Renewable Integration through Risk-Limiting Dispatch and Coordinated Resource Aggregation

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Collaborators

The Team

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Valuable Input from:

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- Pramod Khargonekar
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Risk Limiting Dispatch (RLD)

- Issues with current dispatch rules
  - Sub-optimal staggering of markets
  - Decoupled dispatch
  - Static reliability criteria for non-stationary imbalance statistics
- **RLD**: Dynamically procure reserves and energy by solving multi-stage stochastic control problem
  - Optimizes trade-off between forecast certainty and costs
  - Takes into account future recourse opportunities
  - Minimizes total expected reserve energy and capacity costs
  - Maintains risk of imbalance below a pre-specified level
- Study shows reserve cost greatly reduced by:
  - Additional intra-day energy markets
  - Incorporating better probabilistic forecasts of renewables

R. Rajagopal et al., RLD for Integrating Renewable Power, IJEPES 2012

R. Rajagopal et al., RLD of wind power, IEEE Proc. of ACC 2012

Coordination of Load and Variable Supply...

Coordinate distributed renewable power and flexible loads to reduce distribution system losses and reserve generation

Scenario 1 - Price Differentiated Quality-of-Supply

- Decompose variable renewable power into 'slices' according to their variability
- Each (random) 'slice' is priced separately
- Study shows:
  1. How to allocate and find equilibrium prices of power with different variability
  2. Comparison of this allocation with that achieved by 'real-time' pricing

Recent work: E. Bitar et al., Selling Random Wind, HICSS 2012
Initial idea: Tan et al., Interruptible power service contracts, JEDC 1993
Related work: H.P. Chao, and R.B. Wilson, 1987

Coordination of Load and Variable Supply...

Coordinate distributed renewable power and flexible loads to reduce distribution system losses and reserve generation

Scenario 2 - Coordinated Resource Aggregation

- Tasks (Deferrable loads) must be served by specified deadline
- Energy needs need to be met by renewable or (expensive) grid power
- Study shows large grid energy and capacity reductions can be achieved through coordinated scheduling of tasks

A. Subramanian et al., Real-time Scheduling of Deferrable Electric Loads, IEEE Proc. of ACC 2012

A. Subramanian et al., Optimal Power and Reserve Capacity Procurement Policies with Deferrable Loads, IEEE Proc. of CDC 2012

Proposed follow-on projects for FY2013

RLD

- Extend RLD to include transmission network constraints
- Quantify benefits of improved forecasts

Price-Differentiated QoS

- Analyze contract mechanisms to support supply-demand coordination
- Focus on costs of communication and computation to implement contracts

Coordinated Resource Aggregation

- Quantify benefits for distribution system and grid from coordination of distributed renewables and loads
- **Benefit metrics**: distribution and transmission system utilization; losses; dispatchability of bulk power

Coordinated Resource Aggregation

Outline

Motivation

- Increased interest in renewable energy sources
  - Environmental concerns
  - Energy security / Geopolitical reasons
  - Nuclear power safety
- Adoption of ambitious renewable energy targets
  - CA: 33% energy penetration by 2020
  - US: 20% wind penetration by 2030
  - Denmark: 50% wind penetration by 2025

Renewable Integration Costs

- Renewable generation is:
  - Intermittent
  - Uncertain
- Serious operational challenges for power grid
- Large increases expected in *reserve* power requirements

  Current load following reserve capacity [CA]: **2292 MW**
  Forecasted capacity required: **4423 MW** [Helman '10]
  Other studies indicate similar increases in reserve requirement [Loutan '07]

Significant costs associated with integrating renewables

The Sound-bite

"Flexible loads can absorb variability in renewable generation"

- Examples of deferrable loads:

  Electric Vehicles
  HVAC Systems
  Thermostatically Controlled Loads (TCLs)
- **Direct load control**: Load power profile controlled by central authority (cluster manager)
- **Indirect load control**: Load power profile controlled by customers (in response to price signals)

Goals

- Focus on direct load control (DLC)
- How to do it?

  Algorithms for allocating available power to deferrable loads
- Is it worth it?

  Impact of algorithm choice on reserve requirements

Recent Works

Coordination of flexible loads and renewables

- A. Papasiviliou, and S. Oren, Supplying renewable energy to deferrable loads: Algorithms and economic analysis, PESGM 2010
- M. Ilic, L. Xie, and J.Y. Joo, Efficient coordination of wind power and price-responsive demand, IEEE TPS, 2011

Electric vehicle charging protocols

- S. Chen, T. He, and L. Tong, Optimal Deadline Scheduling with Commitment, Allerton, 2011
- L. Gan, U. Topku, and S. Low, Stochastic Distributed Protocol for Electric Vehicle Charging with Discrete Charging Rate, PESGM 2012
- M. Galus, R. la Fauci, and G. Andersson, Investigating PHEV wind balancing capabilities using heuristics and model predictive control, PESGM 2010

Tasks

- Model deferrable loads as **tasks**
- Tasks are **pre-emptive**: can interrupt and resume servicing
- Task T_i parametrized by $([a_i, d_i], E_i, m_i)$
  - a_i: **arrival time** (beginning of service interval)
  - d_i: **task deadline** (end of service interval)
  - E_i: **energy requirement** over service interval
  - m_i: **maximum power transfer rate**
- Deferrable load announces these parameters to cluster manager **upon arrival**
- Admissible power profiles $p(t)$ for task T_i must satisfy:

$$\int_{a_i}^{d_i} p(t)dt = E_i, \quad 0 \leq p(t) \leq m_i$$

Task properties

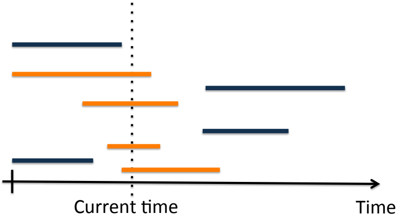
- **Energy state** of task T_i at time t
  (Remaining energy requirement for task T_i at time t)

$$e_i(t) = E_i - \int_{a_i}^{t} p(\tau)d\tau$$

- Task T_i is **active** at time t:

$$a_i \leq t \leq d_i, \quad \text{and} \quad e_i(t) > 0$$

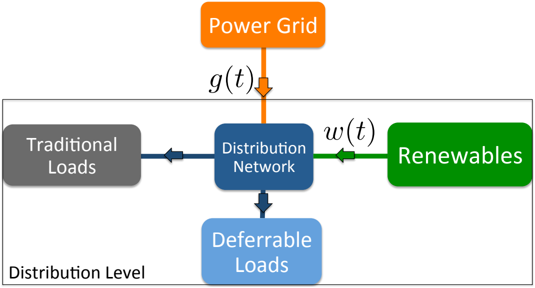
- $\mathbb{A}_t$: Set of all active tasks at time t



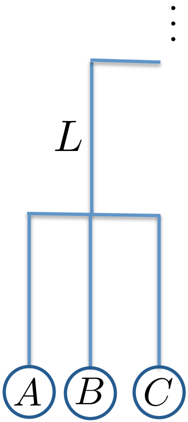
Available Generation

Available generation $p(t)$ split into:

- Renewables: $w(t)$
  - Free but uncertain
- Grid: $g(t)$
  - Load-following reserves, etc...
  - Costly but certain (assuming no transmission outages)



Distribution Network



- Assume radial distribution networks
- Distribution network limits can be modeled as linear constraints
- For sample network shown, limits on line L can be expressed as:

$$p_A(t) + p_B(t) + p_C(t) \leq \bar{L}, \quad \forall t$$

- Ignore such constraints for now

Cost Metric

Cost of generation is:

$$\int_0^T |g(t)|dt + \alpha \max_t |g(t)|$$

- First term penalizes total grid generation **(Grid Energy)**
- Second term penalizes maximum instantaneous grid generation dispatched **(Grid Capacity)**
  - Prevents sudden spikes in amount of reserve dispatched
  - Reduces need for standby generation
  - Reduces capacity requirements at distribution substation

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 $g(t)$

Ideally, we want causal, optimal policies

Theorem

There exist **no** *causal, optimal policies!*
Proof: Counterexample

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 active tasks with least scheduling flexibility (laxity)

Laxity:
$$\phi_i(t) = \underset{\text{[time remaining]}}{(d_i - t)} - \underset{\text{[time required]}}{e_i(t)/m_i}$$

where

t : current time

d_i : deadline for task T_i

$e_i(t)$: remaining energy required to satisfy task T_i

m_i : rate constraint for task T_i

- Laxity is **negative** $\Rightarrow$ task **can not** be satisfied
- Useful heuristic for allocating **grid generation** ['Lax0']: Allocate grid generation to tasks with **laxities close to 0**.

Receding Horizon Control (RHC)

- Can obtain scheduling policies by solving successive optimization problems
- Basic Idea:
    - At time t, compute allocations for all active tasks over some time horizon
    - Apply allocation at time t
    - Repeat process at next time-step $t + \Delta t$ with updated information
- Can incorporate **generation forecasts** and **updated task information**

- Use of RHC is not new to power systems
- Our contribution: Cost function

RHC Problem Formulation

Variables:

N : # of Δt time-steps in horizon.

M : # of active tasks

W : W_{ij} is power delivered from renewables to task i at time $t + j\Delta t$

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

$\hat{w}$: renewable generation forecast over time horizon

RHC Constraints

- Renewable generation forecasts:

$$W^T \mathbf{1} \leq \hat{w} = [\hat{w}_1 \hat{w}_2 \ldots \hat{w}_N]^T$$

- Task requirements - Energy:

$$(W + G)\,\mathbf{1} = E = [E_1 E_2 \ldots E_M]^T$$

- Task requirements - Power:

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

RHC Cost Function

We propose the following cost function:

$$\alpha_1 \|\mathbf{1}^T G\|_1 + \alpha_2 \|\mathbf{1}^T G\|_\infty + \sum_{i \in \mathbb{A}_t} \sum_{k=1}^{N} (N - \phi_i(k))^2$$

where:

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

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

- First term penalizes **grid energy**
- Second term penalized **grid capacity**
- Third term incentivizes earlier allocations of renewable generation

Test Case Description

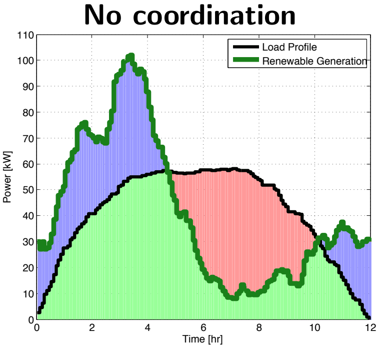
Quantify reduction in reserve energy costs by scheduling flexible loads

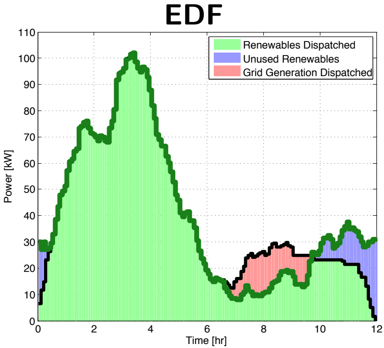
- Wind energy serves 100 electric vehicles over 12 hours
- Allocation decisions made every 5 minutes
- Task parameters chosen randomly based on EV charging specs
- Constant maximum charging rate for all tasks
- Wind data from Bonneville Power Administration
- Generation forecasts for RHC created by adding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

Algorithms compared

1. No coordinated scheduling
2. EDF for scheduling renewables, ‘Lax0’ for grid generation
3. LLF for scheduling renewables, ‘Lax0’ for grid generation
4. RHC for scheduling renewables and grid generation

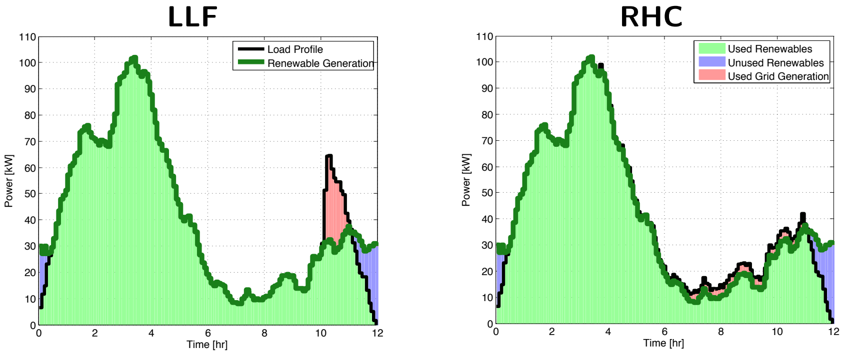
No coordination and EDF





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

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

Grid Energy Requirement

- Average percentage increases in following metrics over 100 test cases.

	EDF	LLF	RHC
Renewable energy used	24.87	26.94	27.16
Grid energy required	**-55.78**	**-62.79**	**-63.02**
Grid capacity required	-12.81	70.90	-66.99

- Coordinated resource scheduling under any policy reduces reserve energy dispatched by at least 50%

Grid Capacity Requirement

- Average percentage increases in following metrics over 100 test cases.

	EDF	LLF	RHC
Renewable energy used	24.87	26.94	27.16
Grid energy required	-55.78	-62.79	-63.02
Grid capacity required	**-12.81**	**70.90**	**-66.99**

- Coordinated resource scheduling under any policy reduces reserve energy dispatched by at least 50%
- The reserve capacity requirement is less for both EDF and RHC

Conclusions and Future Work (FY2013)

Conclusions

- Proposed RHC approach aimed at reduced generation costs
- Compared performance of 3 load scheduling algorithms
- Realized upto 60% cost reductions in simulations using RHC

Future Work

- Quantify benefits for grid from coordination of distributed renewables and loads
  - Distribution and transmission system usage
  - Bulk power dispatches
- Pricing mechanisms to induce consumer participation in deferrable load aggregation schemes

  [E. Bitar and S.Low, Pricing of Deferrable Electric Power Service, IEEE Proc. of CDC 2012]