcal{G}_\alpha \to \mathbb{R}_+, \quad D_\alpha : \mathcal{D}_\alpha \to \mathbb{R}_+. \qquad (6)$$

On the basis of this formulation, we define a cost function with respect to power profile regulation as follows.

Lemma 1. In the notation above, if the generation cost function G_α and the battery usage cost function D_α are convex on convex domains $\mathcal{G}_\alpha$ and $\mathcal{D}_\alpha$, then the profile regulation cost function defined by

$$F_\alpha(x_\alpha) := \min_{(g_\alpha, \delta_\alpha) \in \mathcal{F}_\alpha(x_\alpha)} \Big\{ G_\alpha(g_\alpha) + D_\alpha(\delta_\alpha) \Big\} \qquad (7)$$

is convex on the convex domain $\mathcal{X}_\alpha$.

The value of $F_\alpha(x_\alpha)$ in (7) represents the minimum cost to realize a power profile x_α. Lemma 1 shows that the profile regulation cost function turns out to be convex with respect to generated power profiles, provided that the aggregator adopts the optimal strategy for the determination of the dispatchable power generation profile g_α