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 ➔ frequency fluctuation

Frequency regulation

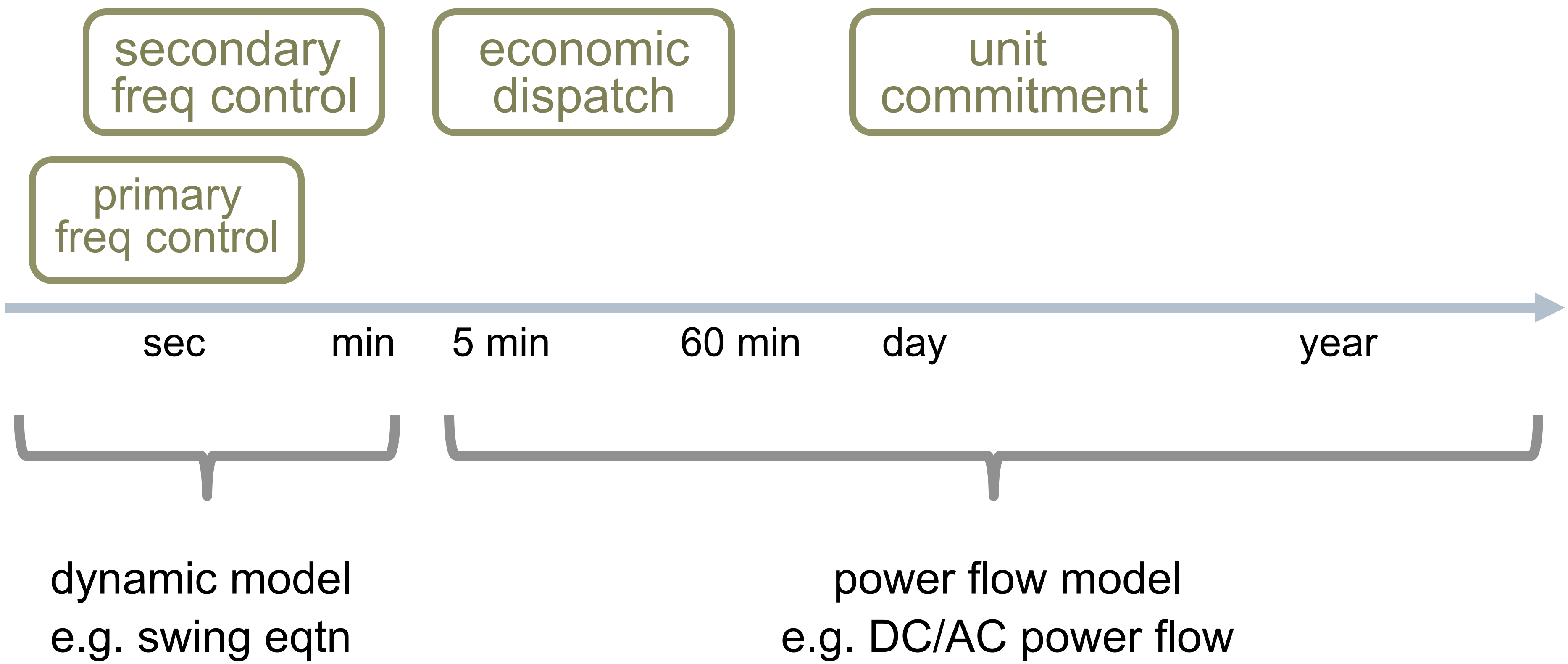
- Generator based
- Frequency sensitive (motor-type) loads

Controllable loads

- Do not react to frequency deviation
- … but intelligent
- Need active control – how?

Frequency control

Frequency control is traditionally done on generation side



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

secondary freq control

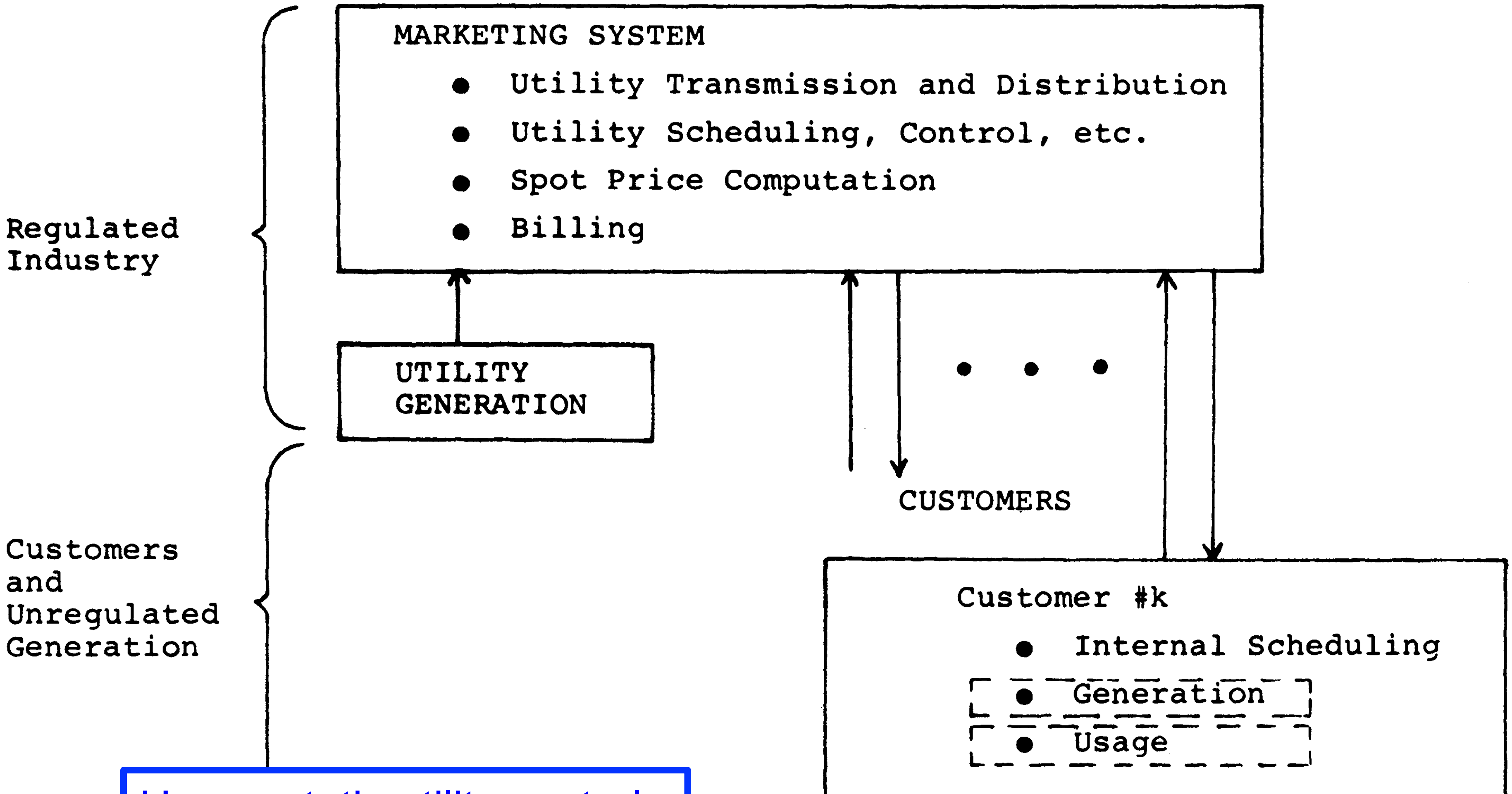
primary freq control

sec | min | 5 min | 60 min | day | year

dynamic model
e.g. swing eqtn

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

Idea dates back to 1970s

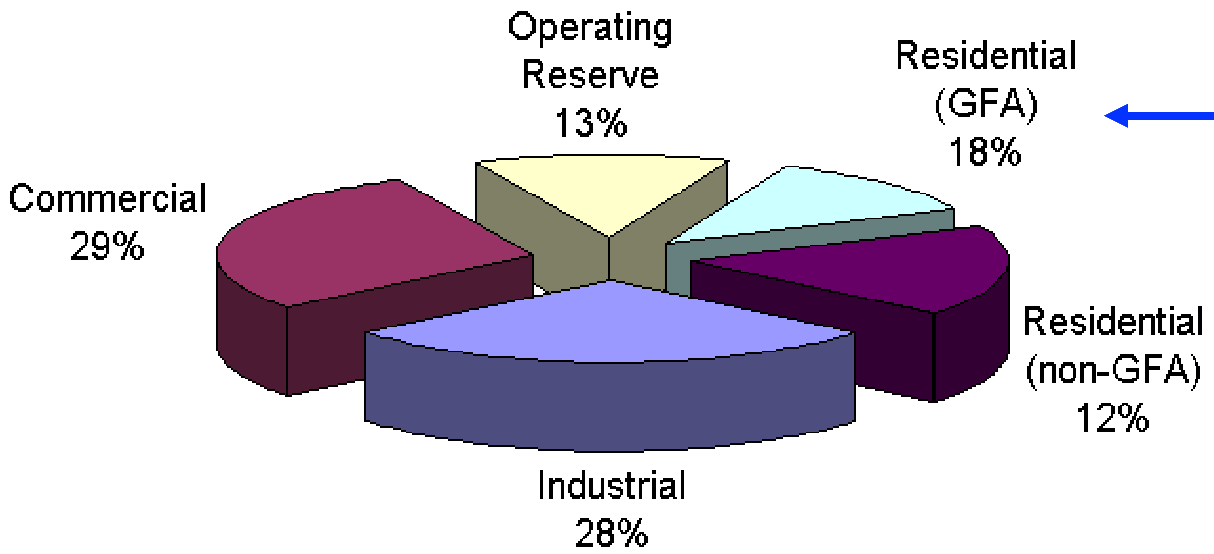


Homeostatic utility control :

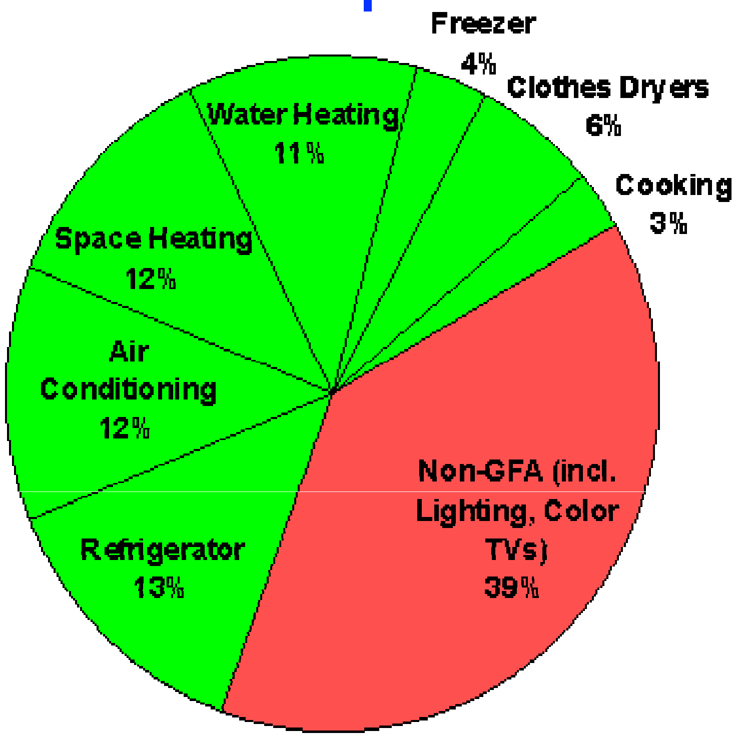
- freq adaptive loads
- spot prices
- IT infrastructure

Schweppe et al (1979, 1980)

Potential benefit



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



US:
operating reserve: 13% of peak
total GFA capacity: 18%

Lu & Hammerstrom (2006), PNNL

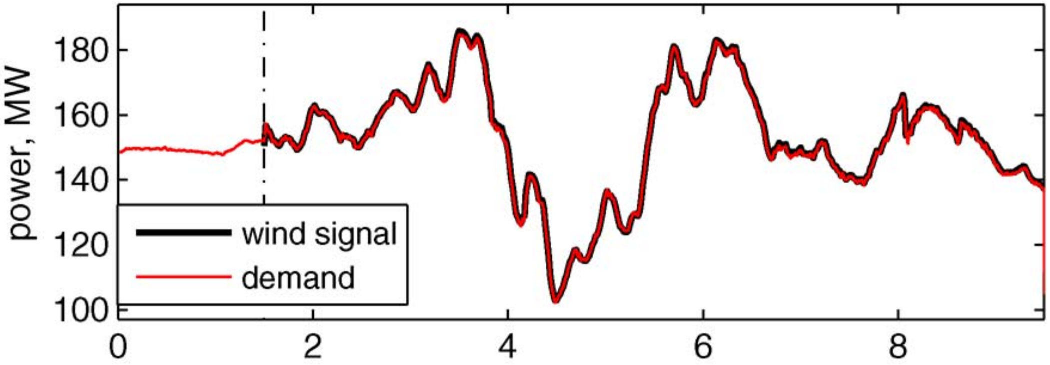
Small demo: PNNL

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

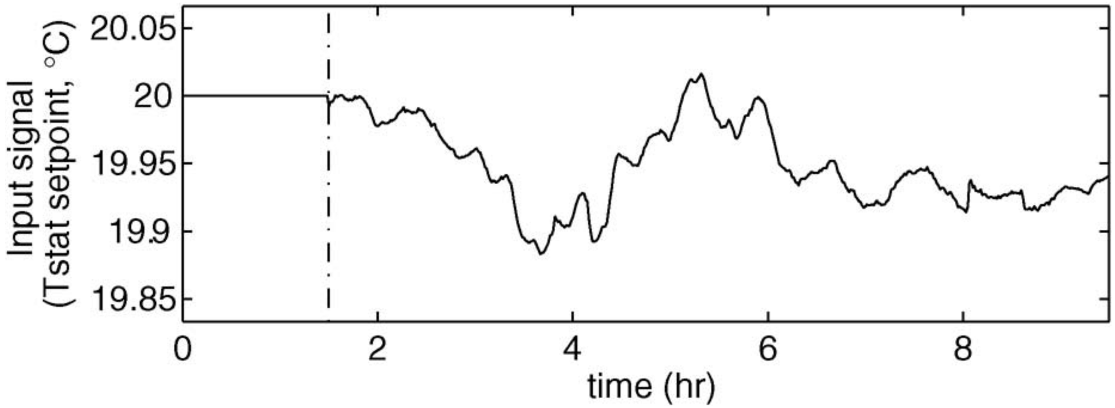
Figure 1.3. GFA Controller Board used in the Grid Friendly Appliance Project

Hammerstrom et al (2007), PNNL



Can household Grid Friendly appliances follow its own PV production?

- 60,000 AC
- avg demand ~ 140 MW
- wind var: +- 40MW
- temp var: 0.15 degC



Dynamically adjust thermostat setpoint

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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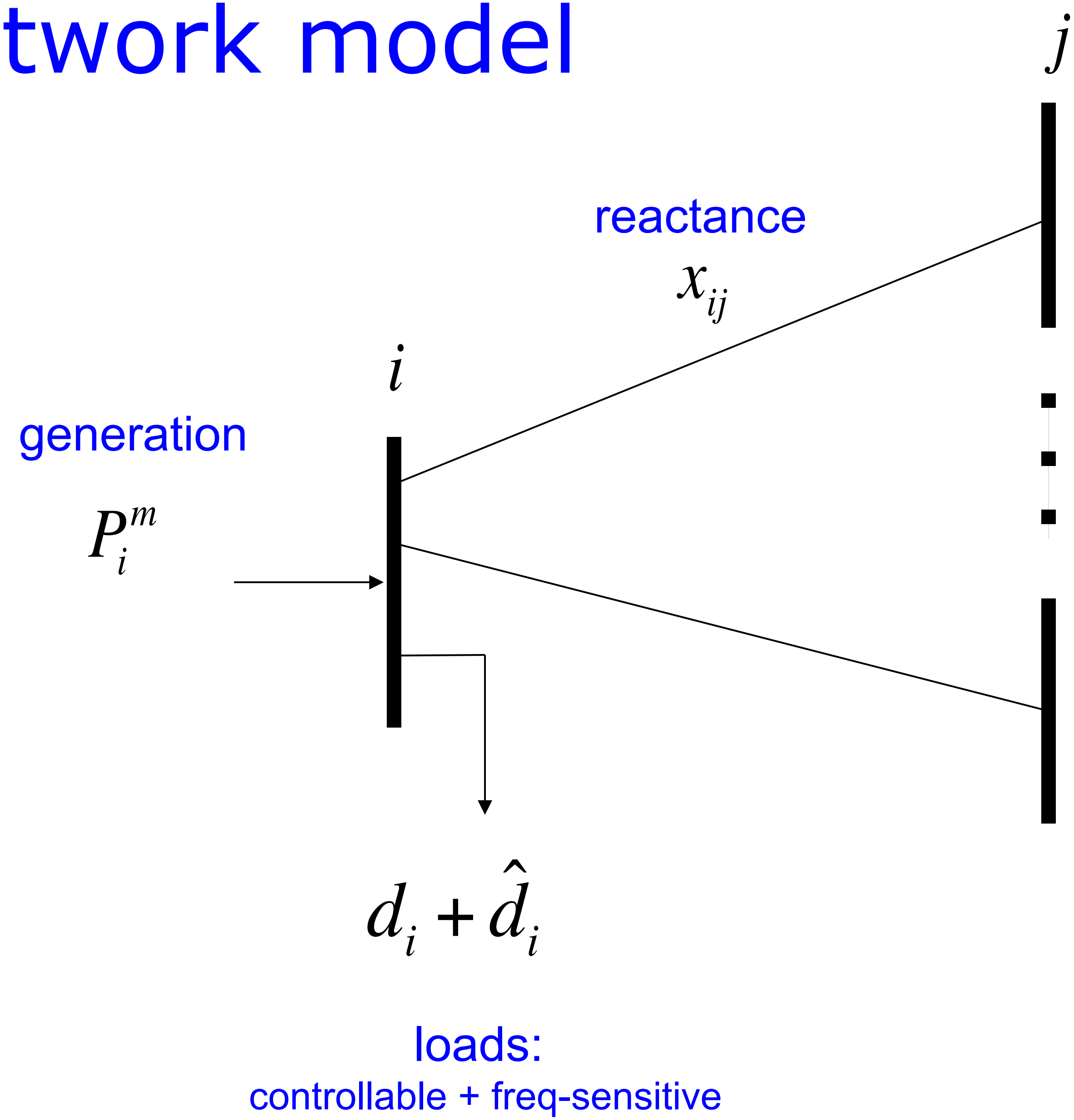
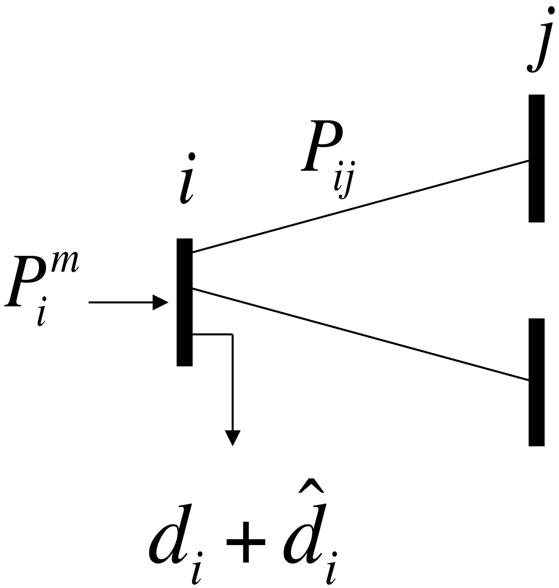
Network model



i : bus/control area/balancing authority

Network model



DC approximation

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

Dynamic model

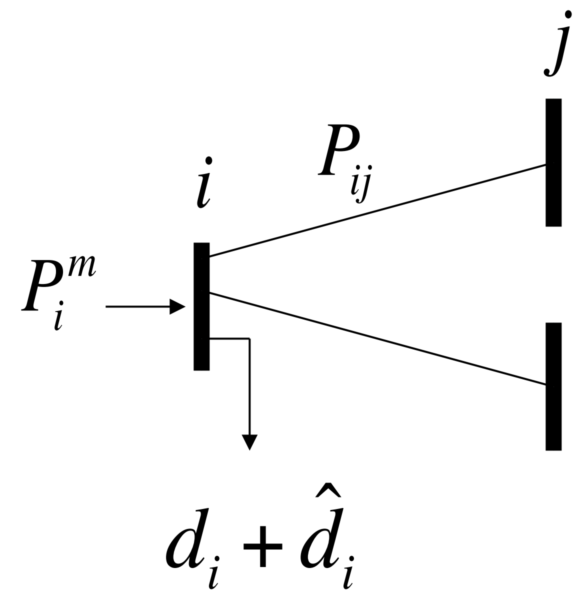
Swing equation on bus i

frequency

mechanical power

electrical power

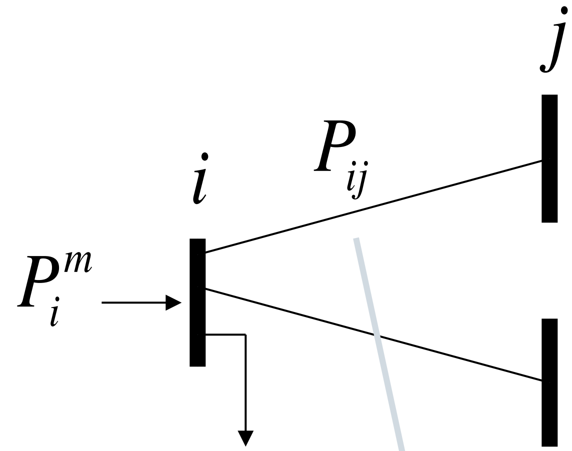
$$M_i \dot{\omega}_i = P_i^m - P_i^e$$



- Newton's 2nd law
- Variables: deviations from nominal values

Dynamic model

Swing equation on bus i



$$d_i + \hat{d}_i$$

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

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

controllable loads

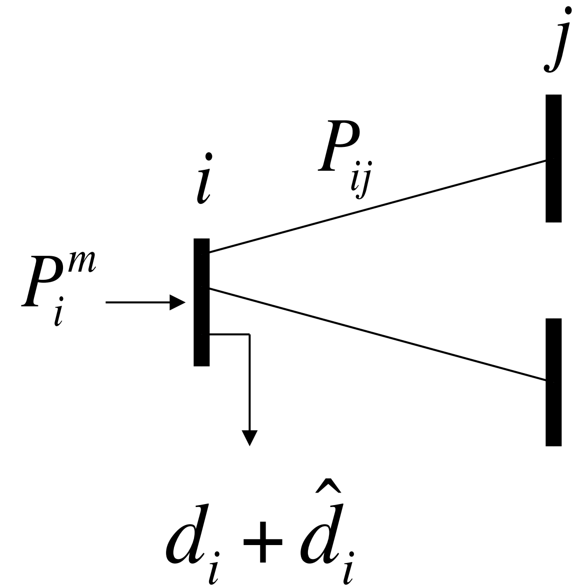
freq-sens loads

branch power flow

Dynamic model

Swing equation on bus i

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



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

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

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

linearization around nominal

Network model

Generator bus (may contain load):

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

Load bus (no generator):

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

Real branch power flow:

$$\dot{P}_{ij} = b_{ij}\left(\omega_i - \omega_j\right) \qquad \forall\ i \to j$$

swing dynamics

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Mallada, Low, 2013

Frequency control

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

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

$$\dot{P}_{ij} = b_{ij}\left(\omega_i - \omega_j\right) \qquad \forall\ i \to j$$

Suppose the system is in steady state

$$\dot{\omega}_i = 0 \qquad \dot{P}_{ij} = 0$$

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

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

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

$$\dot{P}_{ij} = b_{ij}\left(\omega_i - \omega_j\right) \qquad \forall\ i \to j$$

proposed approach

current approach

this talk: ignores generator-side control

Load-side controller design

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

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

$$\dot{P}_{ij} = b_{ij}\left(\omega_i - \omega_j\right) \qquad \forall\ i \to j$$

How to design feedback control law

$$d_i = F_i\left(\omega(t), P(t)\right)$$

Load-side controller design

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

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

$$\dot{P}_{ij} = b_{ij}\left(\omega_i - \omega_j\right) \qquad \forall\, i \to j$$

Control goals

Zhao, Topcu, Li, Low
TAC 2014

Mallada, Low 2013

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

Load-side controller design

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

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

$$\dot{P}_{ij} = b_{ij}\left(\omega_i - \omega_j\right) \qquad \forall\ i \to j$$

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

- simple, scalable
- decentralized/distributed

Load-side controller design

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

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

$$\dot{P}_{ij} = b_{ij}\left(\omega_i - \omega_j\right) \qquad \forall\, i \to j$$

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 Zhao, Topcu, Li, Low, TAC 2014
- Secondary control

Simulations

Optimal load control (OLC)

controllable load ↓   uncontrollable load ↓

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

over

s. t.

Optimal load control (OLC)

controllable load ↓ uncontrollable load ↓

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

$$\text{over} \quad \text{loads } d_l \in \left[\underline{d}_l, \overline{d}_l \right], \ \hat{d}_i$$

s. t

Optimal load control (OLC)

controllable load ↓   uncontrollable load ↓

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

$$\text{over} \quad \text{loads } d_l \in \left[\underline{d}_l, \bar{d}_l\right], \quad \hat{d}_i$$

$$\text{s.t.} \quad \sum_i \left(d_i + \hat{d}_i\right) = \sum_i P_i^m$$

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

controllable load ↓

freq-sens load ↓

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

$$\text{over} \quad \text{loads } d_l \in \left[\underline{d}_l, \overline{d}_l\right], \quad \hat{d}_i$$

$$\text{s.t.} \quad \sum_i \left(d_i + \hat{d}_i \right) = \sum_i P_i^m$$

demand = supply across network

Punchline

swing dynamics (recap)

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

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

implicit

load control

$$d_i(t) := \left[c_i^{'-1}\left(\omega_i(t)\right) \right]_{\underline{d}_i}^{\overline{d}_i}$$

active control

Punchline

Theorem

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

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

Zhao, Topcu, Li, Low, TAC 2014

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 $t \rightarrow \infty$

- $\left(d^*,\ \hat{d}^*\right)$ is unique optimal load control
- ω^* 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

- ω^*: 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 $\left(\omega^* \neq 0\right)$
- No ■ Restore scheduled inter-area flows

Proposed approach: forward engineering

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

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- Secondary control

Mallada, Low, 2013

Simulations

Freq preserving OLC

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

$$\text{s. t.} \quad \sum_i \left(d_i + \hat{d}_i \right) = \sum_i P_i^m$$

demand = supply
across network

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

$$\text{s. t.} \quad d_i + \hat{d}_i = P_i^m - \sum_{e \in E} C_{ie} P_e$$

demand = supply
per bus

$$d_i = P_i^m - \sum_{e \in E} C_{ie} R_e$$

to restore nominal
frequency

Recall primary control for OLC

swing dynamics:

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

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

implicit

load control: $d_i(t) := \left[c_i^{'-1}\left(\omega_i(t) \right) \right]_{\underline{d}_i}^{\overline{d}_i}$

active control

Recall primary control for OLC

swing dynamics:

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

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

implicit

load control: $d_i(t) := \left[c_i^{'-1}\left(\omega_i(t) + \lambda(t)_i\right)\right]_{\underline{d}_i}^{\overline{d}_i}$

computation & communication:

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

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 $t \to \infty$

- $\left(d^*,\ \hat{d}^*\right)$ 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 ~~No~~ — Restore nominal frequency $\left(\omega^* \neq 0\right)$
- No — Restore scheduled inter-area flows

Secondary control restores nominal frequency but requires communication with neighbors

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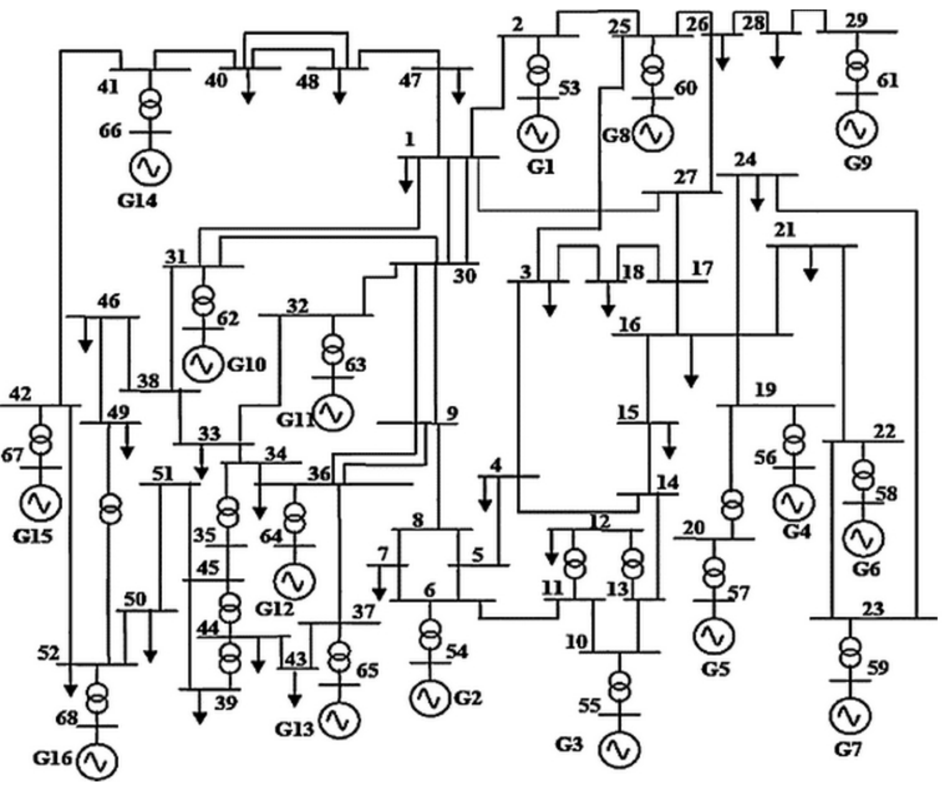
Zhao, Topcu, Li, Low, TAC 2014
Mallada, Low, 2013

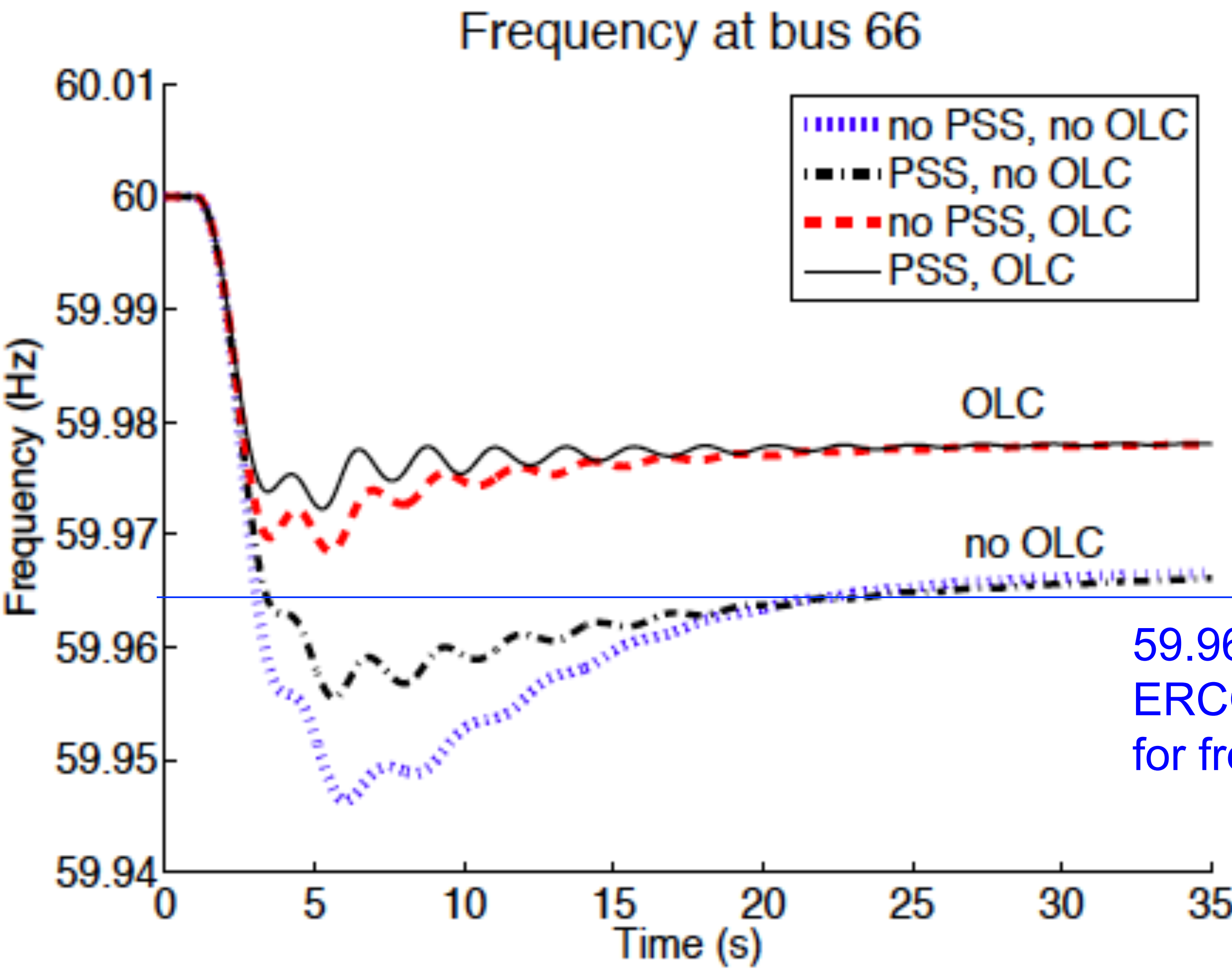
Simulations

Dynamic simulation of IEEE 68-bus system



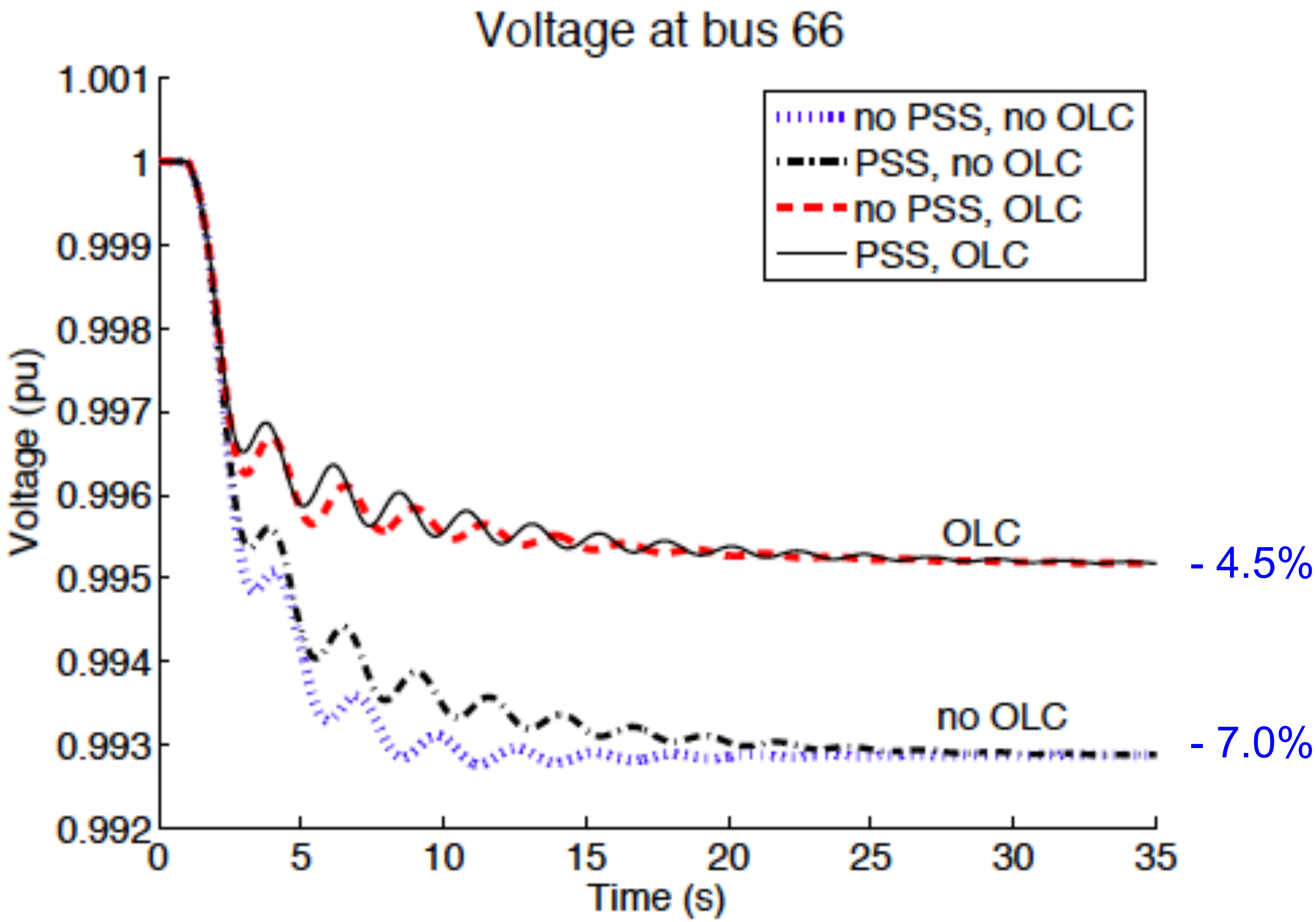
- Power System Toolbox (RPI)
- Detailed generation model
- Exciter model, power system stabilizer model
- Nonzero resistance lines

Simulations



59.964 Hz
ERCOT threshold
for freq control

Simulations



Simulations