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The Role of Uncertainty on Bidding Strategies for Power System Markets*

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(*) See PSerc Web Site Report 03-05 for more on this topic

PSERC

Opening remarks

- *Bidding by market participants is the cornerstone of any market.*
- *It is often assumed that the optimal bidding strategy in uniform price auctions is to bid marginal production costs.*
  - *This is only valid under restrictive assumptions.*
  - *Optimal bidding depends nontrivially on the statistical characterization of the price uncertainty*

Complicating factors

- Uniform price electricity auctions involving more than one product may be sequential.
  - *Expectations of clearing prices in future auction rounds affect bids in earlier rounds*
- The cost characteristics and nature of operational constraints are complex – typically non-convex and with significant inter-temporal features.

Five significant effects

- The nature of uncertain future prices can affect bidding behavior
- Price volatility (not just its mean) can influence bidding behavior
- Operational restrictions can have an impact on bidding behavior
- Correlation between uncertain prices of multiple products (e.g., energy and reserves) can change bidding behavior
- Auction design rules can alter bidding behavior

Operating in a market environment

- Prices are quite variable and volatile
  - Location matters, but *my* location is known
- Uncertainty is the rule, not the exception
- I can sell more than one product: energy and various kinds of reserves
- The problem: How do I bid my generator to optimize my expected profits?

Talk Outline

- Modeling generator behavior
- Modeling price behavior
- Auctions
- Optimal bidding strategies
  - Examples
  - Backward Dynamic Programming

Modeling Generator Behavior

Problems a generator faces

- Prices are uncertain
- It must decide how much to allocate to which market
  - *Energy or various types of reserves*
- It has many operational constraints
- It wants to be able to do “what if” analysis
- It wants to estimate profits and losses

Cost Characteristics

- Generator costs include:
  - Incremental or marginal costs
  - Startup/shutdown costs
  - No-load costs
  - Ramping costs
- Cost may be non-convex because of:
  - Startup and shutdown costs
  - “Valve points”
  - Declining marginal costs

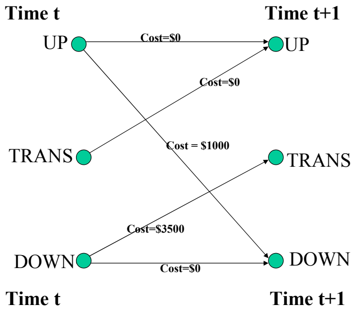
Generator Operational Constraints

- MW limits on energy and reserves
- Sum of energy and reserve MWs limits
- Inter-temporal constraints
  - Minimum up/down times
  - Startup delays
  - Multi-period emissions or energy constraints
  - Ramping rate limits

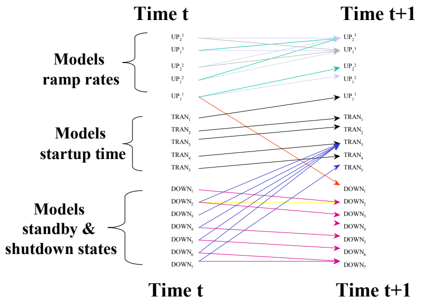
Generator decisions

- Generators must consider their profits over many periods (e.g., one week, one day)
  - Are *expected revenues* > *expected costs*?
- For each period, generators have to decide:
  - Startup/Shutdown?
  - Ramp up/down next hour?
  - Offer reserves or energy?

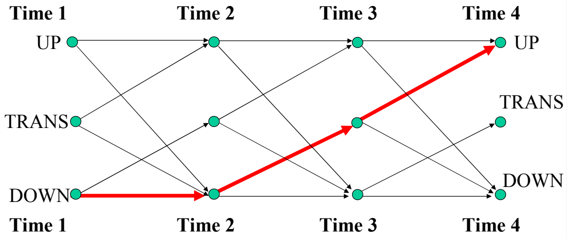
States and State Transitions (1)



States and State Transitions (2)



Multiple Periods



Use *Backward DP* to solve self-commitment problem

Modeling Price Behavior

Handling Price Uncertainty

- Discrete price states (*High, Medium, Low)* are used to model price uncertainty
- Determining optimal bids is similar to determining when to exercise an option
  - Generators are complex options
    - Whether to commit, whether to sell reserves, etc.
- Price correlation issues:
  - Are prices correlated between time periods?
  - Are prices correlated between markets?

Auctions

Auction issues

- Auction type: Uniform price vs. pay as bid
- Single-part vs. multi-part bids
- Simultaneous vs. sequential auctions between markets
  - Energy, regulation, spinning reserves, etc.
- Specific rules of the auction
  - Is the bidding of declining costs permitted?

Auction type

- Uniform Price Auction:
  - all winners are paid “the” market clearing price (*which depends on your location, of course*)
  - bidders have incentives to bid true costs
  - used in the major pools (NE, NY, PJM)
- Pay-as-Bid Auction:
  - all winners get paid what they bid
  - bidders want to bid above costs and close to expected market clearing prices
  - used in bilateral markets

Simultaneous vs. Sequential Auctions

- Since reserve availability costs are mostly opportunity costs in other markets, prices of energy and reserves are interrelated
  - *Auctions for energy and reserves must respect this interdependence*
  - *There are interdependencies among the various reserve prices*

Simultaneous Auctions

- ISO clears all markets simultaneously:
  - determines uniform prices for each service
  - determines winning schedules
  - guarantees profit optimality for all bidders
- Price-taking bidders bid their cost curves
  - At ISO-determined market prices, no bidder can increase profits by changing schedules in the different markets
- *Example: NYISO*

Sequential Auctions

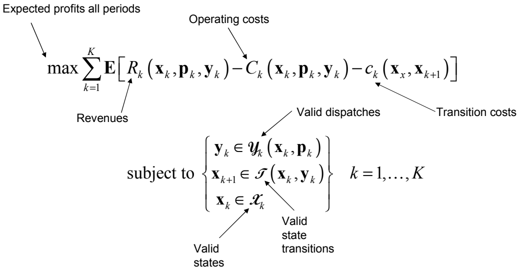
- Markets clear separately:
  - first energy, regulation, spinning reserves, etc.
  - any capacity that is unused after one market clears is bid into the subsequent market
- Winners are paid the uniform market clearing price in each market
- *Example: CAISO’s old market design*

Optimal Bidding Strategies

Optimal Bidding Strategy Model

- Considers price uncertainty
  - At the time of bidding, future prices are uncertain
- Considers opportunity costs
  - Energy market may yield a profit, but reserve markets may yield higher profits
    - Selling energy today may be less optimal than waiting
- Considers inter-temporal constraints and costs
  - Ramp rates, minimum down time, inflow constraints …
  - Startup/shutdown costs, no-load costs …

The model



Expected profits all periods

Operating costs

$$\max \sum_{k=1}^{K} \mathbf{E}\left[R_k(\mathbf{x}_k,\mathbf{p}_k,\mathbf{y}_k) - C_k(\mathbf{x}_k,\mathbf{p}_k,\mathbf{y}_k) - c_k(\mathbf{x}_x,\mathbf{x}_{k+1}) \right]$$

Revenues

Valid dispatches

Transition costs

$$\text{subject to} \begin{Bmatrix} \mathbf{y}_k \in \mathcal{Y}_k(\mathbf{x}_k,\mathbf{p}_k) \\ \mathbf{x}_{k+1} \in \mathcal{T}(\mathbf{x}_k,\mathbf{y}_k) \\ \mathbf{x}_k \in \mathcal{X}_k \end{Bmatrix} \quad k = 1,\dots,K$$

Valid states

Valid state transitions

This model leads to a *nested* Dynamic Programming Problem with *uncertainty*

Optimal Bidding Strategy

- The optimal bidding strategy is a **function**, not just an expected value of the dispatch
- This **function** depends on both the *state* and on *exogenous* prices
- The **function** must satisfy all market (bidding and other) rules

Hydro examples

- You have limited water and a *perfect* energy price forecast. How do you optimally allocate water?
  - *The highest valued period gets the most water, followed by the second highest period, etc.*
- What if you also have an *uncertain* price forecast?
  - *If prices are high, you* may *withhold if prices are correlated*
- What if you have uncertain energy *and reserve* price forecasts?
  - *Are prices among periods correlated?*
  - *Are energy and reserves prices correlated?*
- What if you are *required to bid increasing cost curves?*
  - *Solve previous problems under market design constraints*

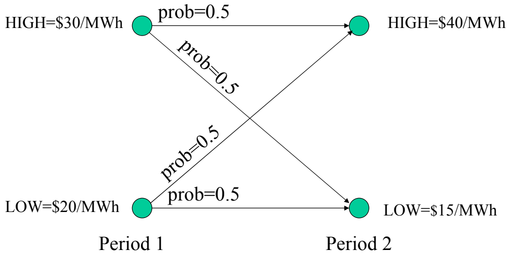
Example parameters

- Two periods with a single energy market.
- The hydro reservoir has 100 MWh of energy.
- No water inflow.
- The cost of producing energy is zero.
- At the end of two periods, the generator must have no energy left.
- The minimum and maximum hourly power limits are 0 and 200 MW respectively.
- The generator is a price-taker.

Rules of the Example

1. The auction is a single-price auction, i.e., all winners are paid the clearing price.
2. MW bids are restricted to be non-decreasing functions of price in $/MWh.
3. Bids are restricted to 50 MW blocks.
4. Period 1 auction is held; after it clears, period 2 bids are accepted and cleared.

Energy-Limited Hydro: Uncorrelated Price Forecast



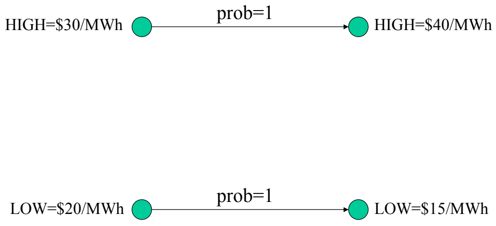
Optimal Bidding Strategy: Uncorrelated Prices

- In period 1, bid all 100 MW between $20/MWh and $30/MWh
- In period 2, bid the remaining energy (if any is left) at less than $15/MWh

BIDDING STRATEGY IS COUNTER-INTUITIVE!

Expected profit for this strategy is $2850

Energy-Limited Hydro: Correlated Price Forecast



HIGH=$30/MWh → prob=1 → HIGH=$40/MWh

LOW=$20/MWh → prob=1 → LOW=$15/MWh

Period 1 Period 2

Optimal Bidding Strategy: Correlated Prices, no bid restrictions

- In period 1, bid 100 MW if price is Low but withhold everything if price is High
  - That is, offer 100 MW at $20 but 0 MW at $30
- In period 2, bid the remaining MW at less than $15/MWh

You probably cannot get away with this type of “bid”!

Profit for this strategy is $3000

Optimal Bidding Strategy: Correlated Prices, non-decreasing bid

- In period 1, withhold all 100 MW
  - Equivalently, bid 100 MW at a price higher than $30/MWh
- In period 2, bid 100 MW at less than $15/MWh

BIDDING STRATEGY IS COUNTER-INTUITIVE!

Expected profit for this strategy is $2750

Observations

- Maximum profits occur if there are no constraints on how you can bid
  - Bidding declining cost curve turns out to be more profitable
- Price correlation matters!
  - The strategy depends on inter-temporal price correlation assumptions
- Optimal strategy maximizes *ex-ante expected* profits
- Because prices are *uncertain*, optimal strategy can *seem* sub-optimal in hindsight
  - Uncorrelated case: if prices in periods 1, 2 *turn out to be* $30/MWh, $40/MWh, the strategy is *ex-post* sub-optimal
  - Correlated case: if prices in periods 1, 2 *turn out to be* $20/MWh, $15/MWh, the strategy is *ex-post* sub-optimal
  - It may *seem* that hydro output was withheld, but this is not true

Thermal generator examples

- Thermal unit can sell power or reserves
- Prices on both energy and reserves are uncertain
- The auctions are sequential
- Two cases:
  - Prices are correlated
  - Prices are uncorrelated

Parameters of the case

- Unit incremental cost is $30/MWh
- Unit can offer 100 MWh energy and 40 MW reserves
- The high price for energy is $40, the low price is $35
  - Each price scenario is equally probable
- The high price for reserves is $12, the low price is $4
  - Each price scenario is equally probable
- The energy market clears first, reserves clear next
- Bids must be non-decreasing

Correlated case bid strategy

- Correlated means that when energy price is $40, the reserve price is $12 and when energy price is $35, the reserve price is $4
- Optimal strategy is:
  - Bid 60 MW of energy below $35
  - Bid 40 MW of reserves below $4

Expected profit from this strategy is $770

Uncorrelated case bid strategy

- Uncorrelated means that whether the energy price is $40 or $35, the reserve price is equally likely to be either $12 or $4
- Optimal strategy is:
  - Bid a 60 MW “stair” of energy below $35
  - Bid a 40 MW “stair” between $35 and $40
  - Bid whatever did not clear as reserves below $4

Expected profit from this strategy is $810

Computational details

- Solve a nested *backward* dynamic programming problem

Dynamic Programming

- There are K **stages**
  - Stages can be: time periods, rounds in an auction or price level, depending on the context
- At each stage k the system can be in any one of N **states** $\mathbf{x}_k \in \mathcal{X}_k$
  - States can be: energy in a reservoir, emissions, unit status, price level, power bid, or a mixture of these
- Revenues as a function of the state are $R_k(\mathbf{x}_k)$
- Objective is to determine optimal state transitions

The principle of optimality

- An optimal strategy contains only optimal sub-strategies
  - An optimal strategy from stage 1 to stage K can be found by finding optimal sub-strategies for all stages from stage k to stage K, starting with k=K and working backward to k=1

Probabilistic DP

- The transition from one state to another is not fully deterministic
  - There is only partial control over transitions
- The state in a stage is the cross product of the generator state x_k and the price level state p_k
  - Transitions are from (x_k,p_k) to (x_{k+1},p_{k+1}) with x_{k+1} deterministic but p_{k+1} uncertain

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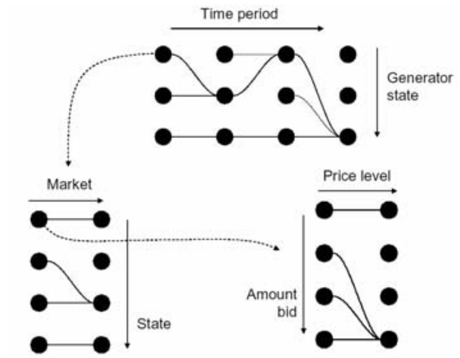
Nested Backward DP

- We want to optimize over time periods
  - This involves a backward DP with time periods as stages
- We want to optimize among markets (energy and reserves)
  - This is a backward DP with auction rounds as stages
- We want to our bids to be "biddable"
  - This involves a backward DP where larger bids require larger prices (no downward transitions allowed)

Each stage is a time period



Each stage is a market

Each stage is a price level

Single vs. multi-part bids

- A more complete (and thus more complex) market design that allows multi-part bids can simplify bidding behavior, leading to *a tradeoff between simplicity of market design and simplicity of bidding behavior*

Comments

- There are benefits to an approach where each generator is considered independently:
  - Avoids large problems
  - Allows decoupling
  - Allows more accurate modeling
  - For price-takers, it gives "the" correct solution
    - Can be used as a test for market power exercise

Conclusions and observations

- Bids must consider
  - market rules
  - inter-temporal constraints and energy limitations
  - bidding into multiple markets
  - price correlation

Profit-maximizing behavior requires adjusting bids according to all these factors. High bids are not necessarily the exercise of market power. Low bids do not exonerate a participant from the possibility of attempting to exercise market power.