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The Increasing Threat of Collusion in Deregulated Electricity Markets
Introduction

- Unlike most other commodities, electricity should be consumed immediately after generation.

- Electricity industry started as vertically integrated monopolies; however, the low performance of these regulated entities has demanded reformation to enhance market efficiency.

- Deregulation aims to maximize social welfare through competition. England and Wales were among the first in the history that embrace the change and become deregulated.
Competition in Electricity Markets

▪ It is observed that some electricity markets behave like oligopolies.

▪ The reasons for electricity markets to retain an oligopoly rather than a perfect competition are as follows:

  ▪ Limited number of generators due to entry barriers for new competitors such as capital investment,

  ▪ transmission constraints and congestion that isolates certain consumers from some generators, and

  ▪ transmission losses that discourage consumers from distant producers.
Collusion in Electricity Markets

- An unfavorable by-product of oligopolistic markets is the likelihood of participants engaging in collusion.

- Collusion is an agreement between multiple parties to curb open competition.

- To attain a competitive market, collusion of all kinds should be mitigated, but it is not easy for regulators to detect tacit collusion *(EEM 2019 - Reformulations of a Bilevel Model for Detection of Tacit Collusion in Deregulated Electricity Markets)*.

- To make matters worse, antitrust agencies are worried that the autonomous pricing algorithms often used by suppliers may learn to collude.
A Game-Theoretic Understanding of Collusion

- By solving an optimal power flow problem, the ISO determines the production amount (dispatched power $P_i$) for each GenCo and the corresponding nodal price ($LMP_i$) at each node.

- GenCos’ profits can be calculated according to $r_i = P_i (LMP_i - C_i)$.

- The yellow cell is the Nash equilibrium of a single-stage non-cooperative game. The green cell is the collusive equilibrium (Folk theorem).
Explicit Collusion

- When the payoff information is common among participants, they can discover the collusive strategy, in which they maximize the minimum payoff ($\text{Max min } r_i$) subject to transmission network constraints; however, explicit collusion in the EM is forbidden for obvious reasons.

Genetic Algorithm

Max Min Payoff = $279/h
GenCo-1 ($b_1$): $51$/MWh
GenCo-2 ($b_2$): $50$/MWh
GenCo-5 ($b_5$): $49$/MWh
GenCo-6 ($b_6$): $36$/MWh
Research Questions

- Can smart (AI-equipped) GenCos find and sustain collusion without communicating with one another (i.e., tacit collusion).

- How can regulators (ISOs) cope with this issue?
Assumptions

- The demand is inelastic and constant, i.e. it does not change from one hour/period to the next.
- GenCos participate only in the day-ahead market.
- No line or generation outage is experienced.
- GenCos do not change their technology.
- GenCos offer their maximum capacity and capacity withholding is not allowed.
- GenCos do not share information with each other; they are not aware of others’ production cost and strategies.
Learning of GenCos

- We employ an enhanced version of Q-learning to replicate intelligence in GenCos; therefore, players can learn from their past actions to improve their long-term profit.

- Parameters:
  - **Recency rate** $\alpha_{it} \in [0, 1]$ determines the level of significance associated by GenCo-$i$ to the most recent observed outcome at iteration $t$.
  - **Exploitation parameter** $\gamma_{it} \in [0, 1]$ adjust the conservativeness of a GenCo-$i$ at iteration $t$. 
Learning of GenCos - Recency Rate

- GenCo-$i$ has a set of bids ($b_{ij} \in B_i$) to choose from.
- For each bid, $Q$-value ($Q_{ij}$) corresponds to the weighted average of the realized profits when $b_{ij}$ was used by GenCo-$i$ in previous iterations.
- $Q$-value is updated after each iteration according to the observed payoff ($r_i$) with a recency rate of $\alpha_{it}$ at iteration $t$ as

$$Q_{ij} = (1 - \alpha_{it})Q_{ij} + \alpha_{it}(r_i)$$

$$\alpha_{it} = \left(1 - \frac{t}{\max_t}\right)(\alpha_{i0}) + \left(\frac{t}{\max_t}\right)\left(\frac{\alpha_{i0}}{10}\right)$$
In the proposed Q-learning algorithm, GenCo-\(i\) selects \(b^*_i\) with probability \(\gamma_{it}\) at iteration \(t\); otherwise, a random bid is selected from \(B_i\).

\[
b^*_i = \arg\max_{b_{ij}} \{Q_{ij}\}.
\]

- Linear decaying function with different \(\varepsilon_{it} = 1 - \gamma_{it}\) over time

\[
\varepsilon_{i0} = 1
\]
\[
\varepsilon_{i0} = 0.95
\]
The results for 2000 iterations and 5 replications demonstrate that GenCos often converge to Nash equilibria and semi-Nash states and collusion can be achieved rarely.

Convergence to Nash or Collusion

- Convergence to Nash or Collusion
- Convergence to Nash & SN
Is it possible to achieve collusion when GenCos act decentralized by applying some basic rules in their bidding strategies?

**Modified Q-Learning (MQL)**

- **Rule:** If a GenCo raises its bid price such that the assigned power of all GenCos stays the same, GenCos’ profit will not decrease.

- **Implementation:** Offer a bid price higher than the best-known bid 
  \( b_{ij} > b_{i^*} \) when GenCo-\(i\) wants to select its best bid with a probability \(\mu\).
Convergence to Nash or Collusion (MQL)

- $\mu = 0\%$
- $\mu = 5\%$
- $\mu = 10\%$
Second Case: Four Active GenCos
Deep Q-Learning (DQN)

- We also analyzed more sophisticated learning algorithms such as DQN. Although DQN could reach to collusive state when two players exist (duopoly), it failed to achieve collusion as the number of players grow.

- This behavior is due to the fact that LMP hides rivals’ actions; therefore, GenCos cannot recognize which rival is deviating from the collusion.

- A similar result has been observed in other studies [Calvano, 2018].

Solution?

- The collusion is mostly happening in oligopolistic markets; therefore, we can eliminate it by moving toward fully competitive market:
  - Supporting Local Electricity Markets (LEMs) can increase the number of players (i.e., Prosumers), and intensify competition.

- Transmission Network Congestion:
  - LEM can remove the load from the network and solve congestion issue as well.
  - Also, grid loss can be alleviated using LEM.