Incentive Compatible Power Market Design by Indirect Groves Mechanisms

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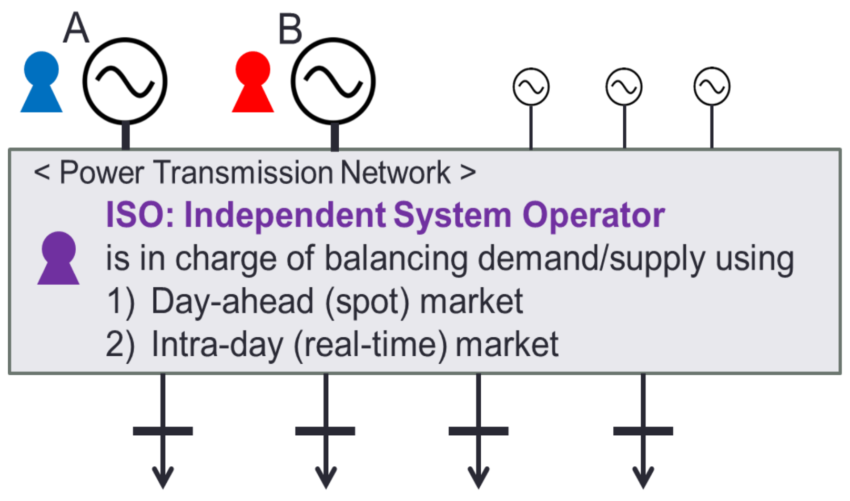
Abstract

In an inappropriately designed oligopolistic power supply market, stakeholders are incentivized to exeicise their market power to manipulate the market in order to maximize their own profit, resulting in a significant loss of social welfare. We discuss this issue in the framework of the indirect mechanism design theory, aiming at implementing socially optimal actions by power generators in a game theoretic equilibrium. We show that indirect Groves mechanisms are not only sufficient but also necessary to implement efficient distributed algorithms in ex-post Nash equilibrium, which can be viewed as a generalization of the Green-Laffont theorem. In particular, we demonstrate that the classical tâtonnement process to find the socially optimal solution can be made incentive compatible by introducing a reward function from the (indirect) Groves class.

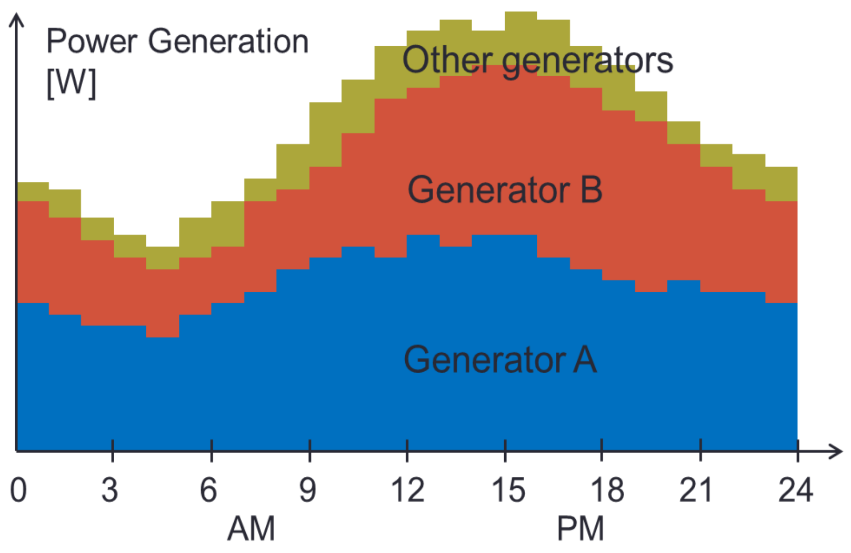
Background

Power supply market is often oligopolistic.



< Power Transmission Network >

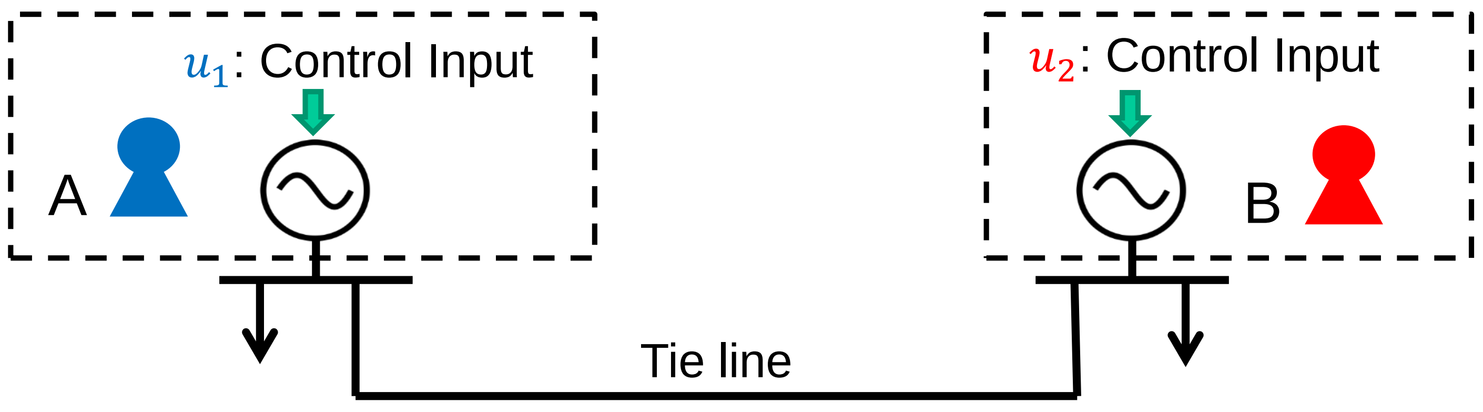
ISO: Independent System Operator is in charge of balancing demand/supply using
1) Day-ahead (spot) market
2) Intra-day (real-time) market



Question: Is it possible to design a day-ahead market mechanism in which generators' selfish bidding strategies in an effort to maximize their own profit lead to a socially optimal outcome?

Problem Set-up

Example: Power supply market with two generators.



$$x_1(t+1) = A_1x_1(t) + B_1u_1(t)$$
$$\delta_1(t+1) = \delta_1(t) + f_1(t)$$
$$H_1f_1(t+1) = H_1f_1(t) + C_1x_1(t) + (\delta_2(t) - \delta_1(t))/X$$

$$x_2(t+1) = A_2x_2(t) + B_2u_2(t)$$
$$\delta_2(t+1) = \delta_2(t) + f_2(t)$$
$$H_2f_2(t+1) = H_2f_2(t) + C_2x_2(t) + (\delta_1(t) - \delta_2(t))/X$$

x_i : Deviation in power generation by the i-th generator.
δ_i : Deviation in mechanical angle of the i-th generator.
f_i : Frequency deviation at the i-th generator.

ISO aims at maximizing social welfare

$$L_0 = \sum_{t=1}^{T}\left[\underbrace{h(f_1(t), f_2(t), \delta_1(t), \delta_2(t))}_{\text{Quality of service}} + \sum_{i=1,2} \underbrace{l_i(x_i(t), u_i(t))}_{\text{Utility (negated cost) functions}}\right]$$

Assume that utility functions l_i are not known to ISO, and that the optimal generation share $x_i(t)$ must be computed by the following tâtonnement process.

(Tâtonnement process)

Repeat
- Each generator updates generation share x_i by
  $\{x_i(t), u_i(t)\}_{t=1}^{T} = \operatorname{argmax}\left(\sum_{t=1}^{T} l_i(x_i(t), u_i(t)) + p(t)x_i(t)\right)$
- Price update by $p(t) \leftarrow p(t) + \eta(\mathrm{Demand}(t) - \sum_i x_i(t))$

Until converge

If all generators participate tâtonnement process faithfully, the process converges to a socially optimal share x^* and the market clearing price p^*.

Generator A maximizes net profit

$$L_1 = \sum_{t=1}^{T} l_1(x_1(t), u_1(t)) + \pi_1$$

Generator B minimizes net profit

$$L_2 = \sum_{t=1}^{T} l_2(x_2(t), u_2(t)) + \pi_2$$

Task: Design reward functions π_i so that no strategic generator is incentivized to deviate from implementing tâtonnement process faithfully.

Naïve Market Mechanism

("Clearing-price" mechanism)

Step 1: Each generator participates tâtonnement process to determine generation share.
Step 2: Compute rewards by
$\pi_i = \sum_{t=1}^{T} p^*(t)x_i^*(t)$. (No price discrimination)

Definition: A market mechanism is said to be ex-post Nash incentive compatible if participating tâtonnement process as designated is a Nash equilibrium for the power generators.

Remark: Although the "clearing-price" mechanism seems natural, it is not incentive compatible in general – a strategic generator with market power can be better-off by manipulating the market clearing price, resulting in a significant loss of social welfare.

Proposed Market Mechanism

(Indirect Groves mechanism)

Step 1: Each generator participates tâtonnement process to determine generation share.
Step 2: Compute rewards by

$$\pi_i = \sum_{j\neq i}\sum_{t=1}^{T} l_j\left(x_j^*(t), u_j^*(t)\right) + k_i$$

where k_i is a quantity that is not dependent on the i-th generator's strategy.

Theorem 1: (Sufficiency) Indirect Groves mechanism is ex-post Nash incentive compatible.

Theorem 2: (Necessity [1]) Under mild assumptions, an efficient (=maximizing social welfare) mechanism is ex-post Nash incentive compatible only if it is in the class of indirect Groves mechanisms.

Remark 1: Direct vs. Indirect mechanisms (e.g., [3])
- Direct mechanisms induce "truth-telling" by agents.
- Indirect mechanisms induce "faithful actions" by agents.

Remark 2: Theorem 2 can be viewed as a generalization of the Green-Laffont theorem to indirect mechanisms.

Pros & Cons

Indirect Groves mechanisms

Pros
- Incentive compatibility
- Distributed computation
- No need to report utility functions

Cons
- Price discrimination
- Communication complexity
- Budget balance

Conclusion

Summary
- "Clearing-price" mechanism fails to be incentive compatible.
- (Indirect) Groves mechanism faithfully implements tâtonnement process.
- (Indirect) Groves mechanism is the only mechanism that implements efficient decision rules in ex-post Nash equilibrium.

Future work
- Budget balance and individual rationality
- Extension to real-time market (e.g., MPC with receding planning horizon)
- Strategic collusions

Reference

[1] Tanaka, Farokhi, and Langbort "Faithful Implementations of Distributed Algorithms and Control Laws" arXiv:1309.4372v3, 2014

[2] Tanaka, Farokhi, and Langbort "A Faithful Distributed Implementation of Dual Decomposition and Average Consensus Algorithms" CDC 2013

[3] Parkes and Shneidman "Distributed implementations of Vickrey-Clarke-Groves mechanisms" Conf. on Autonomous Agents and Multiagent Systems 2004