Operations-Based Planning for Placement and Sizing of Energy Storage in a Grid With a High Penetration of Renewables

K. Dvijotham[1] M. Chertkov[2] S. Backhaus[3]

[1]Computer Science and Engineering
University of Washington, Seattle

[2]Center for Nonlinear Studies and Theoretical Division
Los Alamos National Laboratory

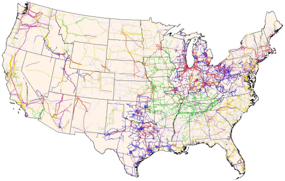
[3]Material Physics and Applications Division
Los Alamos National Laboratory

June 22, 2011

Table of Contents

Table of Contents

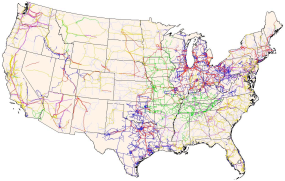
The US Power Grid : The Present



". . . the greatest engineering achievement of the 20th century."

[National Academy of Engineering '10]

The US Power Grid : The Present



". . . the greatest engineering achievement of the 20th century."

[National Academy of Engineering '10]

The Grid : Operation and Planning

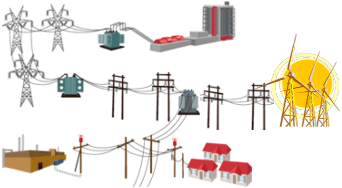
- Expansion/Upgrade Planning : Adding new resources (lines/generators etc.) to the grid
- Operation : How to dispatch generation given current state of grid and forecasted loads/renweables
- Presently Decoupled

The US Power Grid: The Future

The grid is changing:

1. large number of distributed power sources
2. increasing adoption of renewables

$\Rightarrow$ large-scale, complex, & heterogeneous networks with stochastic disturbances

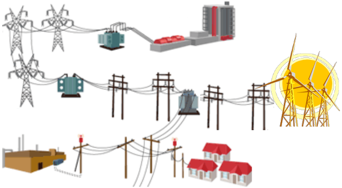


The US Power Grid: The Future

The grid is changing:

1. large number of distributed power sources
2. increasing adoption of renewables

$\Rightarrow$ large-scale, complex, & heterogeneous networks with stochastic disturbances



Implications

- Fluctuations in generation now become significant
- Transmission lines overload, Generators hit limits etc.
- Need "smart control" to compensate
- Planning and Operation can no longer be decoupled

Our Solution

- Use Energy Storage to mitigate renewable fluctuations
- Use Optimal Control to decide how to dispatch power from storage
- Use resulting optimal solutions on a large number of scenarios (profiles of renewable fluctuations) to decide optimal sizing and placement of energy storage

Our Solution

- Use Energy Storage to mitigate renewable fluctuations
- Use Optimal Control to decide how to dispatch power from storage
- Use resulting optimal solutions on a large number of scenarios (profiles of renewable fluctuations) to decide optimal sizing and placement of energy storage

Sneak Peak at Results

- With small amounts of Energy Storage, can handle 30% Renewable Penetration
- Energy Storage only required at small number of nodes
- Using Operations information in Planning/Sizing of Energy Storage yields best results

Table of Contents

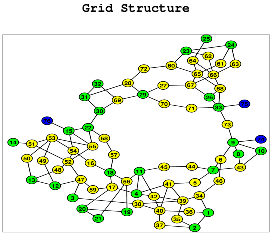
Power Grid : Description

- Topology specified by graph $\mathcal{G} = (\mathcal{V}, \mathcal{E}), |\mathcal{V}| = n$.
- Nodes i denote generators/loads, Edges (i, j) denote transmission lines
- $\mathrm{Neb}(i)$ denotes the neighbors of node i in the grid

Three kinds of nodes in the grid:

- Controllable Generators $\mathcal{G}_g$: Output Controllable within Limits
- Renewable Generators $\mathcal{G}_r$: Output Fluctuating over time
- Loads $\mathcal{G}_l$: Assumed Fixed Here

Modified RTS-96 Grid



DC Power Flow Equations

Given power injected/consumed at every node, compute how much power flows through each transmission line.

- Power generated/consumed at node i : $\mathbf{p}_i$
- Power flowing from node i to j: $\mathbf{f}_{(i,j)}$
- Complex power phase at node i: ψ_i
- Inductance on line (i,j): $\mathbf{x}_{(i,j)}$

DC Power Flow Equations

$$\mathbf{p}_i = \sum_{j \in \mathrm{Neb}(i)} \frac{\psi_j - \psi_i}{\mathbf{x}_{(i,j)}}$$

$$\mathbf{f}_{(i,j)} = \mathbf{x}_{(i,j)}(\psi_j - \psi_i),$$

Constraints on Power Generation

- Graph Laplacian $\mathbf{L} \in \mathbf{R}^{|\mathcal{V}|\times|\mathcal{V}|}$, $\mathbf{L}_{ii} = -\sum_{j\in\mathrm{Neb}(i)} \frac{1}{\mathbf{x}_{(i,j)}}$, $\mathbf{L}_{ij} = \frac{1}{\mathbf{x}_{(i,j)}}$
- Edge incidence matrix $\mathbf{B} \in \mathbf{R}^{|\mathcal{E}|\times|\mathcal{V}|}$, $\mathbf{B}_{(i,j),i} = 1, \mathbf{B}_{(i,j),j} = -1$ and $\mathbf{B}_{(i,j),k} = 0$ if $k \neq i, j$
- DC Power Flow Equations become:

$$\mathbf{f} = \mathbf{B}\mathbf{L}^{\dagger}\mathbf{p}$$

Constraints

$$|\mathbf{B}\mathbf{L}^{\dagger}\mathbf{p}| \leq \bar{\mathbf{f}} \quad \text{(Transmission Capacities)}$$

$$0 \leq \mathbf{p}_{\mathcal{G}_g} \leq \bar{\mathbf{p}}_{\mathcal{G}_g} \quad \text{(Generation Capacities)}$$

$$\sum_i \mathbf{p}_i = 0 \quad \text{(Power Balance)}$$

Optimal Static Power Dispatch

- Assume $\mathbf{p}_{\mathcal{G}_r}, \mathbf{p}_{\mathcal{G}_l}$ are fixed to known values
- Set $\mathbf{p}_{\mathcal{G}_g}$ so as to minimize "cost" of generation

DCOPF

$$\min_{\mathbf{p}_{\mathcal{G}_g}} \sum_{i \in \mathcal{G}_g} c_i \mathbf{p}_i$$

$$\text{Subject to } |\mathbf{B}\mathbf{L}^{\dagger}\mathbf{p}| \leq \bar{\mathbf{f}}$$

$$0 \leq \mathbf{p}_{\mathcal{G}_g} \leq \bar{\mathbf{p}}_{\mathcal{G}_g}$$

$$\sum_{i \in \mathcal{V}} \mathbf{p}_i = 0$$

Proportional Control

- $\mathbf{p}^0$: Generation at every node as decided by DCOPF. If $\mathbf{p}_{\mathcal{G}_l}, \mathbf{p}_{\mathcal{G}_r}$ are fixed in time, DCOPF does the job.

Proportional Control

- $\mathbf{p}^0$: Generation at every node as decided by DCOPF. If $\mathbf{p}_{\mathcal{G}_l}, \mathbf{p}_{\mathcal{G}_r}$ are fixed in time, DCOPF does the job.
- **BUT**: $\mathbf{p}_{\mathcal{G}_r}$ fluctuates over time: $\mathbf{p}_{\mathcal{G}_r}(t) = \mathbf{p}^0_{\mathcal{G}_r} + \mathbf{p}^r_{\mathcal{G}_r}(t)$

Proportional Control

- $\mathbf{p}^0$: Generation at every node as decided by DCOPF. If $\mathbf{p}_{\mathcal{G}_l}, \mathbf{p}_{\mathcal{G}_r}$ are fixed in time, DCOPF does the job.
- **BUT**: $\mathbf{p}_{\mathcal{G}_r}$ fluctuates over time: $\mathbf{p}_{\mathcal{G}_r}(t) = \mathbf{p}^0_{\mathcal{G}_r} + \mathbf{p}^r_{\mathcal{G}_r}(t)$
- Controllable generation responds by changing response proportionally

$$\mathbf{p}_{\mathcal{G}_g} = \mathbf{p}^0_{\mathcal{G}_g} + \alpha_{\mathcal{G}_g} \left(- \sum_{i \in \mathcal{G}_r} \mathbf{p}^r_i(t) \right)$$

Proportions α decided in accordance with generator capacities.

Energy Storage

- Add energy storage (batteries) at some nodes $\mathcal{S} \subset \mathcal{V}$
- Can draw power from/supply power to energy storage
- $\mathbf{p}_i^s$: Power drawn from energy storage at node i ($\mathbf{p}_i^s = 0$ if $i \notin \mathcal{S}$)
- $\mathbf{s}_i$: Energy stored at node i ($\mathbf{s}_i = 0$ if $i \notin \mathcal{S}$)
- $\underbrace{\mathbf{p}}_{\text{Total power}} = \underbrace{\mathbf{p}^s}_{\text{Power from storage}} + \underbrace{\mathbf{p}^{ns}}_{\text{Power without storage}}$

Constraints on Energy Storage

$$0 \leq \mathbf{s}_{\mathcal{S}} \quad \text{(Energy cannot be negative)}$$

Proportional Control with Storage

- If energy storage is present and being dispatched, proportional control response is:

$$\mathbf{p}_{\mathcal{G}_g} = \mathbf{p}^0_{\mathcal{G}_g} + \alpha_{\mathcal{G}_g}\left(-\sum_{i\in\mathcal{G}_r}\mathbf{p}^r_i(t) - \sum_{i\in\mathcal{S}}\mathbf{p}^s_i(t)\right)$$

Net Result

$$\mathbf{p}(t) = \mathbf{p}^0 + \mathbf{p}^r(t) + \mathbf{p}^s(t) + \alpha\left(-\sum_{i\in\mathcal{G}_r}\mathbf{p}^r_i(t) - \sum_{i\in\mathcal{S}}\mathbf{p}^s_i(t)\right)$$

Table of Contents

Optimal Control : Preliminaries

Optimal Control Recipe

- Encode Control Task as Cost Function $q(x, u)$
- Write down (discrete-time) dynamics $x_{t+1} = f(x_t, u_t)$
- Write down optimization problem:

$$\min_{x_0,u_0,x_1,u_1,\cdots,x_{T-1},u_{T-1},x_T} \sum_{t=0}^{T-1} q(x_t, u_t) + q_f(x_T)$$

$$\text{Subject to } x_{t+1} = f(x_t, u_t)$$

- Optimize!

Optimal Control : Preliminaries

Optimal Control Recipe

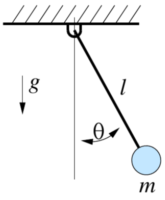
- Encode Control Task as Cost Function $q(x, u)$
- Write down (discrete-time) dynamics $x_{t+1} = f(x_t, u_t)$
- Write down optimization problem:

$$\min_{x_0, u_0, x_1, u_1, \cdots, x_{T-1}, u_{T-1}, x_T} \sum_{t=0}^{T-1} q(x_t, u_t) + q_f(x_T)$$

$$\text{Subject to } x_{t+1} = f(x_t, u_t)$$

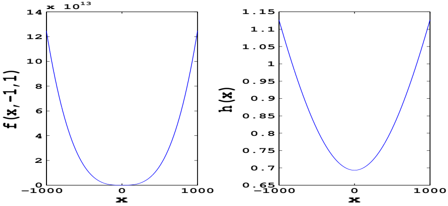
- Optimize!

Optimal Control Example: Pendulum Swing Up



$$x = (\theta, \dot{\theta}), u = \ddot{\theta}$$
$$\frac{\theta_{t+1} - \theta_t}{\Delta} = \dot{\theta}_t$$
$$\frac{\dot{\theta}_{t+1} - \dot{\theta}_t}{\Delta} = u - g \sin(\theta)$$
$$q = (1 + \cos(\theta))^2 + u^2$$

Optimal Energy Storage Control: Cost Function



- $\mathrm{cli}(\mathbf{p})$: Penalize transmission lines overloading: $\mathrm{cli}(\mathbf{p}) = \sum_{(i,j)\in\mathcal{E}} f(\mathbf{M}^{ij}\mathbf{p}, -\bar{\mathbf{f}}_{ij}, \bar{\mathbf{f}}_{ij})$
- $\mathrm{cg}(\mathbf{p}^{ns})$: Penalize controllable generators overloading/underloading: $\mathrm{cg}(\mathbf{p}^{ns}) = \sum_{i\in\mathcal{G}_g} f(\mathbf{p}_i^{ns}, 0, \bar{\mathbf{p}}_i)$
- $\mathrm{csp}(\mathbf{p}^{s})$: Penalize storage use: $\mathrm{csp}(\mathbf{p}^{s}) = \sum_{i\in\mathcal{S}} h(\mathbf{p}_i^{s})$

Optimal Energy Storage Control with Perfect Forecasts

Compute optimal energy storage dispatch $\mathbf{p}^{s*}(t)$ by solving

$$\min_{\mathbf{p}^s_{\mathcal{S}}(0),\ldots,\mathbf{p}^s_{\mathcal{S}}(T_f-1)} \sum_{t=0}^{T_f} \mathrm{cli}\left(\mathbf{p}\right) + \mathrm{cg}\left(\mathbf{p}^{ns}\right) + \mathrm{csp}\left(\mathbf{p}^s\right)$$

subject to

$$\mathbf{s}(t) = \sum_{\tau=0}^{t-1} \mathbf{p}^s(t)\Delta, \mathbf{s}(T_f) = \mathbf{s}(0), \mathbf{p}^s_i(t) = 0 \quad i \notin \mathcal{S}$$

$$\mathbf{p}(t) = \mathbf{p}^0 + \mathbf{p}^s(t) + \mathbf{p}^r(t) + \alpha\left(-\sum_{i\in\mathcal{G}_r} \mathbf{p}^r_i(t) - \sum_i \mathbf{p}^s_i(t)\right)$$

$$\mathbf{p}^{ns}(t) = \mathbf{p}(t) - \mathbf{p}^s(t)$$

Optimal Energy Storage Control: Simplifying Computation

- Can be recast as unconstrained problem using $\mathbf{p}^{s}_{\mathcal{S}}(t+1) = \frac{\mathbf{s}_{\mathcal{S}}(t+1) - \mathbf{s}_{\mathcal{S}}(t)}{\Delta}$
- Leads to sparse block-structured Hessian: Efficient Newton's method
- Use Levenberg-Marquardt correction to achieve convergence in practice

Table of Contents

Sizing and Placement Heuristic

Choose thresholds ϵ, ϵ'

$\mathcal{S} \leftarrow \mathcal{V}$

repeat

  for $k = 1 \to N$ **do**

    Generate Random Time Series Profiles for the Renewables

    Solve optimal control problem for the given profiles to get optimal dispatch $\mathbf{p}^{s*}(t)$

    $A^k \leftarrow \max_t |\mathbf{p}^{s*}(t)|$

  end for

  $A \leftarrow \frac{1}{N}\sum_{k=1}^{N} A^k$

  $\gamma \leftarrow \max\{\gamma : \{\mathrm{perf}(\{i \in \mathcal{S} : A_i \geq \gamma \max(A)\}) < \mathrm{perf}(\mathcal{S}) + \epsilon\}\}$

  $\mathcal{S} \leftarrow \{i \in \mathcal{S} : A_i \geq \gamma \max(A)\}$

until $\gamma \leq \epsilon'$

A more principled approach

$$\min_{\bar{\mathbf{p}^s}, \bar{\mathbf{s}}} \frac{1}{N} \sum_{i=1}^{N} \mathrm{Opt}(\bar{\mathbf{p}^s}, \bar{\mathbf{s}}, \mathbf{p}^{r^i}) + \mathrm{SparsitySizingPenalty}(\bar{\mathbf{p}^s}, \bar{\mathbf{s}})$$

$$\mathrm{Opt}(\bar{\mathbf{p}^s}, \bar{\mathbf{s}}, \mathbf{p}^r) = \min_{\mathbf{p}^s(0),\ldots,\mathbf{p}^s(T_f-1)} \sum_{t=0}^{T_f} \mathrm{cli}\left(\mathbf{p}\right) + \mathrm{cg}\left(\mathbf{p}^{ns}\right) + \mathrm{csp}\left(\mathbf{p}^s\right)$$

Subject to

$$\mathbf{s}(t) = \sum_{\tau=0}^{t-1} \mathbf{p}^s(t)\Delta, 0 \leq \mathbf{s} \leq \bar{\mathbf{s}}, \mathbf{s}(T_f) = \mathbf{s}(0), |\mathbf{p}^s| \leq \bar{\mathbf{p}^s}$$

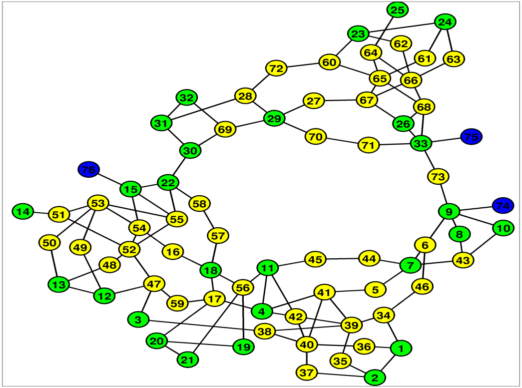
$$\mathbf{p}(t) = \mathbf{p}^0 + \mathbf{p}^s(t) + \mathbf{p}^r(t) + \alpha\left(-\sum_{i \in \mathcal{G}_r} \mathbf{p}_i^r(t) - \sum_i \mathbf{p}_i^s(t)\right)$$

$$\mathbf{p}^{ns}(t) = \mathbf{p}(t) - \mathbf{p}^s(t)$$

Table of Contents

Snapshot of Test Grid

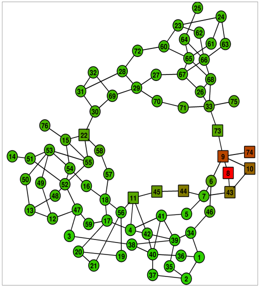
Grid Structure



Square nodes selected, Red:Active, Green:Inactive

Iteration 1

Activity

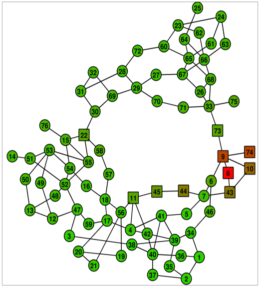


Algorithm Progress

Square nodes selected, Red:Active, Green:Inactive

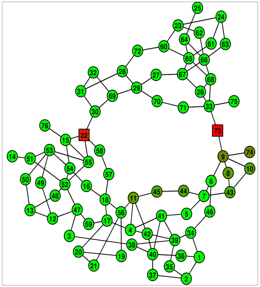
Iteration 1

Activity



Iteration 2

Activity

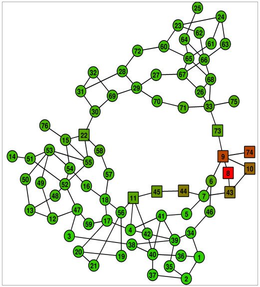


Algorithm Progress

Square nodes selected, Red:Active, Green:Inactive

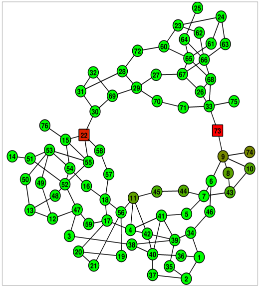
Iteration 1

Activity



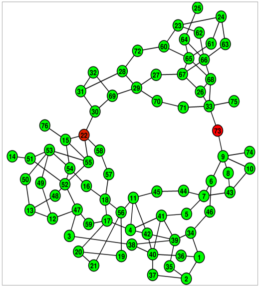
Iteration 2

Activity



Iteration 3

Activity



Characterizing Tradeoffs

Renewable Penetration

$$\frac{\sum_{t=0}^{T_f} \sum_{i \in \mathcal{G}_r} \mathbf{p}_i^{ns}(t)}{\sum_{t=0}^{T_f} \sum_{i \in \mathcal{G}_l} \mathbf{p}_i^{ns}(t)}$$

Normalized Power Capacity

$$\frac{\sum_{j \in \mathcal{S}} \max_t \left|\mathbf{p}^{s*}_j(t)\right|}{\sum_{i \in \mathcal{G}_r} (\max_t \mathbf{p}_i^r(t) - \min_t \mathbf{p}_i^r(t))}$$

Normalized Energy Capacity

$$\frac{\sum_{j \in \mathcal{S}} (\max_t \mathbf{s}_j^*(t) - \min_t \mathbf{s}_j^*(t))}{\sum_{i \in \mathcal{G}_r} (\max_t \mathbf{s}_i^r(t) - \min_t sr_i(t))} \quad \text{where } \mathbf{s}_i^r(t) = \int_0^T \mathbf{p}_i^r(t)\, dt$$

Experimental Setup

4 cases considered:

- *Unconstrained:* Storage at All Nodes
- *Constrained:* Storage at 10 nodes (iteration 2 of algorithm)
- *Highly Constrained:* Storage at 2 nodes (iteration 3 of algorithm)
- *Intuitive Placement:* Storage at Renewables

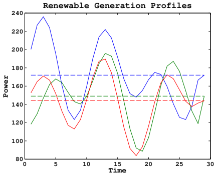
Experimental Setup

2000 trials for each case, each trial consists of:

- Generate a random penetration value p between 0 and .5
- Generate a random zero-mean fluctuation profile for each renewable:

$$\mathbf{p}_i^r(t) = \sum_k \frac{1}{k} \sin\left(\omega_k(t\Delta + \tau) + \phi_k\right)$$

  where ω_k are harmonics of a base frequency and ϕ_k are randomly generated phases.



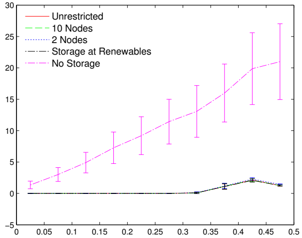
- Scale the fluctuations by the mean and add: $\mathbf{p}_i^{ns}(t) = \mathbf{p}_i^0(t) * (1 + \mathbf{p}_i^r(t)), i \in \mathcal{G}_r$
- Solve the Optimal control problem

Control Helps ..

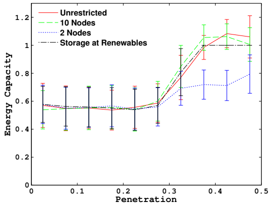
Control Helps ..

A LOT!

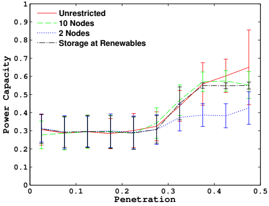
Constraint Violation vs Penetration



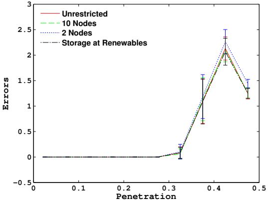
Energy Capacity vs Penetration



Power Capacity vs Penetration



Average Constraint Violation vs Penetration



Summary of Results

General Observations

- Control necessary to maintain grid constraits under fluctuations
- Energy Storage Control solves the problem upto about 30% penetration
- Even a little fluctuation needs control, proportional control fails to maintain all constraints
- Energy/Power capacity required remain constant upto 30%, then shoot up
- Conjecture: Energy/Power capacity requirements can be pushed down with "smarter" control of traditional generators

Summary of Results

Placement Heuristic

- Placing storage at renewables works
- However, requires higher energy/power capacity
- Placement heuristic seems to discover “optimal” placement
- Placed on lines connecting “North” and “South” of grid

Table of Contents

Conclusions

- Control necessary to maintain grid stability at High Penetration Levels
- Operations-driven Planning necessary for Cost-Efficient Renewable Integration
- Optimal Control a useful paradigm in answering this question
- Our intial results indicate that successful Renewable Integration upto 30% Penetration is possible using optimal energy storage control

Future Work

- Investigate principled approach to placement heuristic
- Test algorithm on various graphs, relative placement of renewables, numbers of renewable nodes
- Combine energy storage control with “smart” generation control
- Build feedback controllers to deal with imperfect predictions
- Decentralized/Distributed solutions?

Thank you

Questions?

Acknowledgements

- Yuval Tassa, UW, Levenberg-Marquardt Code
- Florian Dörfler, Introductory slides