Highlights of our Recent Research on Power Markets and Smart Grids

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Uruguayan Context

Industry

- The power sector is dominated by a public utility, UTE.
- Minor participation of private generators in the spot market.
- Traditional sources: hydro, thermal.
- Over the last few years: large deployment of wind energy.
- Increasing interest within UTE in Smart Grid technologies.

Academia

- Historically, power systems at Instituto de Ingeniería Eléctrica (IIE, UdelaR). Strong relation with UTE.
- Recently, interest in Smart Grids by:
  - ⋆ Power researchers at IIE.
  - ⋆ Researchers coming from Telecom, including my own MATE group at Universidad ORT.
- Research support from ANII-Fondo Sectorial de Energía.

Our lines of research

1. Decision making in forward power markets with supply and demand uncertainty.
   With Pablo Belzarena - Pablo Monzón, IIE/UdelaR.
2. Economic operation of distribution networks with tools from Optimal Power Flow.
   With Enrique Briglia - Sebastián Alaggia, UTE.
3. Controlling aggregates of deferrable loads for power system regulation.
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1. Decision making in forward power markets with supply and demand uncertainty [CISS, Princeton ’14]

- Electric power market is subject to uncertainty.
  - Demand fluctuates due to e.g. weather conditions.
  - Supply becoming uncertain due to renewable energy.
- Essentially no storage $\Longrightarrow$ Exact balance required.
- However, some dispatch must be defined in advance. Multiple market solution:
  - Forward (e.g. day-ahead) market settled in advance.
  - Imbalance market close to real-time to settle deviations.

Forward and imbalance prices

- p_F: unit price of energy traded in the forward market.
- p_S (short imbalance price), unit price for shortfall of energy
- p_L (long imbalance price), unit sale price of excess energy

Differentiation of imbalance prices may arise because:

- If market is short, reserve generators must be summoned close to real-time, they charge a premium.
- If market is long, dispatchable loads must be summoned who buy at a discount, or some generation curtailed.

Ex ante (e.g. during forward bidding) situation is uncertain. Agents may estimate p_L, p_S based on prior experience.

Standing assumption: $\boxed{p_L \le p_F \le p_S}$.

Supply side: rational bidding for uncertain generation

You are e.g. a wind generator who expects a random energy W, with cumulative distribution $F(w)$, supported in $[0, M]$. Given p_F, p_S, p_L, what amount y do you offer in advance?

- Risk-neutral optimization of revenue: $\max_y \mathbb{E}[R(y, W)]$,

$$\text{where} \quad R(y, w) = p_F\, y - p_S[y - w]^+ + p_L[w - y]^+.$$

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- Solution [Dent et al '11, Bitar et al. '12]:

  $$y^* : \quad F(y^*) = \frac{p_F - p_L}{p_S - p_L}.$$

  Optimal quantity to bid is a quantile of the distribution, corresponding to the above differential price-ratio in $[0, 1]$.
- Special case of the *newsvendor* problem in OR.

The demand side: inelastic case

- Purchase power in the forward market to cover uncertain demand Q, with cumulative distribution $G(q)$ in $[m, M]$.
- Given p_F, p_S, p_L, minimize $\mathbb{E}[C(x, Q)]$ over x, where

$$C(x, q) = p_F x + p_S[q - x]^+ - p_L[x - q]^+$$

- Optimal reservation x^* is also a quantile:

$$G(x^*) = \frac{p_S - p_F}{p_S - p_L} = 1 - \frac{p_F - p_L}{p_S - p_L}.$$

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- But demand is becoming more elastic:
  - Demand Response (DR) programs are being deployed to make consumer load sensitive to market prices.
  - DR studies [e.g. Li-Chen-Low ’11, Gatsis-Giannakis’13, Kraining et al’13, etc.] do not consider uncertainty.

Elastic, uncertain demand optimization

- Let $U(q,\theta)$ represent consumer utility, where the parameter θ is drawn from a random variable Θ with cdf $G(\theta)$.
- Two decisions: choice of reservation x ahead of time, and consumption q upon revelation of uncertain “type” θ.
- 2nd decision, given x:

$$q^*(x,\theta) := \text{argmax}_q \left\{ U(q,\theta) - C(x,q) \right\}.$$

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- Forward decision: maximize over x the expected surplus

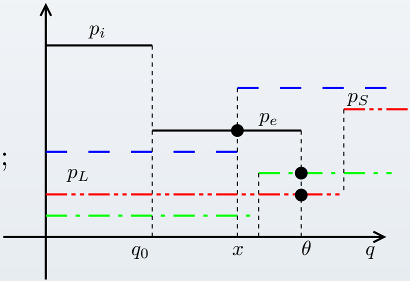
$$\bar{S}(x) := \mathbb{E}_\Theta \left[U(q^*(x,\Theta),\Theta) - C(x,q^*(x,\Theta))\right]$$

- Optimality condition $p_F = \mathbb{E}_\Theta \left[{C_{p_L}^{p_S}}'(q^*(x^*,\Theta) - x^*)\right]$,

$$\text{where} \quad {C_{p_L}^{p_S}}'(\xi) := \begin{cases} p_S & \text{if } \xi > 0; \\ p_L & \text{if } \xi < 0. \end{cases}$$

Example: elasticity in portion of demand

$$U'(q,\theta) = \begin{cases} p_i & \text{if } q < q_0; \\ p_e & \text{if } q_0 < q < \theta; \\ 0 & \text{if } q > \theta. \end{cases}$$



- Suppose $p_e < p_F$, otherwise $x^* = q_0$.
- Graph shows second decision stage, intersection with marginal cost $C_{p_L}^{p_S\prime}(q^* - x)$.
- Optimal quantile decision:

$$G(x^*) = \mathbf{1}_{\{p_e > p_F\}} \cdot \frac{\min\{p_e, p_S\} - p_F}{\min\{p_e, p_S\} - p_L}.$$

Integrated forward market

1. Consumers with uncertainty, who submit the bid curve

$$x^*(p_F) = \arg\max_x \mathbb{E}\left[\max_q \{U(q,\Theta) - C(x,q)\}\right].$$

Here the expectation is over Θ, and possibly p_S, p_L.

2. Renewable energy suppliers, who submit the offer curve

$$y^*(p_F) = \arg\max_y \mathbb{E}\left[R(y,W)\right].$$

Here the expectation is over W and possibly p_S, p_L.

3. Dispatchable generation with marginal cost curve $\mathcal{C}'(z)$. Imposing $\mathcal{C}'(z^*) = p_F \implies$ increasing offer curve $z^*(p_F)$.

Market clearing: $z^*(p_F) + \sum_j y_j^*(p_F) = \sum_i x_i^*(p_F)$.

Open questions

- Social welfare: could a central planner choose p_S, p_L, p_F so that the market equilibrium maximizes global surplus? Condition for p_F follows, not trivially decoupled.
- Comparisons with single-price imbalance markets.
- For profit retailer/aggregator managing a demand response program under uncertainty.
- Including network topology in day ahead markets.

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Distribution networks – past and future

State of affairs:

- *Distribution* is the outermost portion of the grid. Radial (tree) topology, switches allow feeder reconfiguration.
- Main concerns: reliability, voltage within pre-specified tolerances, power losses.
- Discrete control actions: switches, transformer taps, capacitor banks. Often telecontrolled, but mostly with human in the decision loop.
- Power flow simulation software used to predict electrical variables for a given choice of actions, loads.
- Significant trial-and-error, not robust to variations.

Distribution networks – past and future

What's coming:

- Distributed generation (DG): solar-photovoltaic, wind, etc.
- Demand response (DR): heating, AC, etc..
- Batteries, EV charging.
- New actuation possibilities: e.g. reactive power control through inverters in DG.

Concerns:

- DG, DR, introduce variability out of the control of the distributor: hard to guarantee quality of service.
- Incentives may not be aligned with "social welfare"; e.g. variability costs may outweigh benefit of DG.
- Required: an efficient computational tool to optimize network degrees of freedom in an economic sense.

Our work [Briglia et. al, to be submitted]

- Apply the “DistFlow” OPF ([Baran-Wu ’89]), with the SOCP convex relaxation proposed in [Farivar, Low et al. ’11-12].
- Make the cost function economically relevant, including:
  - Wholesale cost of supply, purchases from external DG.
  - Regulatory penalties for voltage and quality of service.
  - Switching costs.
- Include models of new devices under control of the distributor: inverters in DG, etc.
- Optimize in Matlab/CVX (relaxation always exact in practice!). Add search over a moderate amount of discrete variables: topology switches, key transformer taps.
- Simulate real network (110 buses in La Paz/Las Piedras, suburb of Montevideo) with added DG. Preliminary conclusions very enlightening, sometimes unforeseen.

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Frequency regulation

- Markets match supply and demand as much as possible, but additional control actions are required at very fast time-scales. Otherwise frequency deviates from its nominal value (50Hz, 60Hz).
- Traditionally, such "ancillary service" is provided by fast-responding generators.
- Regulation needs are growing with renewable sources.
- Can the demand side help with regulation?
- Key idea: exploit load *deferrability*, adjusting service schedule to desired power profile (e.g. Berkeley group, Poolla and students, '13-'14).

An aggregate model of load deferrability
[Bliman-Ferragut-P', to appear in ACC 2015, Chicago]

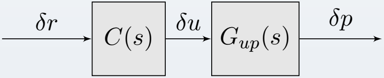
- Motivation: avoid micro-managing the list of loads.
- Keep track of aggregates by a fluid queue:

$$\dot{n}(t) = \lambda - \frac{1}{\tau} n(t)u(t) + v(t)$$
$$p(t) = p_0 n(t)u(t).$$

  - $n(t)$ is the number of loads in the system, arriving at rate λ
  - p_0 is mean service power, Q_0 mean energy.
  - $\tau = Q_0/p_0$ is mean service time. Load *deadline* is $d > \tau$.
  - Control signal $u(t)$ defines *fraction* of loads to be turned on.
  - Noise term $v(t)$ reflect randomness in arrival/service times.

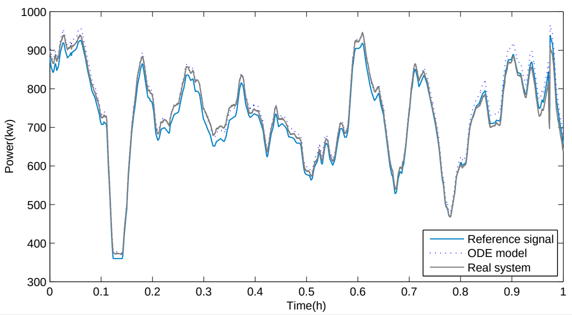
Regulation control

- Feedforward control for regulation tracking (ignoring noise):



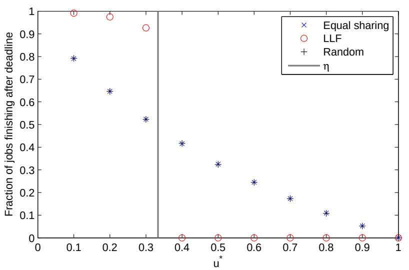
$$\xrightarrow{\delta r} \boxed{C(s)} \xrightarrow{\delta u} \boxed{G_{up}(s)} \xrightarrow{\delta p}$$

- Noise can be compensated with additional feedback.
- Results with PJM regulation signal:



Impact on deadline satisfaction

- Regulation performance is agnostic to *which* loads are scheduled. But deadline satisfaction is not.
- Fraction of jobs served after the deadline with varying u^*:



- Deadline aware policies such as Least Laxity First (LLF) achieve high satisfaction provided $u^* > \eta = \frac{\tau}{d}$.
- Ongoing work with two-state model: achieve hard deadlines, decentralized implementation.

Conclusions

- We have described three lines of academic research on power markets and Smart Grids.
- In particular, tools developed in other disciplines (convex optimization, economics, queueing theory, telecom networks, control) have proven useful for this new area.
- We have begun to build international presence in this field.
- Active local collaboration: a new ANII-sponsored joint project (MATE-ORT/IIE-Udelar) starts in April.
- We have ties to UTE, seeking further industrial transitions.