Coordinated Aggregation of Distributed Resources

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Co-conspirators

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... and thanks to many useful discussions with:
Eilyan Bitar, Alejandro Domínguez-García, Felix Wu

Outline

Distributed Energy Resources

- Controllable loads
    - Electric Vehicles
    - HVAC Systems
    - Thermostatically Controlled Loads [TCLs]
- Electricity storage
- Distributed renewable generation [rooftop solar]

The Sound-bite

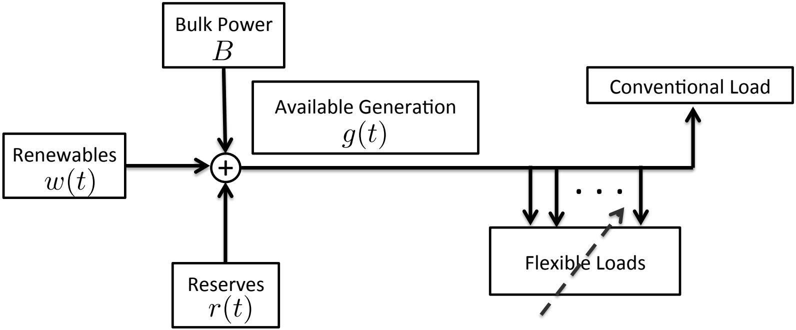
“DERs can absorb variability in renewable generation”

- devil is in the details
- what variability?
    - variability in wind or rooftop solar?
    - what time scales?
    - wind ramps or routine fluctuations?
- how much reserves are needed?
    - capacity
    - reserve energy use

Power Balance

- Available power $g(t)$
  - Bulk power B
  - Load-following reserve power $r(t)$
  - Uncertain renewable generation $w(t)$
- Uncertain load $L(t) = L_1(t) + L_2(t)$
  - Conventional loads $L_1(t)$
  - Flexible loads $L_2(t)$
  - Simple model: $L = (1 - \delta)L + \delta L$
    δ: flexible load participation factor

Power Balance ...



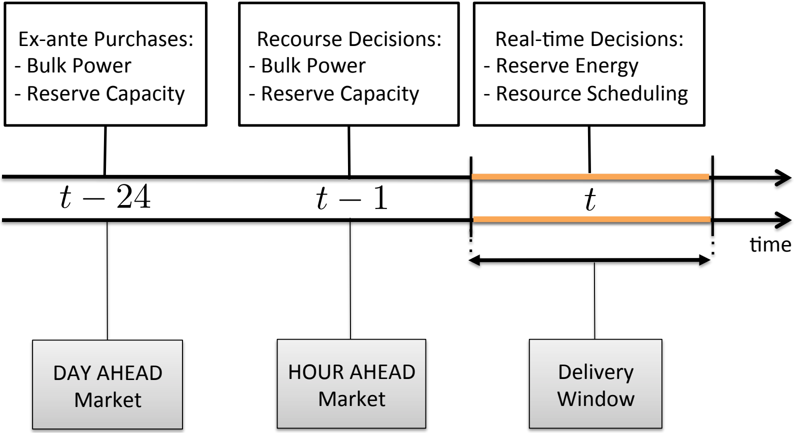
ex ante Decisions

- Multiple *ex ante* purchase opportunities:
  $k = t-24, t-6, t-1, \cdots$
- At each opportunity k, decide on
  - Bulk power B_k at price q_k
  - Reserve capacity for up-regulation R_k^+ at price p_k^+
  - Reserve capacity for down-regulation R_k^- at price p_k^-
- Decisions are
  - Based on available information up to time k
  - Purchases are in blocks: 1 hour, 10 min, 5 min, $\cdots$

Real-time Decisions

- Made during operating hour $[0, W]$
- Scheduling:
  - σ_r for reserves
  - σ_s for storage
  - σ_t for flexible loads
- Scheduling policies use available information in real-time

Timeline



Ex-ante Purchases:
- Bulk Power
- Reserve Capacity

Recourse Decisions:
- Bulk Power
- Reserve Capacity

Real-time Decisions:
- Reserve Energy
- Resource Scheduling

DAY AHEAD Market

HOUR AHEAD Market

Delivery Window

Flexible Load Models

- Ex: energy needs of an electric vehicle
  - arrival a, departure d, needs energy E, max rate m

$$\int_a^d p(t)dt = E, \quad 0 \leq p(t) \leq m$$

  - minimum charge rates make scheduling problems very hard: mixed integer programming
- Ex: Thermostatically controlled loads (TCLs)
  - duty cycle modeling: must deliver energy E every W secs

$$\int_{kW}^{kW+W} p(t)dt = E, \quad 0 \leq p(t) \leq m$$

  - E depends on user settings, ambient temp, etc
- Ignoring details: range for E, quantized power levels, ...

Tasks

- Model flexible loads as tasks.
- Task T parametrized by $(E, m, [a, d])$.
- Energy need for T:

$$\int_a^d p(t)dt = E, \quad 0 \leq p(t) \leq m$$

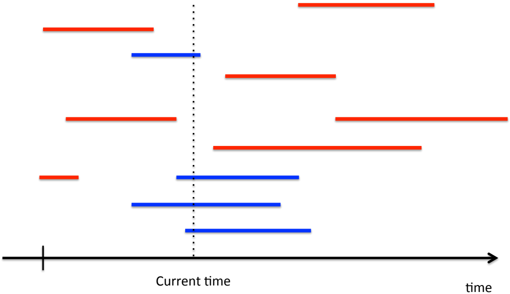
- Task announces its parameters to cluster manager upon arrival
- Tasks are *pre-emptive*: can interrupt and resume servicing else problems become NP hard (bin packing)

Task properties

- Energy state of task T at time t: $e(t) = E - \int_a^t p(\tau)d\tau$
- Active task at time t (with parameters $(E, m, [a, d])$):

$$a \leq t \leq d, \quad \text{and} \quad e(t) > 0$$

- $\mathbb{A}_t$: Set of all active tasks at time t



Information State

- $\mathbb{T} = \{T_i\}_{i=1}^{M}$: Collection of M tasks.
- $g(t)$: Available power (generation) profile to serve $\mathbb{T}$
- $\mathcal{I}_t$: Information state at time t:
    - Task parameters $(E_i, m_i\, [a_i, d_i])$ for all active tasks
    - Energy states $e_i(t)$ for all active tasks
    - Past values of available power profile: $g(\tau), \tau \leq t$

Task Scheduling Policy

Task scheduling policy σ:

- Algorithm that allocates available power profile $g(t)$ to tasks
- For collection of tasks $\mathbb{T}$,

$$\sigma(g,t) = (p_1(t), p_2(t), \ldots, p_m(t))$$

$p_i(t)$: power allocated to task i at time t

$$\sum_{i=1}^{M} p_i(t) \leq g(t)$$

- σ is causal if allocations at time t depend only on information state $\mathcal{I}_t$

Scheduling Policy

- $g(t)$ is feasible if there exists some [possibly non-causal] scheduling policy σ that completes all tasks:

$$e_i(d_i) = 0 \text{ for all tasks } T_i$$

- σ is optimal if allocations under σ complete all tasks for any feasible power profile $g(t)$

Earliest Deadline First (EDF)

- Available generation assigned to tasks with most imminent deadlines
- Proven optimal for single processor time allocation [Liu ('73)], [Dertouzos ('74)]
- Single Processor Time Allocation versus resource scheduling:

Resource Scheduling	Processor Time Allocation
Available generation is variable.	Processor capacity is fixed.
Rate constraints limit power delivery.	No rate constraints.
Multiple tasks served concurrently.	Single task served at a time.

- Can be shown to be optimal for resource scheduling with no rate constraints.

Least Laxity First (LLF)

- Available generation assigned to tasks with least scheduling flexiblity (laxity).
- Laxity: $$\phi_i(t) = \begin{array}{ccc} (d_i - t) & - & e_i(t)/m_i \\ \text{[time remaining]} & - & \text{[time required]} \end{array}$$

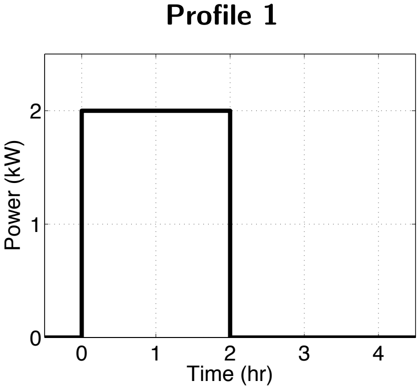
  where

  $$\begin{aligned} t &: \text{current time} \\ d_i &: \text{deadline for task } T_i \\ e_i(t) &: \text{remaining energy required to satisfy task } T_i \\ m_i &: \text{rate constraint for task } T_i \end{aligned}$$

- Laxity is negative ⇒ task can not be satisfied
- Laxity-based policy a good heuristic for task and reserve scheduling

Causal Optimal Policies don't exist

- Task A: $E_A = 2, m_A = 2$ over $[0, 2]$
- Task B: $E_B = 2, m_B = 1$ over $[0, 4]$



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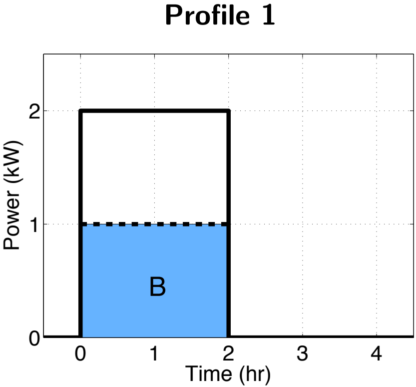

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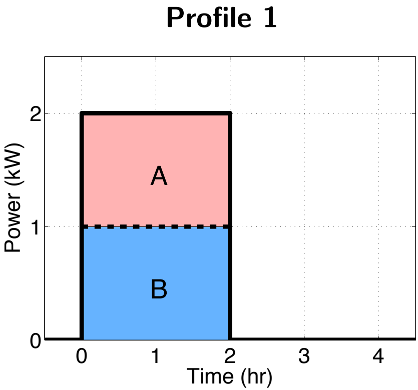

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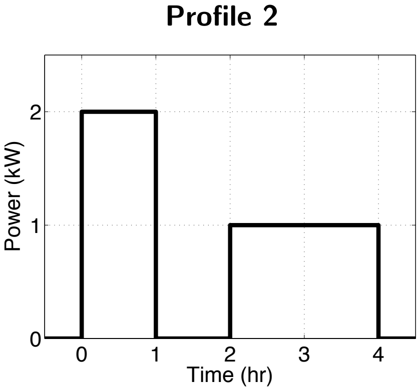

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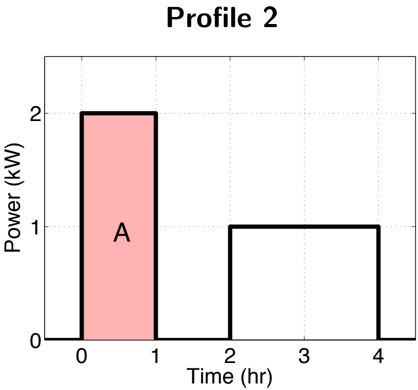

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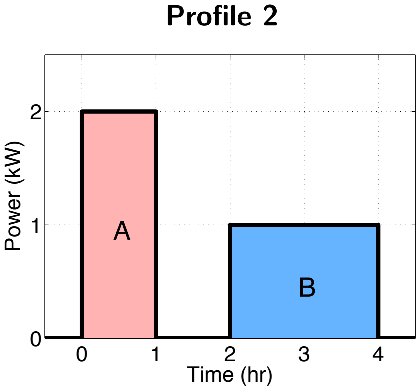


Causal Optimal Policies don't exist

- Allocations shown for profiles 1 and 2 are unique. Both profiles are feasible
- Profiles 1 and 2 identical over $t \in [0, 1)$.
- Any causal policy must offer identical allocations for both profiles.
- But different allocations are necessary depending on power profile!

Causal optimal policy does not exist

Receding Horizon Control (RHC)

Idea:

- Can obtain scheduling policies via RHC-based approach
- Compute policy over some time horizon at time t to schedule all active tasks using generation forecasts
- Apply decisions at time t and repeat optimization at next time-step $t + \Delta t$

Variables:

N : # of Δt time-steps in horizon.

M : # of active tasks

F : F_{ij} is power delivered from generation to task i at time $t + j\Delta t$

G : G_{ij} is power delivered from reserves to task i at time $t + j\Delta t$

$\hat{g}$: generation forecast over time horizon

RHC Problem Formulation

$$\min_{F,G} \quad \alpha\|\mathbf{1}^T G\|_2 + \sum_{i\in\mathbb{A}_t}\sum_{k=1}^{N}(N-\phi_i(k))^2$$

subject to:

(i) $F^T\mathbf{1} \leq \hat{g} = [\hat{g}_1\hat{g}_2\ldots\hat{g}_N]^T$

(ii) $(F+G)\,\mathbf{1} = E = [E_1E_2\ldots E_M]^T$

(iii) $\forall k, F_{i,k}+G_{i,k}\begin{cases} =0 & \forall i: t+k\Delta t > d_i \\ \in[0,m_i\Delta t] & \forall i: t+k\Delta t \leq d_i \end{cases}$

(iv) $\phi_i(k) = d_i - (t+k\Delta t) - \frac{e_i(k)}{m_i}$

(v) $e_i(k) = E_i - \sum_{k'=1}^{k} F_{i,k'} + G_{i,k'}$

Task information

- RHC with perfect power profile forecasts is not optimal
- Information about future tasks is important

Theorem

Assume available generation is known.
There exists no optimal policy causal with respect to task information.

Theorem

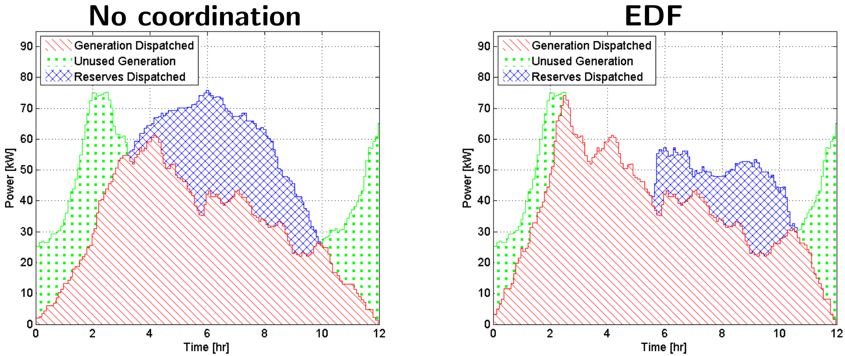
Assume service interval is identical for all tasks.
Then LLF is optimal with respect to task information and available generation

Simulation - Test Case Description

Quantify reduction in reserve energy costs by scheduling flexible loads

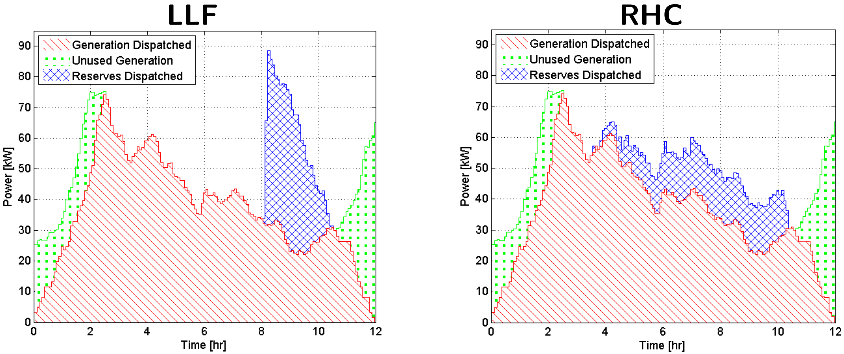
- Wind energy serves 100 electric vehicles over 12 hours
- Allocation decisions made every 5 minutes
- Task parameters chosen randomly based on EV charging specs
- Constant maximum charging rate for all tasks
- Wind data from Bonneville Power Administration
- Generation forecasts for RHC simulated by adding Gaussian noise to wind power profiles
- Variance of added noise increases with forecast horizon

Simulation - No coordination and EDF



- Under EDF, load profile is closer to generation profile
- Value of coordinated resource scheduling immediately apparent

Simulation - LLF and RHC



- Reserve procurement occurs towards the end of intervals
- Under LLF, laxities for all tasks are equal when reserves are called: explains ‘spike’ when reserves first called

Simulation - Reserve Energy Requirement

	No Coord	EDF	LLF	RHC
Generation dispatched (kWh)	378.56	436.18	437.49	437.48
Reserves dispatched (kWh)	140.09	82.47	81.16	81.34
Reserve capacity (kW)	38.82	30.99	56.85	16.95

- Coordinated resource scheduling under any policy reduces reserve energy dispatched by at least 40%

Simulation - Reserve Capacity Requirement

	No Coord	EDF	LLF	RHC
Generation dispatched (kWh)	378.56	436.18	437.49	437.48
Reserves dispatched (kWh)	140.09	82.47	81.16	81.34
Reserve capacity (kW)	38.82	30.99	56.85	16.95

- Coordinated resource scheduling under any policy reduces reserve energy dispatched
- The reserve capacity requirement is less for both EDF and RHC

Cost Function & Constraints

Cost function:

$$J = \begin{array}{ll} q_1 B_1 + \cdots + q_k B_k & \text{bulk power} \\ + \; p_1^+ R_1^+ + \cdots + p_k^+ R_k^+ & \text{up-regulation reserve capacity} \\ + \; p_1^- R_1^- + \cdots + p_k^- R_k^- & \text{down-regulation reserve capacity} \\ + \; \int_0^W r^+(t) c^+ dt & \text{up-regulation reserve energy} \\ + \; \int_0^W r^-(t) c^- dt & \text{down-regulation reserve energy} \end{array}$$

Constraints:

$$\begin{array}{rl} \text{LOLP} & \text{Prob}\left\{ \sum B_i + \sum r_i + w(t) < L(t) \right\} \leq \epsilon \\ \text{reserve capacity} & r^+(t) \leq R^+, \quad r^-(t) \leq R^- \end{array}$$

General Optimization Problem

- Causal Dispatch & Scheduling

$$\min_{B_1, R_1 | \mathcal{I}_1} \cdots \min_{B_k, R_k | \mathcal{I}_m} E_w \min_{\sigma_s, \sigma_r, \sigma_\tau} J(B, R, r, w)$$

- Similar to RLD, but not equivalent
- Difficult problem because of causal policies

Simpler Problem

- Single *ex ante* opportunity
- Symmetrical reserve costs
- No storage: don't need σ_s
- Single task: don't need σ_t

$$\min_{B,R} \quad E_w \min_{\sigma_r} qB + pR + c\int_0^T |r(t)|dt + dE$$

$$\text{subject to} \quad \begin{cases} E = (\max|r(t)| - R)^+ & \text{excess reserves} \\ r \text{ causal fn of } w & \text{causal scheduling} \\ \int_0^T (B + r(t) + w(t))\, dt = E & \text{task needs} \end{cases}$$

Intuitive Solution

- Average wind on operating interval:

$$v = \frac{1}{W} \int_0^W w(t)dt$$

- Buy bulk power B in forward market:

$$B + m_v = E/W$$

- Buy reserves in forward market

$$R = 3\sigma_v$$

Intuitive Solution ...

- Reserve scheduling: m_v forecast is accurate
  - wait until last opportunity

$$r(t) = \begin{cases} 0 & t < W \\ \int_0^W (v(t) - m_v)dt & t = W \end{cases}$$

- Reserve scheduling: m_v forecast is bad
  - spread the needed reserves over $[0, W]$

$$r(t) = v(t) - m_v$$

- General principle:
  - ISO makes decisions based on averaging net load over a window W
  - W: single parameter that captures load flexibility
  - respects legacy operations

Many Open Issues

- Is there a market?
  - how much renewable penetration justifies the market?
  - how much DER flexibility is needed?
  - is the market for peak shaving, up/down regulation, frequency regulation, contingencies?
- How should we manage DERs?
  - architecture
  - compatible with legacy operations
- How do we incentivize DER participation?
  - fair revenue sharing
  - lottery methods