15-884 – Future Directions in Smart Grid Research

J. Zico Kolter

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- Numerous areas of interest for computation in the future of sustainable energy
  - Renewable integration
  - Grid security and resilience
  - Smart homes / energy disaggregation
  - Demand response
  - Microgrids
- Many more areas: see e.g. IEEE Transactions on Smart Grid

Renewable integration

- Challenge: many states have ambitious legislation requiring some fraction of energy to come from renewable sources
  - E.g.: California requires 33% of energy from renewable sources by 2020

- Unlike traditional generation, wind and solar are not dispatchable, can't schedule or guarantee them in advance

- You are already looking at a research-level consideration of these issues in problem set 4

- The basic problem: given current infrastructure, increased renewable penetration increases the need for regulation and reserve

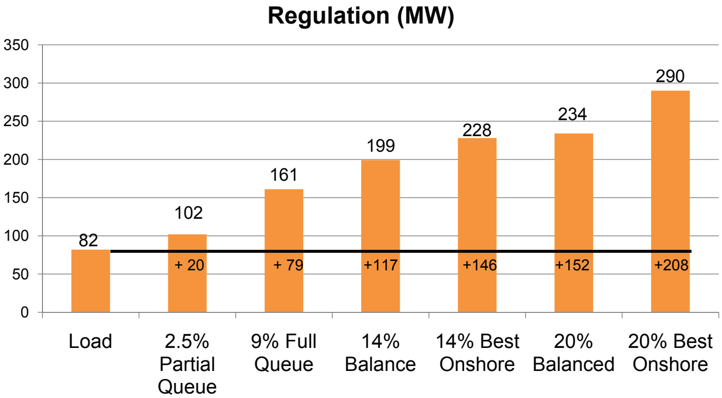


Figure source: ISO-NE New England Wind Integration Study, 2010

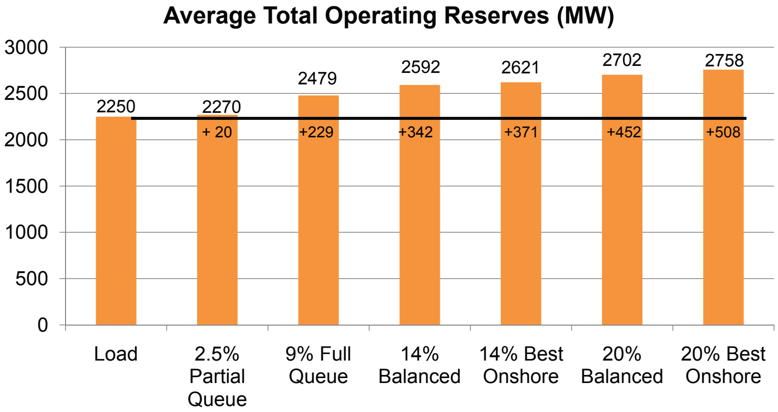


Figure source: ISO-NE New England Wind Integration Study, 2010

- As context, today's maximum forecasted load in NE is 17,500 MW, so this is a sizable fraction of generation (often not doing anything)

- How did they come up with these estimates?

  - Very similar to what you are doing for the homework: run many simulations of market planning and dispatch using different wind conditions, see how much "fast acting generation" is required

- Another line of work: analytical solutions for certain special cases of renewable dispatch

  - Rajagopal et al., Risk-Limiting Dispatch for Integrating Renewable Power, 2011

  - Su and El Gamal, Modeling and analysis of the role of fast-response energy storage in the smart grid, 2011

Grid security and resilience

- "Security" can mean two things in the smart grid: cybersecurity (securing grid resources from cyber attack), or system security (resilience in the face of failures)
  - Cyber security, e.g.: Khurana et al., Smart-Grid Security Issues, 2010, McDaniel and McLaughlin, Security and Privacy Challenges in the Smart Grid, 2009
  - Grid resilience, e.g.: Schainker et al., Real-time dynamic security assessment: fast simulation and modeling applied to emergency outage security of the electric grid, 2006

- Resilience in the face of generator outages

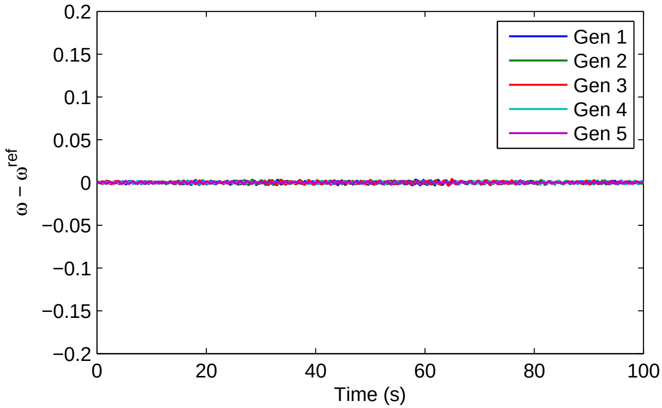
- Our favorite linear dynamical system

$$\dot{\theta} = \omega - \omega^{\mathrm{ref}}$$
$$\dot{\omega} = \frac{1}{2H}(u - (B_{GG} - B_{GL}B_{LL}^{-1}B_{LG})\theta - B_{GL}B_{LL}^{-1}p_L)$$

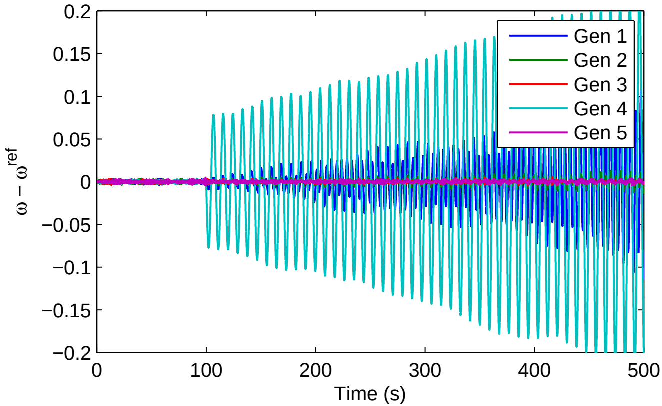
- PI control for frequency regulation (say we don't care about absolute voltage angles)

$$e_i = e_i + (\omega_i - \omega^{\mathrm{ref}})$$
$$u_i = -K_p(\omega_i - \omega^{\mathrm{ref}}) - K_i e_i$$

- Under "normal" operation, everything works (system is able to regulate frequency)



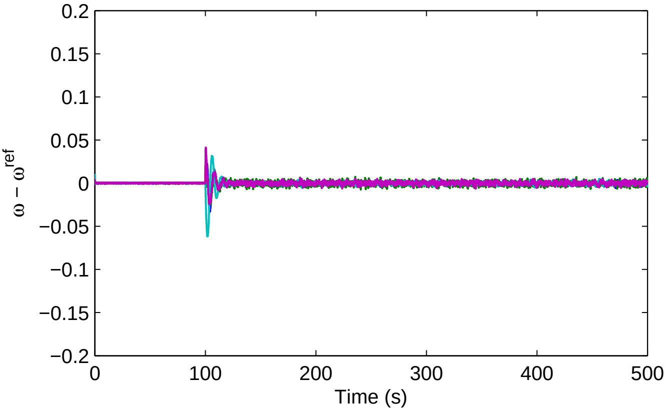
- Now suppose at time $t = 100$, generators 1 and 4 go offline



- Though it's a bit hard to see in the figure, the frequency at all the buses are unstable (will eventually diverge); "myopic" solution is just to shut off all generators

- But, system is controllable with only three generators!

- They just need to work together (e.g., LQR control that takes into account all the states for planning action)



Demand Response

- Throughout our units on power, load was always treated as fixed
- As communication with loads becomes more possible, we have the ability to adjust loads to current grid conditions
- Kirschen et al., Factoring the elasticity of demand in electricity prices, 2000

- An example: controlling thermostatic loads (refrigerators, air conditioners, etc) to adjust load

- These devices maintain temperature within a given range, but within that range we could control them to

- One direction of work: look at control that requires only aggregate monitoring of all the loads, and a single broadcasted control signal

  – Mathieu et al., State Estimation and Control of Electric Loads to Manage Real-Time Energy Imbalance, 2012

  – Koch et al., Modeling and control of aggregated heterogeneous thermostatically controlled loads for ancillary services, 2011

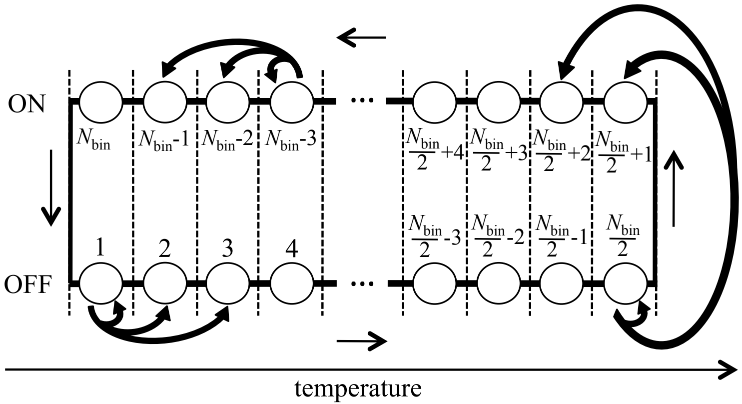


Figure source: Koch et al., 2011

$$\boldsymbol{x}_{k+1} = \boldsymbol{A}\boldsymbol{x}_k + \boldsymbol{B}\boldsymbol{u}_k$$
$$\boldsymbol{y}_k = \boldsymbol{C}\boldsymbol{x}_k \quad ,$$

$$0 \leqslant x_i \leqslant 1 \qquad \forall \quad i = 1, \ldots, N_{\text{bin}} \quad ,$$
$$-1 \leqslant u_{\text{bin},i} \leqslant 1 \qquad \forall \quad i = 1, \ldots, N_{\text{bin}}/2$$

$$J_k = \sum_{l=k}^{k+N_{\text{pred}}-1} \Big(Q_{\text{track}} \left(P_{\text{total},l} - P_{\text{set},l}\right)^2 \tag{20}$$
$$+ \quad \boldsymbol{u}_{\text{bin},l}^{\text{T}} \boldsymbol{R}_{\text{bin}} \boldsymbol{u}_{\text{bin},l} + \left(\boldsymbol{x}_l - \boldsymbol{x}_{\text{set},l}\right)^{\text{T}} \boldsymbol{Q} \left(\boldsymbol{x}_l - \boldsymbol{x}_{\text{set},l}\right) \Big) \ .$$

Equations from Koch et al., 2011

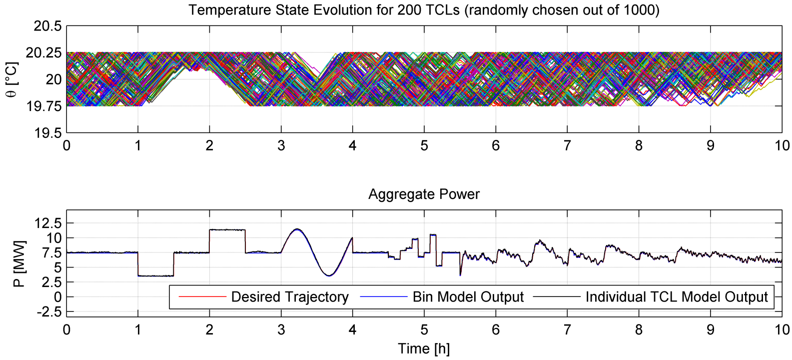


Figure source: Koch et al., 2011

Microgrids

- Idea: build all the elements of a typically grid (generation, distribution, control, and load) on a small scale

- Can ideally provide more efficiency, reliability than existing grid

- Hatziargyriou et al., Microgrids, 2007; Lasseter and Paigi, Microgrid: a conceptual solution, 2004

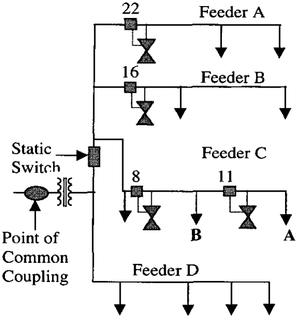


Figure 2 Microgrid

Figure source: Lasseter and Paigi, 2004

- Squares correspond to breaker boxes, can isolate portions of the system from the larger grid
- Need to ensure that each subsystem has the ability (with generation, storage) to provide for its consumption over short periods of time