Mitigation-Aware Bidding Strategies in Electricity Markets

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Abstract—Market power exercise in the electricity markets distorts the market and diminishes social welfare. Many markets have implemented market power mitigation processes to eliminate the impact of such behavior. In order to evaluate the effectiveness of the existing mitigation mechanisms, this paper proposes a mitigation-aware strategic bidding model and studies market participants’ bidding behavior under current practice. The proposed bidding model has a bilevel structure with the strategic participant’s profit maximization problem in the upper level and the dispatch problem for market operators in the lower level. In particular, the consideration of potential offer mitigation is incorporated as upper-level constraints based on the conduct and impact tests. This bilevel problem is reduced to a mixed-integer linear program using the KKT conditions, duality theory, and linearization. Numerical results illustrate how a strategic participant can exercise market power even under mitigation and the consequent social impact.

Index Terms—Bidding strategy, electricity market, market power mitigation.

I. INTRODUCTION

The restructuring of the traditional monopoly-based power industry dates back to the early 1980s with the aim of introducing fair competition and improving economic efficiency [1]. A typical liberalized market is hierarchical with a market operator and a group of market participants, e.g., generation companies (GenCos), large consumers, and renewable investors. In theory, well-defined markets can lead to perfect competition and maximized social welfare. However, existing electricity markets have shown their vulnerability to price distortion and market manipulation. The ability of a single market participant (or group of participants) to influence price and distort the market is referred to as market power [2].

In the wholesale electricity market, as a profit-seeking entity, a strategic participant may exercise market power via two different approaches: economic withholding and physical withholding. Economic withholding involves submitting strategic bids that deviate from the true marginal cost or utility. Physical withholding entails a participant not offering to sell or not scheduling an output according to its actual capacity or load. According to the market reports in [3], there can be observed market-wide potential economic and physical withholding at ∼2% and ∼3% of capacity, respectively, with a noticeable growing trend over recent years. This work focuses attention on economic withholding.

As an attempt to hedge risks and maximize profit, market participants often embed predicted clearing results into their decision-making process. A bilevel optimization problem is commonly used to build such a bidding strategy [4]–[8]. The upper-level (UL) problem maximizes the profit of the strategic player calculated with the generation output and clearing prices from the dispatch problem in the lower level. The lower-level (LL) problem determines the market outcome based on the strategic player’s offer and those from its competitors.

Market power mitigation has been a persistent challenge in liberalized wholesale electricity markets. Significant effort has been made to investigate the potential for strategic bidding and the design of specialized mitigation mechanisms. Among the existing electricity markets in the US, two fundamental approaches are utilized to mitigate market power: the structural approach and the conduct and impact (C&I) approach. The former approach checks for the existence of pivotal players according to their ability to relieve congestion along certain transmission lines. For the latter case, a two-step process is employed first to detect a player’s strategic conduct and then to assess the impact of such conduct on the market-clearing price. More details can be found in [9]. The performance of these two fundamentally different approaches is still a topic of intense debate [10]. This paper examines the C&I approach.

Very few studies have paid attention to the effects of market power mitigation from a strategic bidding perspective. Based on this observation, we propose a mitigation-aware strategic bidding model to investigate the feasibility of exercising market power under the existing market power mitigation mechanisms and obtain insight into the influence and effectiveness of these practices. GenCos are considered as the strategic entities in this paper. The proposed bidding model is formulated as a bilevel optimization problem with the consideration of offer mitigation in the UL problem.

The main contributions of this paper are two-fold:

1) The development of a simple optimization-based model...
that demonstrates the profitability of a strategic market participant under offer mitigation processes. The mitigation-aware strategic player can gain additional profit by taking advantage of its market share as well as network congestion. Our model also captures the fact that non-strategic GenCos may benefit in the presence of mitigation-aware strategic market participants.

2) Illustration of the vulnerability of electricity markets to market power exercise with limited offer mitigation tools. Even non-strategic players have insufficient incentive to resist the exercise of market power. The proposed mitigation-aware bidding framework can serve as an analysis tool for alternative market designs.

II. MODEL FORMULATION

A. Mitigation-Unaware Bidding Strategy

Consider a power network modeled as a graph $\mathcal{G} := (\mathcal{N}, \mathcal{E})$, where each edge $(m, n) \in \mathcal{E}$ represents a branch, and each node $m \in \mathcal{N}$ represents a bus. For each branch $(m, n) \in \mathcal{E}$, let $p_{mn}$ denote the power flow from bus $m$ to $n$. For each bus $m \in \mathcal{N}$, let $D_m$ denote the aggregate load and $\theta_m$ the voltage phase angle. We assume there are $N$ GenCos in the market. However, we take the perspective of considering a single GenCo $G_i$, and its associated set of generating units $\Omega_i$. The remaining $N-1$ GenCos are considered as a single entity with generating units in the set $\Omega_G \setminus \Omega_i$. For each unit $i \in \Omega_G \cup \Omega_i$, $g_i$ denotes the generation output. The generation dispatch problem of the market operator is formulated using the DC power flow model as follows:

$$\min \sum_{i \in \Omega} \hat{\lambda}^i g_i + \sum_{j \in \Omega} \hat{\lambda}^j g_j$$

s.t. $\sum_{i \in \Omega} g_i + \sum_{j \in \Omega} g_j = D_m + \sum_{m, m \neq n} p_{mn}$

$$\text{s.t. } \sum_{i \in \Omega} g_i + \sum_{j \in \Omega} g_j = D_m + \sum_{m, m \neq n} p_{mn} \leq \lambda_m, \forall m \in \mathcal{N}$$

where $\mathcal{G} = \{g_i, g_j, p_{mn}, \theta_m\}$ is the set of LL decision variables. Note that generation variables have been partitioned into sets corresponding to GenCo $G_i$ and the lumped GenCos (this will facilitate future analysis). Equation (1a) minimizes the total generation cost, (1b) represents the nodal supply and demand balance, (1c) is the linear approximation of the line flow, (1d) enforces the transmission capacity limits of each line, (1e) and (1f) are generation bounds for units, (1g) imposes voltage angle bounds for each bus. $L_i$ identifies the generating units connected to bus $m$. The associated dual variables are indicated following the respective equations. In particular, $\lambda_m$, the dual variable associated with (1b), is interpreted as the market clearing price, i.e., locational marginal price (LMP).

Fig. 1 gives the workflow for one market clearing period. At the beginning, the market operator collects offers from the market participants and performs a two-step C&I assessment. In the conduct test, participants’ offers are compared to the reference levels maintained by the market operator. If the submitted offer exceeds a specific threshold, it fails the conduct test. In this case, an impact test will be executed. This test evaluates the impact of the conduct-test-failed offers by comparing the resulting market prices to the ones obtained from replacing

Generally, a market clearing price cap $\overline{\lambda}$ is necessary to guarantee the availability and accessibility of electricity under certain extreme conditions [11].

From the strategic GenCo’s perspective, each GenCo develops its bidding strategies using the bilevel bidding model, where it maximizes its profit in the upper level and incorporates the market dispatch problem (1) in the lower level. Market participants generally bid with pairs of the offer price and quantity $(\hat{c}_i, \hat{g}_i)$ in the electricity market. Note that only economic withholding scenarios are discussed in this paper; thus, it is assumed that the quantity offers are submitted as nominal values, i.e., $\hat{g}_i = G_i, \forall i \in \Omega_i$. The bilevel problem of the strategic GenCo $G_i$ is formulated as follows:

$$\max_{\hat{c}_i, \hat{g}_i, \lambda_m(i)} \sum_{i \in \Omega} (\lambda_m(i) - c_i) g_i$$

s.t. $0 \leq \hat{c}_i \leq \tau, \forall i \in \Omega_G$

$$0 \leq \lambda_m \leq \overline{\lambda}, \forall m \in \mathcal{N}$$

$$\lambda_m, g_i \in \arg \min_{\hat{c}_i, \hat{g}_i, \lambda_m} \sum_{i \in \Omega} \hat{c}_i g_i + \sum_{j \in \Omega} \hat{\lambda}^j g_j$$

s.t. (1b) - (1g)

where the objective function (2a) represents the profit of the considered GenCo, $\lambda_m(i)$ is the clearing price of unit $i$ under bus $m$, and (2b) and (2c) represents the market offer and clearing price cap, respectively.

B. Mitigation-Aware Bidding Strategy

We incorporate the consideration of possible mitigation policies such as C&I assessment into a strategic player’s optimal bidding model. The strategic bidding model (2) presented above is referred to as the mitigation-unaware bidding model, and the one accounting possible offer mitigation is the mitigation-aware bidding model.

![Fig. 1. Market clearing workflow with market power mitigation process based on the C&I tests. GenCos $G_i - G_{i-1}$ correspond to the lumped GenCos.](image-url)
the submitted offers with their reference levels. If an offer fails both tests, it will be mitigated to its reference level before it is transferred to the final market clearing process. The reference levels used throughout the mitigation process are determined based on units’ incremental costs, previously accepted offers, previous market prices or negotiated rates [9]. Offer mitigation is typically imposed with different thresholds in different areas: constrained and unconstrained areas. Constrained areas correspond to frequently congested regions, thus often having higher shadow prices. These areas are generally subject to more stringent thresholds.

Clearly it is in the interest of a strategic player to implement a bidding strategy that can circumvent the mitigation process. A submitted offer can bypass the mitigation process if it is able to satisfy the following constraints:

\[
|\hat{c}_i - c^0_i| \leq x_i, \quad \forall i \in \Omega_G \tag{3a}
\]

\[
|\hat{\lambda}_m - \lambda^0_m| \leq y_m, \quad \forall m \in \mathcal{N} \tag{3b}
\]

where (3a) and (3b) correspond to the conduct test and the impact test, respectively. \(c^0_i\) represents the estimated reference level of offer price, and \(\lambda^0_m\) indicates the estimate for a competitive market clearing price. \(x_i\) and \(y_m\) are test thresholds.

Ideally, including one of the constraints (3a) or (3b) in the UL problem will be sufficient to avoid the possible mitigation. Though the exact reference levels are not provided to the strategic unit, and Unit \(A\) is typically imposed with different thresholds in different areas: constrained and unconstrained areas. Constrained areas correspond to frequently congested regions, thus often having higher shadow prices. These areas are generally subject to more stringent thresholds.

III. NUMERICAL EXPERIMENTS

Our case study is performed on a 2-bus test system, as depicted in Fig. 2. Due to lack of space, more involved examples are relegated to [15]. Four bidding strategies are tested and compared:

1) Non-strategic bidding: Offer with true marginal costs.
2) Mitigation-unaware bidding: Offer based on (2).
3) Conduct-aware bidding: Offer based on (4) with only (3a).
4) Impact-aware bidding: Offer based on (4) with only (3b).

The case with two GenCos is considered: Unit \(A\) is the strategic unit, and Unit \(B\) is a non-strategic competitor. Perfect prediction is assumed as strategic players accurately estimate market outcomes, and the market operator sets the reference levels at participants’ true operational parameters. The mitigation thresholds for C&I tests are set at 100% higher than the reference levels [9]. The market offer cap \(\bar{\lambda}\) and clearing price cap \(\bar{\tau}\) are set at $100/MWh and $200/MWh, respectively. For impact-aware players, the estimation for reference price \(\lambda^0_m\) is carried out by solving (1) with the reference-level offers. In practice, to guarantee fair dispatch among the price-tied units, the market operator applies “tie-breaking” constraints to these units. We include these in our model; for clarity of exposition, the details are deferred to Appendix of [15].

A. Mitigation-unaware bidding & market power mitigation

We first consider various bidding strategies for the strategic unit \(A\), results given in Table I. “Profit,” suggests the predicted profits for the strategic units as they make the bidding decisions. \(\hat{\lambda}_i\) represents the clearing prices for each unit.

where \(\xi := \{\hat{c}_i, \hat{\lambda}_m, \lambda_j, \sigma_{mn}, \mu_j, \mu^+_j, \delta_m, \delta^+_m\}\) is the set of decision variables for (5). Equation (5c)–(5f) correspond to the dual constraints of the LL problem (4c) and (4d), and constraints (5g)–(5m) enforce the complementarity constraints. The notation \(\perp\) denotes orthogonality in addition to the stated inequalities.

The single-level equivalent (5) is nonconvex and can be linearized through optimality conditions [4] and the Special Ordered Sets of Type 1 (SOS1) variables [14]. The linearization techniques are explained in Appendix of [15].
in the table mean that the mitigation is not triggered and the clearing results remain unchanged after mitigation.

For the case of non-strategic bidding, Unit A makes no explicit profit through market clearing since the clearing price equals its marginal cost. Assuming that a strategic unit always attempts to expand its profits, it may adopt the mitigation-unaware bidding model and exercise economic withholding. As a result, Unit A offers at the maximum acceptable price $7, raises the clearing price and makes a high profit of $1600. Meanwhile, it can be seen that Unit B also benefits from Unit A’s strategic behavior and makes an even higher profit of $2400. The reason for this is that when Unit A offers higher than its true marginal cost, Unit B becomes the first-to-clear unit and makes higher profits with the same clearing prices even being non-strategically. Indeed, this somewhat counterintuitive outcome is observed in practice [16].

Next, we apply the mitigation process to the submitted offers, and the results are summarized in the right half of Table I. It can be seen that the strategic offers generated from the mitigation-unaware bidding model are vulnerable to offer mitigation. Once detected in the mitigation process, bidding offers are reset to the reference level, which leaves the strategic unit with a relatively narrow profit margin. This motivates market participants to adopt a smarter bidding model.

**B. Effects of mitigation-aware bidding**

The clearing results adopting mitigation-aware bidding strategies are shown in Table I. It can be seen that mitigation-aware bidding (either conduct- or impact-aware strategies) can successfully bypass the offer mitigation and achieve a higher profit. The clearing results from the conduct- and impact-aware bidding are identical due to the same operational parameters for units. Compared to the mitigation-unaware bidding, the mitigation-aware bidding offers at $40/MWh instead of $100/MWh and yields $400 higher profit for Unit A.

What is worth noting is the lower profits of Unit A compared to that of Unit B at the end of the clearing period, which means Unit B earns more even if it gets mitigated and cleared at a reference-level offer. However, the relatively lower profits still promise a better return compared to the outcome from non-strategic or mitigation-unaware bidding strategies. Besides, if the competitor also adopts a mitigation-aware bidding strategy, two units will evenly supply the total demand and make a profit of $500 for each. That is, mitigation-aware bidding strategies lead to a suboptimal outcome. It also shows that the capacity limit is one major source of exercising market power.

**C. Comparison between conduct- & impact-aware bidding strategies**

The difference between conduct- and impact-aware bidding becomes more clear when considering units with different marginal costs. We now set the marginal costs as $c_A = $10/MWh and $c_B = $20/MWh, results shown in Table II. Under the conduct-aware bidding, Unit A obtains its offer at $(20-\varepsilon)/MWh (\varepsilon > 0)$ and gets cleared with 30 MW. Using the impact test, Unit A offers at $40/MWh and closes the deal with 20 MW. Though the generation output is lower, impact-aware bidding ends up with higher profits. It can be concluded that when the strategic unit is not at the marginal position according to its true marginal cost, it’s rational to bid under the impact-aware strategy and pursue a higher profit. As such, the conduct-aware bidding strategy is shown to be more conservative than the impact-aware strategy. This result is aligned with the fact that only a small portion of the conduct-test-failed offers are eventually mitigated after the impact test in reality.

We further examine the effects of mitigation thresholds on mitigation-aware bidding. It is easy to imagine that the profits will linearly increase with the growth of thresholds when $c_A = c_B$ or $c_A > c_B$ and be identical in adopting conduct- or impact-aware bidding strategies. The results when $c_A = $10/MWh and $c_B = $20/MWh are shown in Fig. 3(a). The thresholds are selected as 50%–300% higher than the reference levels. For the case of conduct-aware bidding, the profit of Unit A remains steady at $300 when the threshold is relatively lower, because Unit A offers lower than Unit B and gets cleared with higher output at Unit B’s offer price. It can be seen that the profit difference between conduct- and impact-aware bidding becomes more significant as the thresholds increase.

The exercise of market power will eventually jeopardize social welfare due to the increase in the total generation cost. Consider the case $c_A < c_B$. Once the generating unit A submits an offer claiming $c_A > c_B$, the market operator will prioritize clearing Unit B. Then, the total generation cost is increased compared to perfect competition. The impact-aware bidding case in Table II is one typical example of this. Assuming that the marginal utility of demand is $25/MWh [5], the original social welfare is supposed to be $550 while...
it drops to $450 under impact-aware bidding. Therefore, from the market operator’s point of view, it is important to consider the limitation of their mitigation mechanism.

D. Effects of line congestion

Scenarios without line congestion can be understood as the local competition isolated by exterior congestion. We now examine the effects of line congestion. The transmission line limit is set to 23 MW, a value slightly lower than the evenly dispatching decisions. For this new scenario, the clearing results are presented in Table III. First, the difference from the uncongested scenario is reflected in the generation output. Here, the market share remains at 27 MW due to the line congestion. Secondly, line congestion causes different clearing prices at different nodes of the congested line. A higher price under this condition can be interpreted as a reward for relieving the congestion. As a result, the suboptimal situation for the strategic unit is resolved. Altogether, the profits for the strategic unit in the congested scenario are higher than those in the uncongested area. Hence, congestion serves as a persistent second major source of market manipulation and puts the strategic unit in a better position for profit-seeking.

Fig. 3(b) gives the clearing results considering different mitigation thresholds when the network is congested. The trend for profit increase is similar to that in the uncongested scenario. The profits are eventually higher as discussed above. The conduct-aware bidding produces a higher profit with lower thresholds attributed to higher output. It is reasonable to conclude that the strategic unit is in a preferable position to exercise market power in a high-demand and frequently congested area. This explains the reason why a more restrictive mitigation policy is open implemented in constrained areas to prevent extreme exploitation of market power.

The effects of line congestion are more subtle when the graph representing the physical structure of the network contains loops. A simplified single loop example and a more realistic bidding scenario accounting for multiple agents and multi-block offer curves are presented in Appendix of [15].

IV. CONCLUSIONS

A mitigation-aware bidding model is proposed to investigate bidding behavior of the strategic market participants under existing market power mitigation mechanisms and the effectiveness of these practices investigated. Through this model, market participants make bidding decisions on account of offer mitigation and market dispatch results. Numerical results reveal the vulnerability of the electricity market to market power exercise and consequent loss of social welfare with limited mitigation tools. Strategic participants are shown to achieve a higher profit by taking advantage of market scarcity and network congestion and circumventing offer mitigation. Meanwhile, even the non-strategic participants may benefit from the exercise of market power within the market. Future work will examine strategic behavior in terms of physical withholding and remove the perfect prediction assumption.

TABLE III
CLEARING RESULTS IN THE CONGESTED NETWORK

| Strategy of Unit A | Before Mitigation | After Mitigation |
|--------------------|-------------------|------------------|
|                    | \( \hat{c}_i \) | \( g_i \) | \( \lambda_i \) | Profit | \( \hat{c}_i \) | \( g_i \) | \( \lambda_i \) | Profit |
| Non-Strategic A    | 20 27 20         | 0               | 0               | 0      | 20 27 20 | 0               | 0               | 0      |
| B                  | 20 23 20         | 0               | 0               | 0      | 20 23 20 | 0               | 0               | 0      |
| Mitigation-        | 100 27 100       | 2160            | 20 27 20        | 0      | 100 27 100 | 2160            | 20 27 20        | 0      |
| Unaware            | 20 23 20         | 0               | 0               | 0      | 20 23 20 | 0               | 0               | 0      |
| Conduct-Aware      | 40 27 40         | 540             | -               | -      | 40 27 40 | 540             | -               | -      |
| Impact-Aware       | 20 23 20         | 0               | -               | -      | 20 23 20 | 0               | -               | -      |

Fig. 3. Post-mitigation clearing results with different mitigation thresholds.

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