Load-side Frequency Control

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Outline

Motivation

Dynamic network model

Load-side frequency control

Simulations

Zhao, Topcu, Li, Low, TAC 2014
Mallada, Low, 2013
Motivation: frequency control

Synchronous network
- All buses synchronized to same nominal frequency (US: 60 Hz)
- Supply-demand imbalance $\rightarrow$ frequency fluctuation

Frequency regulation
- Generator based
- Frequency sensitive (motor-type) loads

Controllable loads
- Do not react to frequency deviation
- ... but intelligent
- Need active control – how?
Frequency control is traditionally done on generation side.

- **Primary frequency control**
  - Dynamic model: e.g., swing equation
  - Time scales: sec, min, 5 min, 60 min, day, year

- **Secondary frequency control**
  - Economic dispatch
  - Unit commitment

- **Power flow model**
  - Time scales: sec, min, 5 min, 60 min, day, year
  - Dynamic model: e.g., DC/AC power flow
Advantages of load-side control

Distributed loads can supplement generator-side control
- faster (no/low inertia!)
- no waste or emission
- more reliable (large #)
- localize disturbance

It’s about supply-demand balance, but synchronous frequency helps

dynamic model e.g. swing eqtn
Idea dates back to 1970s

Regulated Industry

MARKETING SYSTEM
- Utility Transmission and Distribution
- Utility Scheduling, Control, etc.
- Spot Price Computation
- Billing

CUSTOMERS

Customer #k
- Internal Scheduling
- Generation
- Usage

Customers and Unregulated Generation

UTILITY GENERATION

Homeostatic utility control:
- freq adaptive loads
- spot prices
- IT infrastructure

Schweppe et al (1979, 1980)
Potential benefit

US:
- Operating reserve: 13% of peak
total GFA capacity: 18%

Residential load accounts for ~1/3 of peak demand
61% residential appliances are Grid Friendly

Commercial 29%
Industrial 28%
Residential (GFA) 18%
Residential (non-GFA) 12%
Operating Reserve 13%

Lu & Hammerstrom (2006), PNNL
PNNL Grid Friendly Appliance Demo Project
(early 2006 – March 2007)

- 150 clothes dryers, 50 water heaters
- Under-frequency threshold: 59.95 Hz (0.08% dev)
- 358 under-freq events during project, lasting secs – 10 mins
- All GFA detected events correctly and loads shedded as designed, despite wide geographical distribution
- Survey reported no customer inconvenience

Hammerstrom et al (2007), PNNL
A model can be formulated as a minimum variance controller that computes changes in thermostat setpoint required to achieve desired aggregated power responses.

Fig. 7 depicts one of the central results of the paper. The top panel of the figure shows two lines. The first is the zero-mean high-frequency component of a wind plant's output plus a direct current (dc) shift equal to the average demand of the TCL population under control. The second line is aggregate demand from the controlled population (in this case, 60,000 air conditioners), where they are subjected to shifts in their temperature setpoint as shown in the bottom panel of the figure (these shifts are dictated by the minimum variance controller). The middle panel of the figure shows the controller error, which is relatively small.

In Section III-D, load controllability was discussed in the context of availability and willingness to participate. These concepts are implicitly taken into account in the hysteretic form of control associated with thermostats. As the temperature nears either end of the deadband, a TCL becomes available for control. It becomes increasingly willing to participate in control as the temperature approaches the switching limit. However, once the TCL has switched state (encountered the deadband limit), it is temporarily no longer available for control.

Assuming relatively constant ambient temperature, the controllability of a large population of TCLs will vary little over time. However, large temperature changes affect the availability of TCLs for control. For example, a significant drop in ambient temperature would eventually result in far fewer air conditioning loads. System operations would need to take account of such temporal changes in load controllability.

B. Plug-In Electric Vehicles

PEVs are expected to comprise around 25% of all automobile sales in the United States by 2020 [59]. At those penetration levels, PEVs will account for 3%–6% of total electrical energy consumption. It is anticipated that most vehicles will charge overnight, when other loads are at a minimum. The proportion of PEV load during that period will therefore be quite high. Vehicle charging tends to be rather flexible, though must observe the owner-specified completion time. PEVs therefore offer another excellent end-use class for load control.

Motivated by the control strategy for TCLs developed in [33], a hysteretic form of local control can be used to establish system-level controllability of PEV charging loads. The proposed local control strategy is illustrated in Fig. 8. The nominal SoC profile is defined as the linear path obtained by uniform charging, such that the desired total energy $E_{\text{tot}}$ is delivered to the PEV over the period defined by owner-specified start and finish times. The nominal SoC profile lies at the center of a deadband; for this example, the deadband limits are given by

$$\frac{1}{C_0} \leq \frac{\text{SoC}(t)}{C_0} \leq \frac{1}{C_1} + \frac{\text{E}_{\text{tot}}}{C_1}$$

where $\text{SoC}(t)$ is the nominal SoC at time $t$.

When the charger is turned on, the SoC actually increases at a rate that is faster than the nominal profile, so

Can household Grid Friendly appliances follow its own PV production?

Fig. 7. Load control example for balancing variability from intermittent renewable generators, where the end-use function—in this case, thermostat setpoint—is used as the input signal.

Callaway, Hiskens (2011)
Callaway (2009)
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Mallada, Low, 2013
Network model

Generation

$P_i^m$

di + $\hat{d}_i$

loads:
controllable + freq-sensitive

$i$ : bus/control area/balancing authority

reactance

$X_{ij}$
Network model

DC approximation

- Lossless network ($r=0$)
- Fixed voltage magnitudes
- Reactive power ignored
- Do not assume small angle difference
Dynamic model

Swing equation on bus $i$

$$M_i \ddot{\omega}_i = P_i^m - P_i^e$$

- Newton’s 2nd law
- Variables: deviations from nominal values
Dynamic model

Swing equation on bus $i$

\[ M_i \dot{\omega}_i = P_i^m - P_i^e \]

\[ P_i^e := d_i + D_i \omega_i + \sum_{i \sim j} P_{ij} \]

- controllable loads
- freq-sens loads
- branch power flow
Dynamic model

Swing equation on bus $i$

$$M_i \dot{\omega}_i = P^{m}_i - P^{e}_i$$

$$\dot{P}^{e}_{ij} = b^{ij} (\dot{\omega}_i - \dot{\omega}_j) + \sum_{i \sim j} P_{ij}$$

$$b^{ij} = 3 \frac{|V_i| |V_j|}{x^{ij}} \cos \left( \theta_i^0 - \theta_j^0 \right)$$

linearization around nominal
Network model

Generator bus (may contain load):

$$\dot{\omega}_i = -\frac{1}{M_i} \left( d_i + D_i \omega_i - P_i^m + \sum_{i \rightarrow j} P_{ij} - \sum_{j \rightarrow i} P_{ji} \right)$$

Load bus (no generator):

$$0 = d_i + D_i \omega_i - P_i^m + \sum_{i \rightarrow j} P_{ij} - \sum_{j \rightarrow i} P_{ji}$$

Real branch power flow:

$$\dot{P}_{ij} = b_{ij} \left( \omega_i - \omega_j \right) \quad \forall \ i \rightarrow j$$
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Mallada, Low, 2013
Frequency control

\[
\dot{\omega}_i = -\frac{1}{M_i} \left( d_i + D_i \omega_i - P_i^m + \sum_{i \rightarrow j} P_{ij} - \sum_{j \rightarrow i} P_{ji} \right)
\]

\[
0 = d_i + D_i \omega_i - P_i^m + \sum_{i \rightarrow j} P_{ij} - \sum_{j \rightarrow i} P_{ji}
\]

\[
\dot{P}_{ij} = b_{ij} (\omega_i - \omega_j) \quad \forall \ i \rightarrow j
\]

Suppose the system is in steady state

\[
\dot{\omega}_i = 0 \quad \dot{P}_{ij} = 0
\]

and suddenly …
Frequency control

Given: disturbance in gens/loads

Current: adapt remaining generators $P_i^m$
- to re-balance power
- (and restore nominal freq, zero ACE)

Our goal: adapt controllable loads $d_i$
- to re-balance power
- while minimizing disutility of load control
Frequency control

$$\dot{\omega}_i = -\frac{1}{M_i}\left( d_i + D_i \omega_i - P_i^m + \sum_{i \rightarrow j} P_{ij} - \sum_{j \rightarrow i} P_{ji} \right)$$

$$0 = d_i + D_i \omega_i - P_i^m + \sum_{i \rightarrow j} P_{ij} - \sum_{j \rightarrow i} P_{ji}$$

$$\dot{P}_{ij} = b_{ij}(\omega_i - \omega_j) \quad \forall \ i \rightarrow j$$

proposed approach

current approach

this talk: ignores generator-side control
Load-side controller design

\[ \dot{\omega}_i = -\frac{1}{M_i} \left( d_i + D_i \omega_i - P_i^m + \sum_{i \rightarrow j} P_{ij} - \sum_{j \rightarrow i} P_{ji} \right) \]

\[ 0 = d_i + D_i \omega_i - P_i^m + \sum_{i \rightarrow j} P_{ij} - \sum_{j \rightarrow i} P_{ji} \]

\[ \dot{P}_{ij} = b_{ij} \left( \omega_i - \omega_j \right) \quad \forall \ i \rightarrow j \]

How to design feedback control law

\[ d_i = F_i \left( \omega(t), P(t) \right) \]
Load-side controller design

\[
\dot{\omega}_i = -\frac{1}{M_i} \left( d_i + D_i \omega_i - P_{im} + \sum_{i\rightarrow j} P_{ij} - \sum_{j\rightarrow i} P_{ji} \right)
\]

\[
0 = d_i + D_i \omega_i - P_{im} + \sum_{i\rightarrow j} P_{ij} - \sum_{j\rightarrow i} P_{ji}
\]

\[
\dot{P}_{ij} = b_{ij} (\omega_i - \omega_j) \quad \forall \ i \rightarrow j
\]

Control goals

- Rebalance power
- Resynchronize/stabilize frequency
- Restore nominal frequency
- Restore scheduled inter-area flows

Zhao, Topcu, Li, Low  
TAC 2014

Mallada, Low 2013
Load-side controller design

\[
\dot{\omega}_i = -\frac{1}{M_i} \left( d_i + D_i \dot{\omega}_i - P_i^m + \sum_{i \rightarrow j} P_{ij} - \sum_{j \rightarrow i} P_{ji} \right)
\]

\[
0 = d_i + D_i \dot{\omega}_i - P_i^m + \sum_{i \rightarrow j} P_{ij} - \sum_{j \rightarrow i} P_{ji}
\]

\[
\dot{P}_{ij} = b_{ij} (\omega_i - \omega_j) \quad \forall \ i \rightarrow j
\]

Desirable properties of \( d_i = F_i(\omega(t),P(t)) \)

- simple, scalable
- decentralized/distributed
Load-side controller design

\[
\dot{\omega}_i = -\frac{1}{M_i} \left( d_i + D_i \omega_i - P_i^m + \sum_{i \rightarrow j} P_{ij} - \sum_{j \rightarrow i} P_{ji} \right)
\]

\[
0 = d_i + D_i \omega_i - P_i^m + \sum_{i \rightarrow j} P_{ij} - \sum_{j \rightarrow i} P_{ji}
\]

\[
\dot{P}_{ij} = b_{ij} (\omega_i - \omega_j) \quad \forall \ i \rightarrow j
\]

Proposed approach: forward engineering

- formalize control goals into OLC objective
- derive local control as distributed solution
Outline

Motivation

Dynamic network model

Load-side frequency control
  - Primary control
  - Secondary control

Simulations
Optimal load control (OLC)

\[
\min \sum_{i} \left( c_i(d_i) + \frac{1}{2D_i} \hat{d}_i^2 \right)
\]

over

s. t.
Optimal load control (OLC)

\[
\begin{align*}
\text{controllable load} & \quad \text{uncontrollable load} \\
\downarrow & \quad \downarrow \\
\min \quad \sum_i \left( c_i(d_i) + \frac{1}{2D_i} \hat{d}_i^2 \right) \\
\text{over} \quad \text{loads } d_l \in [d_l, \bar{d}_l], \quad \hat{d}_i \\
\text{s. t} & 
\end{align*}
\]

Optimal load control (OLC)
Optimal load control (OLC)

\[
\begin{align*}
\text{min} & \quad \sum_i \left( c_i(d_i) + \frac{1}{2D_i} \hat{d}_i^2 \right) \\
\text{over} & \quad \text{loads } d_l \in [\underline{d}_l, \overline{d}_l], \quad \hat{d}_i \\
\text{s. t.} & \quad \sum_i \left( d_i + \hat{d}_i \right) = \sum_i P_i^m
\end{align*}
\]

demand = supply across network

disturbances
Punchline

Theorem

swing dynamics + frequency-based load control = primal-dual algorithm that solves OLC

- Completely decentralized
- Not need explicit communication
- Not need detailed network data
- Exploit free global control signal

… reverse engineering swing dynamics
Recall OLC

\[
\begin{align*}
\text{min} \quad & \sum_i \left( c_i(d_i) + \frac{1}{2D_i} \hat{d}_i^2 \right) \\
\text{over} \quad & \text{loads } d_i \in [\underline{d}_i, \overline{d}_i], \quad \hat{d}_i \\
\text{s. t.} \quad & \sum_i \left( d_i + \hat{d}_i \right) = \sum_i P_i^m \\
\end{align*}
\]

demand = supply across network
Punchline

swing dynamics (recap)

\[ \dot{\omega}_i = -\frac{1}{M_i}\left( d_i(t) + D_i \omega_i(t) - P_i^m + \sum_{i \rightarrow j} P_{ij}(t) - \sum_{j \rightarrow i} P_{ji}(t) \right) \]

\[ \dot{P}_{ij} = b_{ij} \left( \omega_i(t) - \omega_j(t) \right) \]

load control

\[ d_i(t) := \left[ c_i^{-1} \left( \omega_i(t) \right) \right]_{\bar{d_i}} \]
Punchline

Theorem

System trajectory \( \left( d(t), \hat{d}(t), \omega(t), P(t) \right) \)

converges to \( \left( d^*, \hat{d}^*, \omega^*, P^* \right) \) as \( t \to \infty \)

Zhao, Topcu, Li, Low, TAC 2014
Theorem

system trajectory \( \left( d(t), \hat{d}(t), \omega(t), P(t) \right) \)
converges to \( \left( d^*, \hat{d}^*, \omega^*, P^* \right) \) as \( t \to \infty \)

- \( \left( d^*, \hat{d}^* \right) \) is unique optimal load control
- \( \omega^* \) is unique optimal for DOLC
- \( P^* \) is optimal for dual of DOLC

Load-side primary frequency control works!

Zhao, Topcu, Li, Low, TAC 2014
Implications

- Freq deviations contains right info on *global* power imbalance for *local* decision

- Decentralized load participation in primary freq control is stable

- $\omega^*$: Lagrange multiplier of OLC info on power imbalance

- $P^*$: Lagrange multiplier of DOLC info on freq asynchronism
Recap: control goals

Yes  ■ Rebalance power
Yes  ■ Resynchronize/stabilize frequency

No  ■ Restore nominal frequency \( (\omega^* \neq 0) \)
No  ■ Restore scheduled inter-area flows

Proposed approach: forward engineering
  ■ formalize control goals into OLC objective
  ■ derive local control as distributed solution
Outline

Motivation

Dynamic network model

Load-side frequency control

- Primary control
- Secondary control

Mallada, Low, 2013

Simulations
Freq preserving OLC

\[
\min \sum_i \left( c_i(d_i) + \frac{1}{2D_i} \hat{d}_i^2 \right)
\]

s. t. \[\sum_i (d_i + \hat{d}_i) = \sum_i P^m_i\]

demand = supply across network

\[
\min \sum_i \left( c_i(d_i) + \frac{1}{2D_i} \hat{d}_i^2 \right)
\]

s. t. \[d_i + \hat{d}_i = P^m_i - \sum_{e \in E} C_{ie} P_e\]

demand = supply per bus

\[d_i = P^m_i - \sum_{e \in E} C_{ie} R_e\]

to restore nominal frequency
Recall primary control for OLC

swing dynamics:

\[ \dot{\omega}_i = -\frac{1}{M_i} \left( d_i(t) + D_i \omega_i(t) - P_i^m + \sum_{e \in E} C_{ie} P_e(t) \right) \]

\[ \dot{P}_{ij} = b_{ij} \left( \omega_i(t) - \omega_j(t) \right) \]

load control: \[ d_i(t) := \left[ c_i^{-1} \left( \omega_i(t) \right) \right] \bar{d}_i \]
Recall primary control for OLC

**Swing Dynamics:**

\[
\dot{\omega}_i = -\frac{1}{M_i} \left( d_i(t) + D_i \omega_i(t) - P^m_i + \sum_{e \in E} C_{ie} P_e(t) \right)
\]

\[
\dot{P}_{ij} = b_{ij} \left( \omega_i(t) - \omega_j(t) \right)
\]

**Load Control:**

\[
d_i(t) := \left[ c_i^{-1} \left( \omega_i(t) + \lambda(t) \right) \right]_{d_i}
\]

**Computation & Communication:**

\[
\dot{\lambda}_i = -\gamma_i \left( d_i(t) - P^m_i + \sum_{e \in E} C_{ie} R_e(t) \right), \quad \dot{R}_{ij} = a_{ij} \left( \lambda_i(t) - \lambda_j(t) \right)
\]

*implicit*
Punchline

**Theorem**

System trajectory \( (d(t), \hat{d}(t), \omega(t), P(t)) \) converges to \( (d^*, \hat{d}^*, \omega^*, P^*) \) as \( t \to \infty \)

- \( (d^*, \hat{d}^*) \) is unique optimal load control
- \( \omega^* = 0 \)

Load-side secondary frequency control works!

Mallada, Low 2014
Recap: control goals

- Yes  ■ Rebalance power
- Yes  ■ Resynchronize/stabilize frequency
- Yes  ■ Restore nominal frequency \( (\omega^* \neq 0) \)
- No   ■ Restore scheduled inter-area flows

Secondary control restores nominal frequency but requires communication with neighbors
Outline

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Load-side frequency control

Simulations

Zhao, Topcu, Li, Low, TAC 2014
Mallada, Low, 2013
Simulations

Dynamic simulation of IEEE 68-bus system

- Power System Toolbox (RPI)
- Detailed generation model
- Exciter model, power system stabilizer model
- Nonzero resistance lines
Simulations

Frequency at bus 66

59.964 Hz
ERCOT threshold for freq control
Simulations

Voltage at bus 66

- 4.5%
- 7.0%
Simulations

![Graph showing frequency evolution over time](image1)

![Graph showing frequency evolution over time with magnification](image2)