Control and Optimization of Smart Grid

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Computing + Math Sciences
Electrical Engineering

Caltech

March 2015
Cornell Ithaca

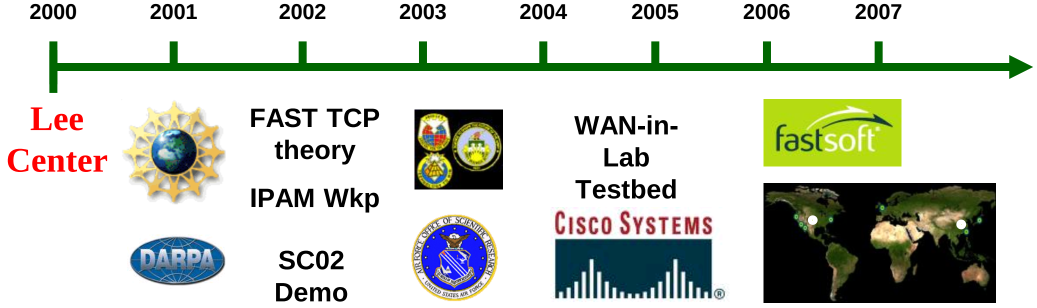
NetLab

prof steven low

Lee Center

rsrg SISL

Caltech FAST Project



2000 2001 2002 2003 2004 2005 2006 2007

Lee Center

DARPA

FAST TCP theory

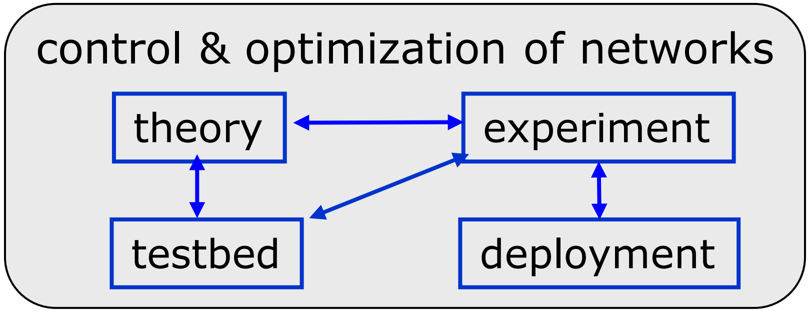
IPAM Wkp

SC02 Demo

WAN-in-Lab Testbed

Cisco Systems

fastsoft



control & optimization of networks

theory

experiment

testbed

deployment

Collaborators: Profs Doyle (Caltech), Newman (Caltech), Paganini (Uruguay), Tang (Cornell), Andrew (Swinburne), Chiang (Princeton);
CACR, CERN, Internet2, SLAC, Fermi Lab, StarLight, Cisco, Level(3)

theory

Internet: largest distributed nonlinear feedback control system

Reverse engineering: TCP is real-time distributed algorithm over Internet to maximize utility

$$\max_{x\geq 0} \sum U_i(x_i) \quad \text{s.t.} \quad Rx \leq c$$

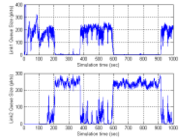
Forward engineering: Invention of FastTCP based on control theory & convex optimization

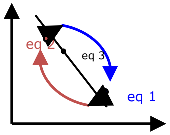
$$\dot{x}_i = \frac{\gamma_i}{T_i}\left(\alpha_i - x_i(t)\sum_l R_{li}\, p_l(t)\right)$$

$$\dot{p}_l = \frac{1}{c_l}\left(\sum_i R_{li}\, x_i(t) - c_l\right)$$

testbed

WAN-in-Lab : one-of-a-kind wind-tunnel in academic networking, with 2,400km of fiber, optical switches, routers, servers, accelerators





experiment

Scientists have used FastTCP to break world records on data transfer between 2002 – 2006

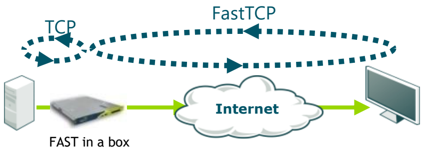

SC 2004

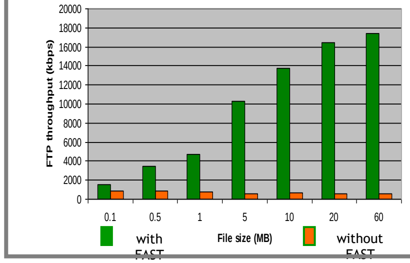
Internet2 LSR
SuperComputing BC

NATIONAL GEOGRAPHIC · BBC · The Economist · nature · THE AUSTRALIAN · COMPUTERWORLD · NewScientist · BusinessWeek · YAHOO! · PC MAGAZINE · MSNBC · REUTERS · CNN · cnet

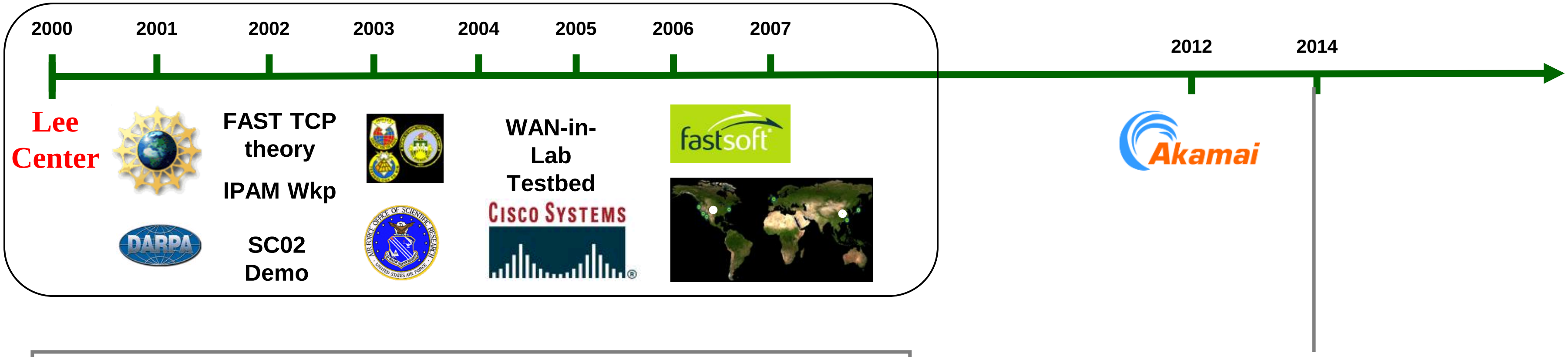
deployment

FAST is commercialized by FastSoft; it accelerates world's 2nd largest CDN and Fortune 100 companies





Caltech FAST Project



accelerating largest social networks, studios, and other Fortune 100 companies

GOLF CHANNEL · facebook · LinkedIn · Zappos.com · myspace.com · HONDA · ANIMAL LOGIC · Distinguished Programs · Beta · i-One · 20th Century Fox · gettyimages · Limelight Networks · NetDNA · BELKIN · Insight · GREY group · Microsoft · Symantec · ChinaCache · INTERNAP · HIGHWINDS · Symantec · CAPSILON · BRUSH WELLMAN · PIE · ESPN · BAE SYSTEMS · zazzle · filesanywhere · shopzilla · Disney · overstock.com · YARDI · ReSourcePro · PAÏKO · TECHNICOLOR by THOMSON · STARGATE STUDIOS · PAR · CambridgeSoft · ALLANGRAY · Wonderware · dish NETWORK · abbaKan · INTIER · Polysius ThyssenKrupp · Raytheon · EMC² · ib Internet Brands · SAMPLE DIGITAL · SIRCA · SpotGenie · X-O digital · finsphere · CNLink · VIRTUAL RADIOLOGIC · DataLine

“FAST TCP is accelerating >1TB of internet traffic every second !”

Vision (20+ yrs)

Global energy demand will continue to grow

Traditional supply is unsustainable

There is more renewable energy than the world ever needs

- Someone will figure out how to capture and store it

There will be connected intelligence everywhere

- Cost of computing, storage, communication and manufacturing will continue to drop

➔ Power system will transform into the largest and most complex Internet of Things

- Generation, transmission, distribution, consumption, storage

Mission

To develop technologies that will enable and guide the historic transformation of our power system

- Generation, transmission, distribution, consumption, storage
- Devices, systems, theory, algorithms
- Control, optimization, stochastics, data, economics

Outline

Overview & challenges

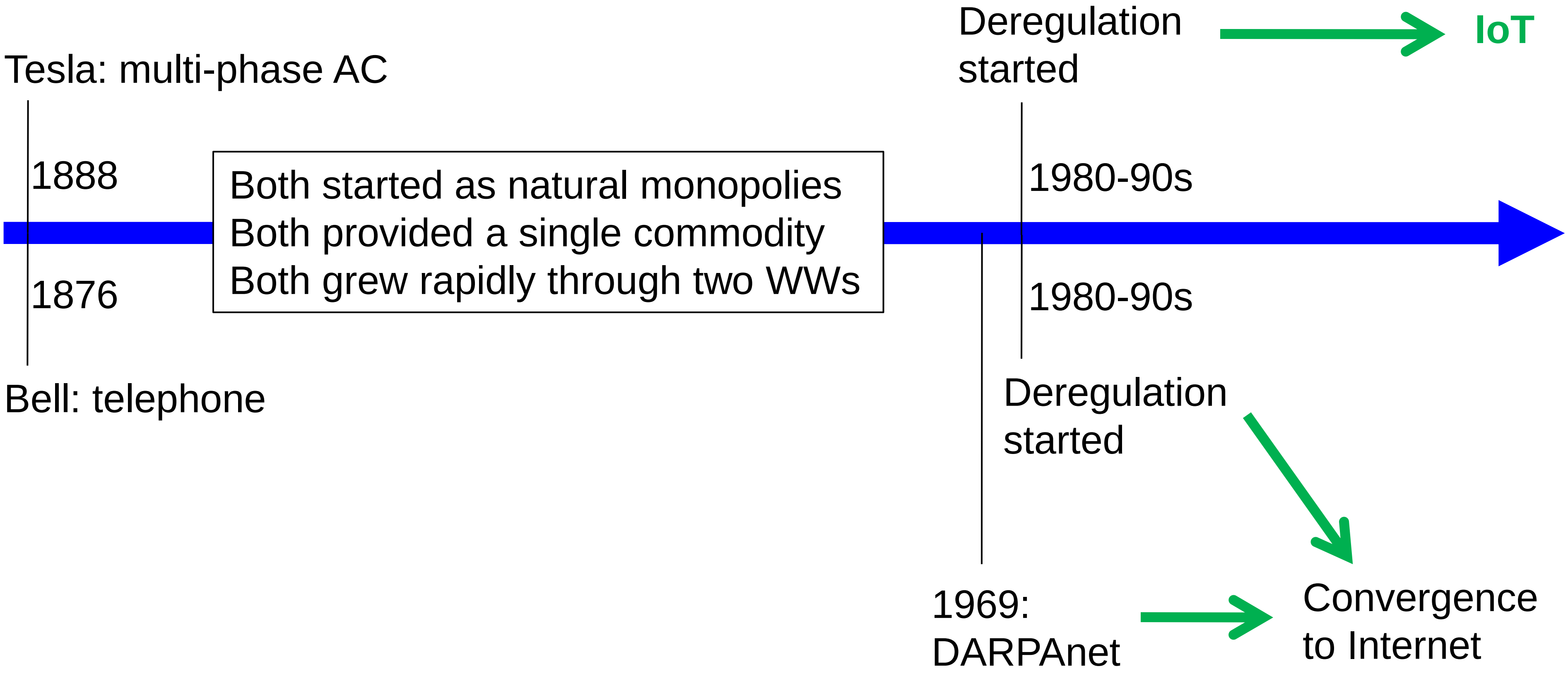
Optimal power flow

Frequency regulation

Applications

Watershed moment

Power network will undergo similar **architectural transformation** that phone network went through in the last two decades



Tesla: multi-phase AC

1888

1876

Bell: telephone

Both started as natural monopolies
Both provided a single commodity
Both grew rapidly through two WWs

Deregulation started

1980-90s

IoT

1980-90s

Deregulation started

1969: DARPAnet

Convergence to Internet

Watershed moment

Industries will be destroyed & created

AT&T, MCI, McCaw Cellular, Qualcom

Google, Facebook, Twitter, Amazon, eBay, Netflix

Infrastructure will be reshaped

Centralized intelligence, vertically optimized

Distributed intelligence, layered architecture

What will drive power network transformation ?

Four drivers

Proliferation of renewables

Electrification of transportation

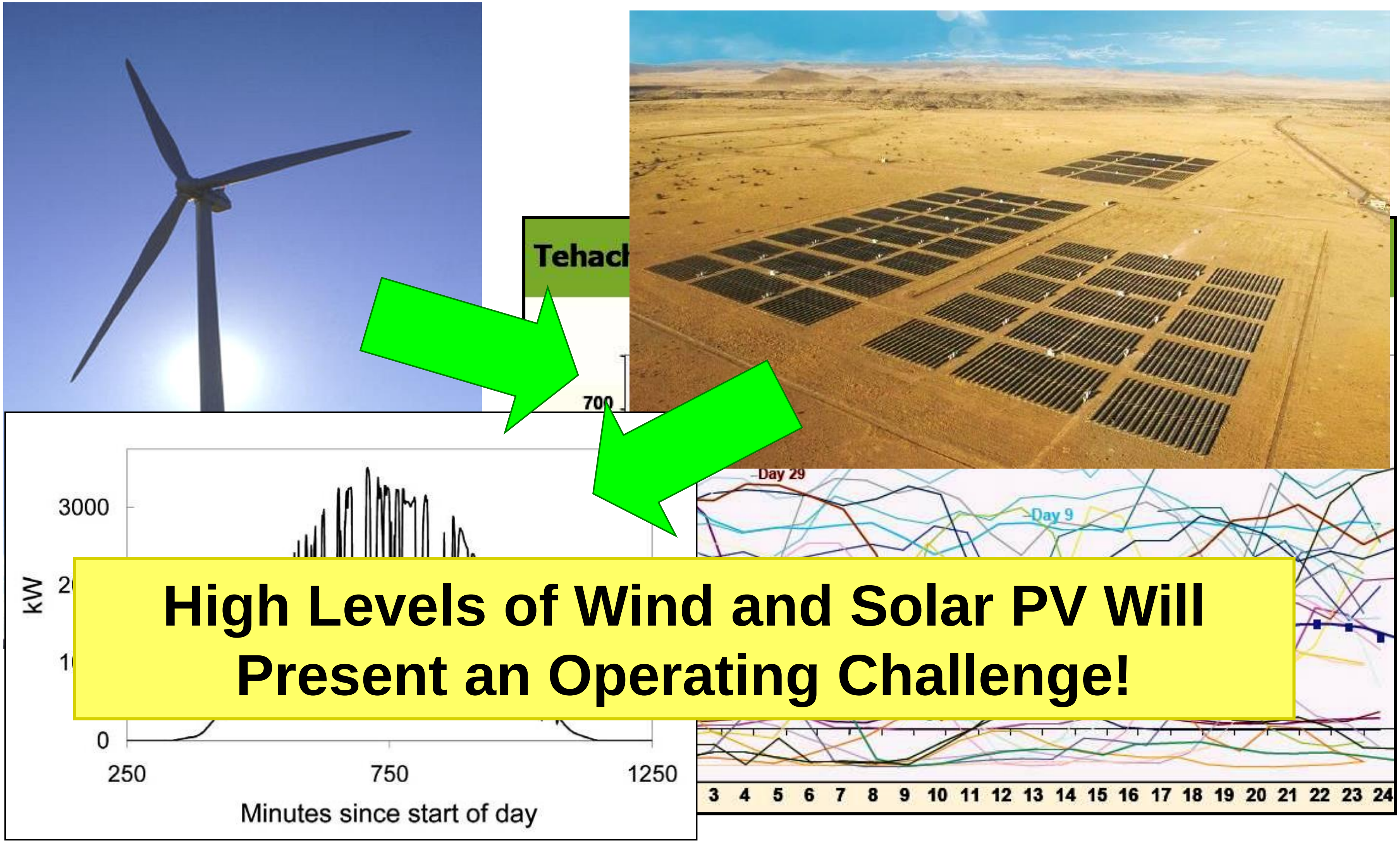
challenges

Advances in power electronics

Deployment of sensing, control, comm

enablers

Uncertainty

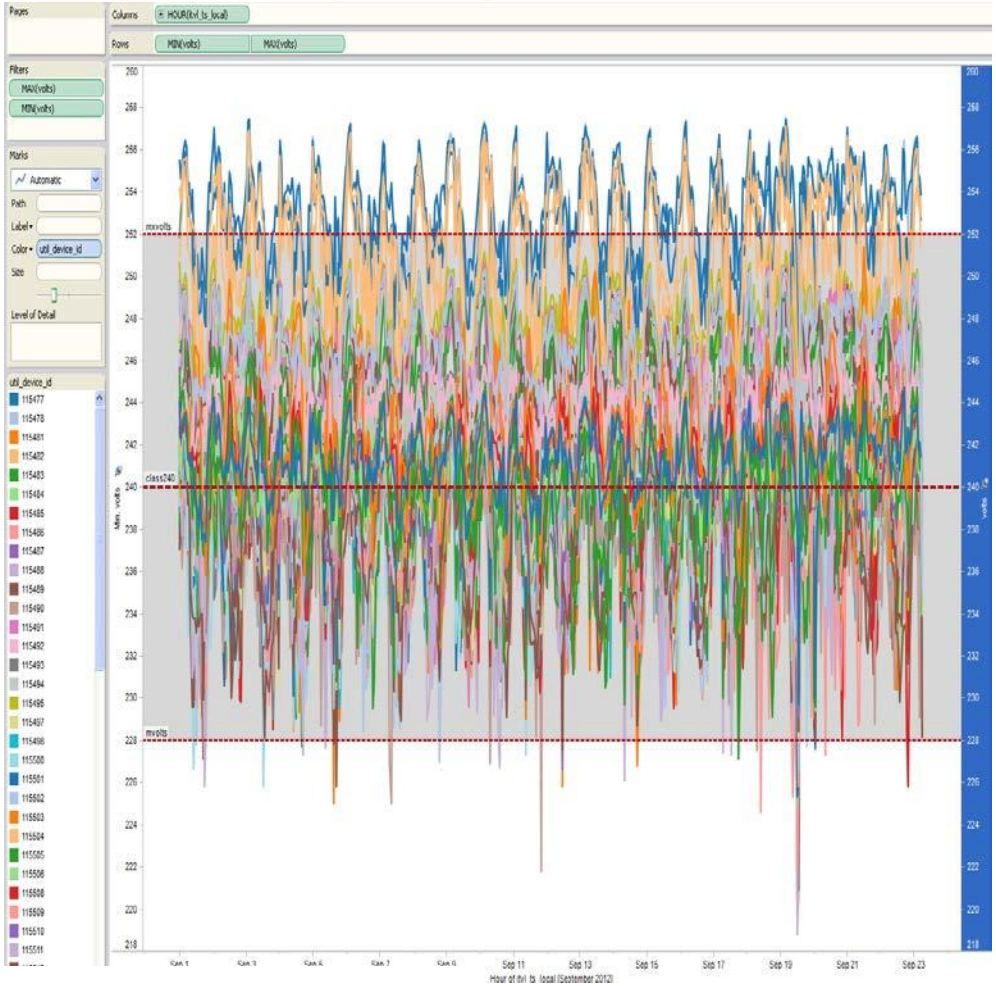


High Levels of Wind and Solar PV Will Present an Operating Challenge!

Source: Rosa Yang, EPRI

Hourly Voltage Overview[1]

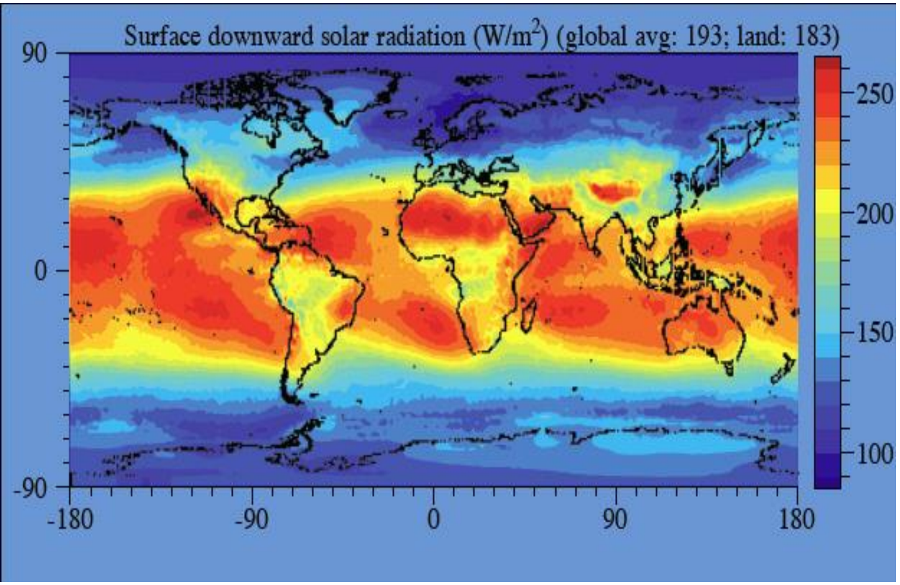
- 68 meters (residential)
- Sept 2012 (23 days)
- 240 volts
- +-5% min-228/max-252
- Hourly by meter #
- A few “high” meters
- Larger # of low meters

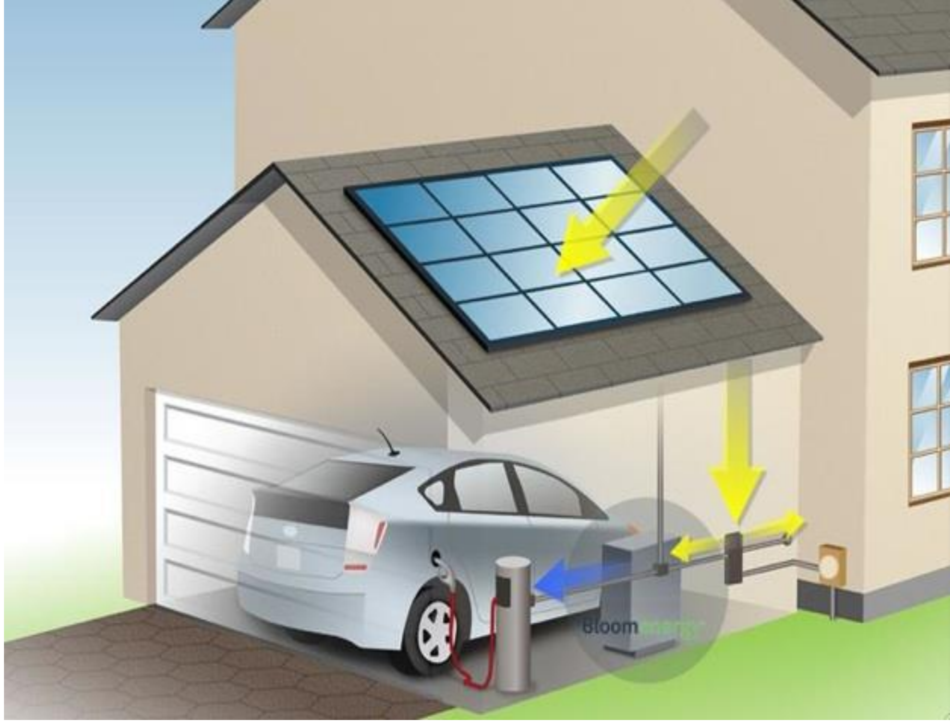


Voltage violations are quite frequent

Source: Leon Roose, University of Hawaii
Development & demo of smart grid inverters for high-penetration PV applications

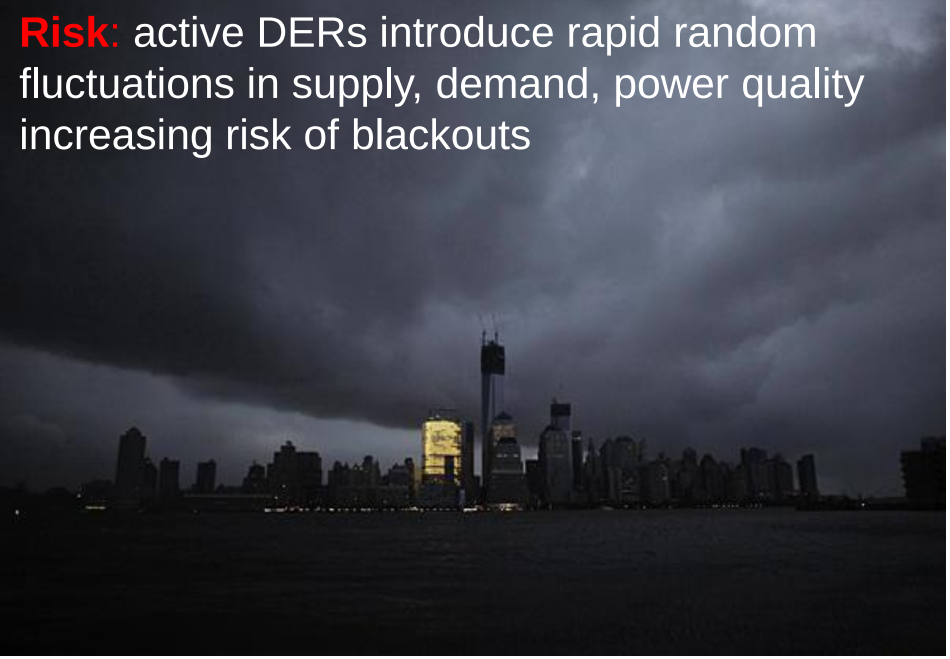
Solar power over land:
> 20x world energy demand





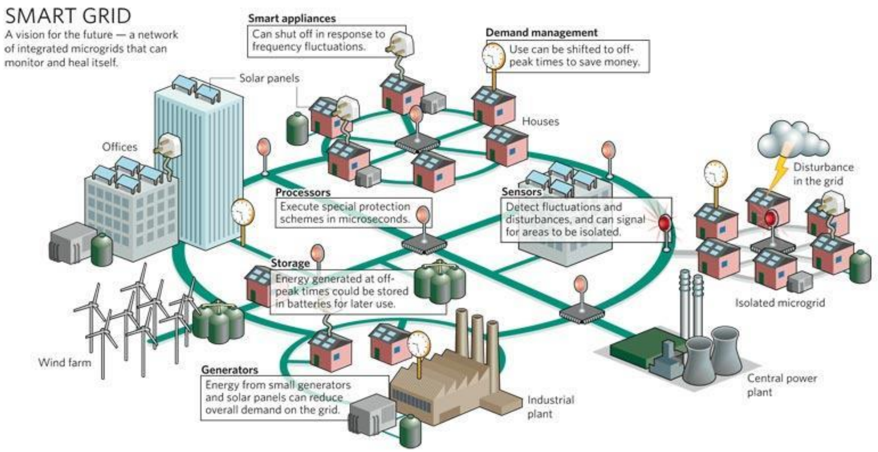
network of
billions of active
distributed energy
resources (DERs)

DER: PV, wind tb, EV, storage, smart appliances

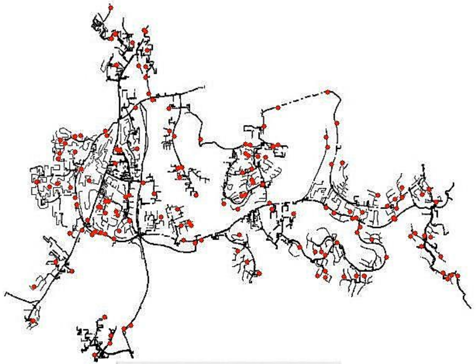


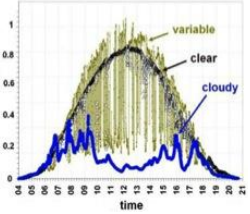
Risk: active DERs introduce rapid random fluctuations in supply, demand, power quality increasing risk of blackouts

Opportunity: active DERs enables realtime dynamic network-wide feedback control, improving robustness, security, efficiency



Caltech research: distributed control of networked DERs





- Foundational theory, practical algorithms, concrete applications
- Integrate engineering and economics
- Active collaboration with industry

NSF arpa·e SOUTHERN CALIFORNIA EDISON RESNICKINSTITUTE science + energy + sustainability CISCO SYSTEMS

Active DERs: implications

Current control paradigm works well today

- Centralized, open-loop, human-in-loop, worst-case preventive
- Low uncertainty, few active assets to control
- Schedule supplies to match loads

Future needs

- Closing the loop, e.g. real-time DR, volt/var
- Fast computation to cope with rapid, random, large fluctuations in supply, demand, voltage, freq
- Simple algorithms to scale to large networks of active DER
- Market mechanisms to incentivize

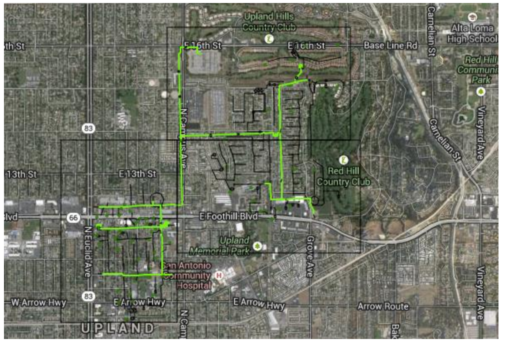
Need for distributed control

Example: Southern California Edison

- 4-5 million customers

SCE Rossi feeder circuit

- #houses: 1,407; #commercial/industrial: 131
- #transformers: 422
- #lines: 2,064 (multiphase, inc. transfomers)
- peak load: 3 – 6 MW
- #optimization variables: 50,000



SCE has 4,500 feeders

- ~100M variables

United States

- 131M customers, 300K miles of transmission & distr lines, 3,100 utilities

Key challenges

Nonconvexity

- Convex relaxations

Large scale

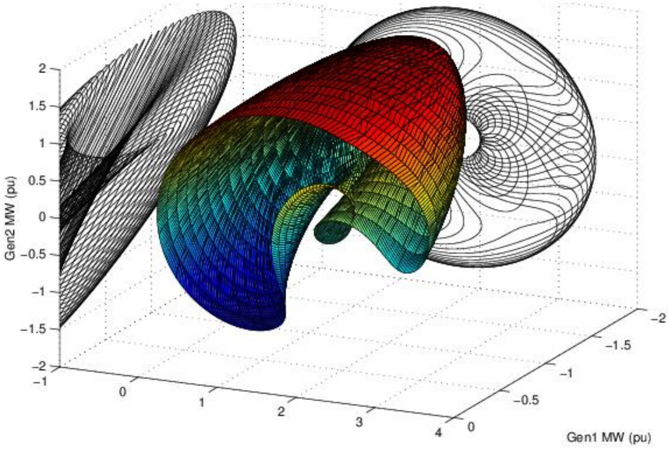
- Distributed algorithms

Uncertainty

- Risk-limiting approach

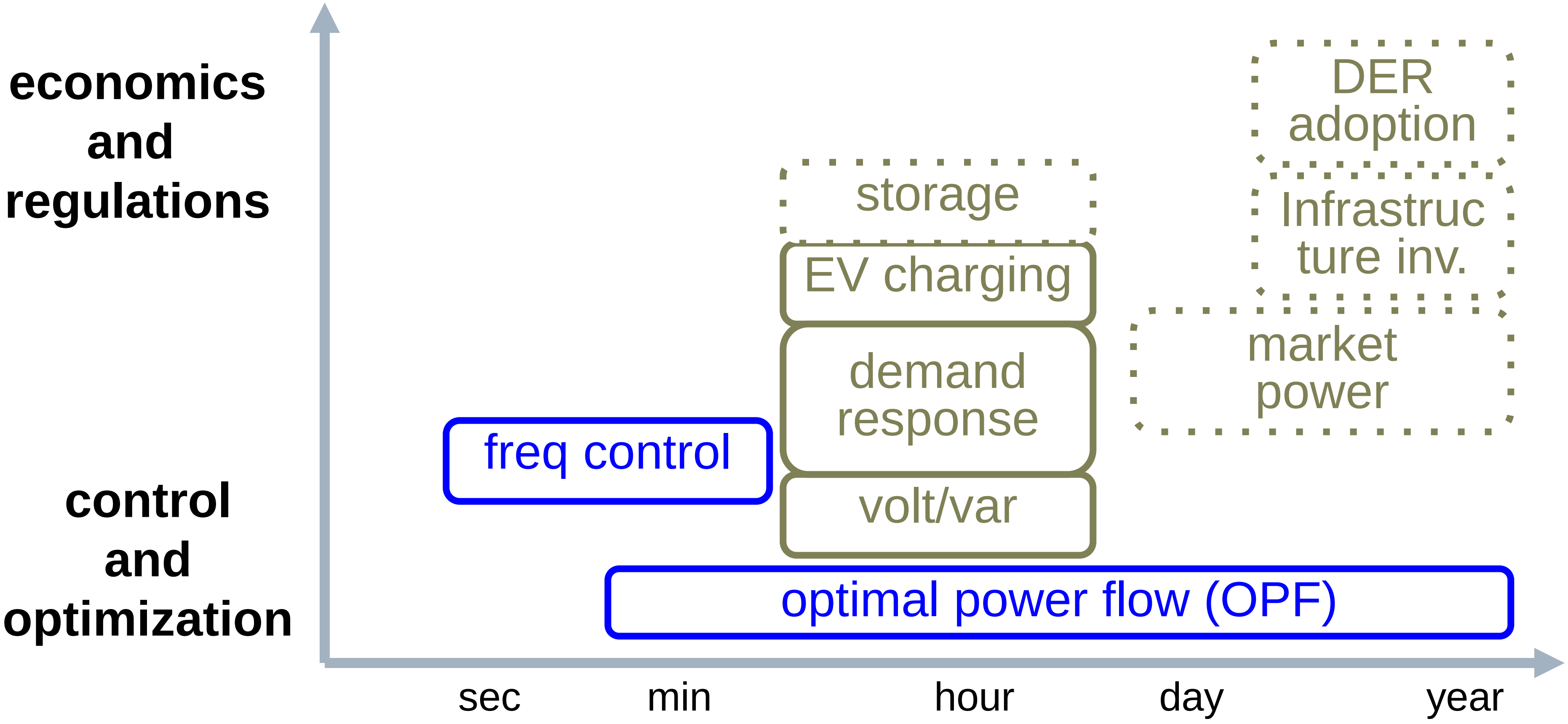
Multiple timescales

- Decomposition



Ian Hiskens, Michigan

Our research



economics and regulations

control and optimization

DER adoption

storage

Infrastructure inv.

EV charging

market power

demand response

freq control

volt/var

optimal power flow (OPF)

sec

min

hour

day

year

Outline

Overview & challenges

Optimal power flow (OPF)

- problem formulation
- semidefinite relaxations
- exact relaxation

Frequency regulation

Applications

Optimal power flow (OPF)

OPF is solved routinely for

- network control & optimization decisions
- market operations & pricing
- at timescales of mins, hours, days, …

Non-convex and hard to solve

- Huge literature since Carpentier 1962
- Common practice: DC power flow (LP)
- Also: Newton-Raphson, interior point, …

Optimal power flow (OPF)

OPF underlies many applications

- Unit commitment, economic dispatch
- State estimation
- Contingency analysis
- Feeder reconfiguration, topology control
- Placement and sizing of capacitors, storage
- Volt/var control in distribution systems
- Demand response, load control
- Electric vehicle charging
- Market power analysis
- …

Nonconvexity of OPF

Semidefinite relaxations of power flows

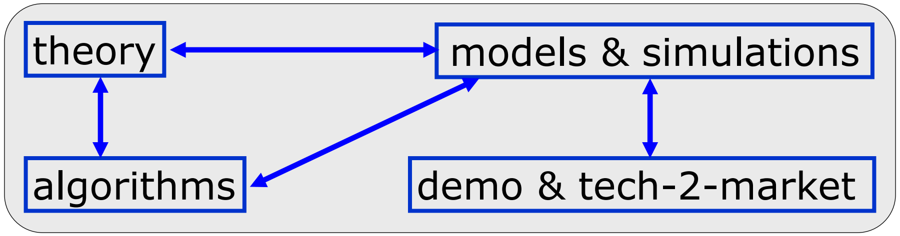
- Physical systems are nonconvex …
- … but have hidden convexity that should be exploited

Convexity is important for OPF

- Foundation of LMP, critical for efficient market theory
- Required to guarantee global optimality
- Required for real-time computation at scale

Distributed Control of Networked DER

an arpa·e GENI project



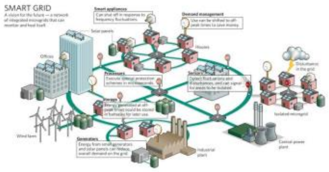
theory

models & simulations

algorithms

demo & tech-2-market

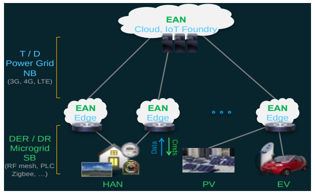
Caltech: Profs Chandy, Doyle, **Low (PI)**; Drs. Bunn, Mallada; Students: Agarwal, Cai, Chen, Farivar, Gan, Guo, Matni, Peng, Ren,Tang, You, Zhao
SCE: Auld, Castaneda, Clarke, Gooding, Montoya, Shah, **Sherick (PI)**
Newport/Caltech: DeMartini (advisor)
Alumni: Bose (Cornell), Chen (Colorado), Collins (USC), Gayme (JHU), Lavaei (Columbia), Li (Harvard), Topcu (UPenn), Xu (SUTD)



EAN
Energy Adaptive Networks Corp

- Increase asset utilization and efficiency
- Improve power quality and stability
- Move data in motion analytics to edge

- EAN analytics and optimization
  DER placement, asset opt, analytics
- EAN enabled control
  DER co-optimization, frequency reg



Contact: **Michael Enescu**, co-founder CEO, enescu@alumni.caltech.edu

applications and T2M

theory

Convex relaxation of OPF: Theoretical foundation for semi-definite relaxations of power flow

OPF:

$$\min_{V} \ \operatorname{tr}\left(CVV^*\right)$$

$$\text{s. t.} \quad \underline{s}_j \le \operatorname{tr}\left(Y_j^* V V^*\right) \le \overline{s}_j, \quad \underline{v}_j \le \left|V_j\right|^2 \le \overline{v}_j$$

SDP relaxation

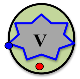
quadratic in V
linear in W !

$$\min_{W} \ \operatorname{tr}\left(CW\right)$$

$$\text{s. t.} \quad \underline{s}_j \le \operatorname{tr}\left(Y_j^* W\right) \le \overline{s}_j, \quad \underline{V}_j \le W_{jj} \le \overline{V}_j$$

$$W \succeq 0, \quad \boxed{\operatorname{rank} W = 1}$$

ignore this (only) nonconvex constr

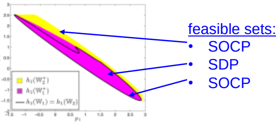


Exact relaxations: Sufficient conditions for recovering global optimum of OPF from relaxations

algorithms

Relaxation algorithms:

- single-phase balanced, multiphase unbalanced
- centralized, distributed



feasible sets:
- SOCP
- SDP
- SOCP

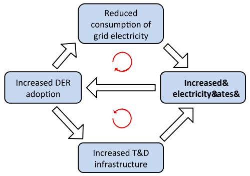
$$\begin{tikzcd}
\mathbf{V} \arrow[d, leftrightarrow] & & \\
\mathbf{W} \arrow[r, leftrightarrow] \arrow[d, shift right] & \mathbf{W}_{c(G)} \arrow[r, leftrightarrow] \arrow[d, shift right, "\text{relaxation}"'] & \mathbf{W}_G \arrow[d, shift right] \\
\mathbf{W}^+ \arrow[u, shift right] \arrow[r, leftrightarrow] & \mathbf{W}^+_{c(G)} \arrow[u, shift right, "\text{exact recovery}"'] \arrow[r, leftrightarrow, "\text{radial}"] & \mathbf{W}^+_G \arrow[u, shift right]
\end{tikzcd}$$

SDP relaxation	Chordal relaxation	SOCP relaxation
• tightest superset	• equivalent superset	• coarsest superset
• max # variables	• much faster for sparse networks	• min # variables
• slowest		• fastest

models

DER adoption model & software

- Sophisticated feedback model
- Cloud service for PV-uptake: http://etechuptake.appspot.com/



Reduced consumption of grid electricity

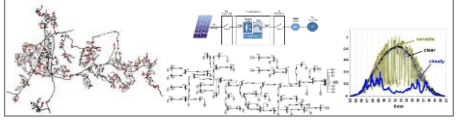
Increased electricity rates

Increased T&D infrastructure

Increased DER adoption

volt/var control with renewables

- SCE circuits, DER forecasts
- advanced OPF solver

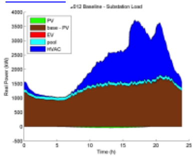


simulations

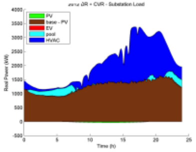
Realistic simulations

- SCE feeder model, 2,000 buses
- DER: inverters, HVAC, pool pumps, EV
- Multiphase unbalanced radial

baseline

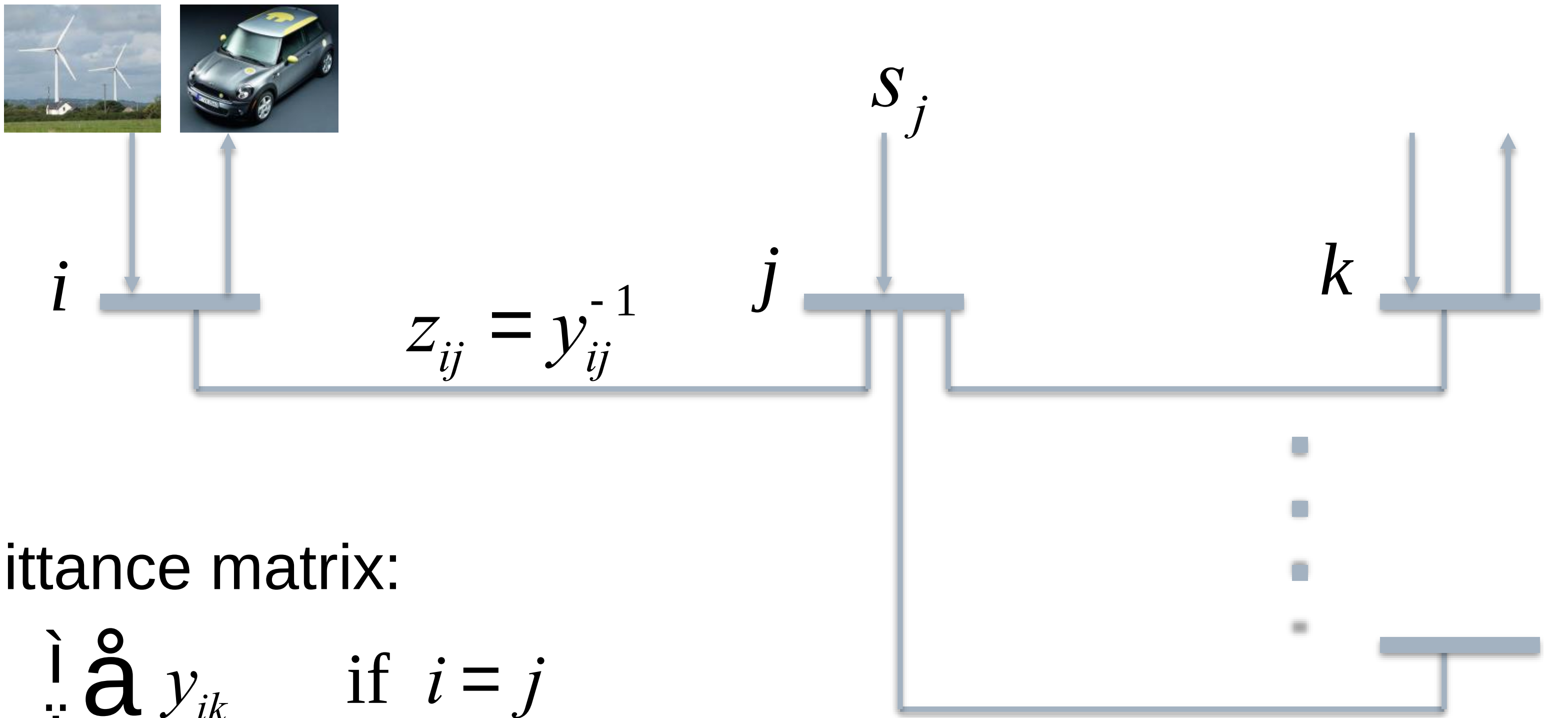


optimized



Lead: Prof Mushkin
Undergrads: Chang, Li, Yap, Zhou

Bus injection model



admittance matrix:

$$Y_{ij} := \begin{cases} \sum_{k\sim i} y_{ik} & \text{if } i = j \\ -y_{ij} & \text{if } i \sim j \\ 0 & \text{else} \end{cases}$$

graph G: undirected

Y specifies topology of G and impedances z on lines

Bus injection model

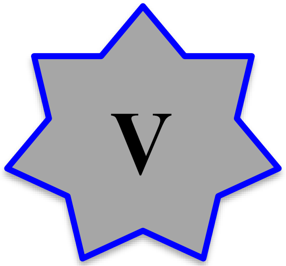
In terms of V:

$$s_j = \mathrm{tr}\left(Y_j^H V V^H\right) \qquad \text{for all } j$$

$$Y_j = Y^H e_j e_j^T$$

Power flow problem:

Given (Y, s) find V



isolated solutions

OPF: bus injection model

min $\operatorname{tr}\left(CVV^H\right)$

gen cost,
power loss

over $\left(V, s\right)$

subject to $\underline{s}_j$ £ s_j £ $\overline{s}_j$ $\underline{V}_j$ £ $|V_j|$ £ $\overline{V}_j$

OPF: bus injection model

$$\min \quad \mathrm{tr}\left(CVV^H\right)$$

gen cost,
power loss

$$\text{over} \quad (V, s)$$

$$\text{subject to} \quad \underline{s}_j \le s_j \le \bar{s}_j \qquad \underline{V}_j \le |V_j| \le \overline{V}_j$$

$$\boxed{s_j = \mathrm{tr}\left(Y_j^H V V^H\right)}$$

power flow equation

OPF: bus injection model

$$\begin{aligned} \min \quad & \operatorname{tr} CVV^H \\ \text{subject to} \quad & \underline{s}_j \le \boxed{\operatorname{tr}\left(Y_j V V^H\right)} \le \bar{s}_j \qquad \underline{v}_j \le |V_j|^2 \le \bar{v}_j \end{aligned}$$

nonconvex QCQP

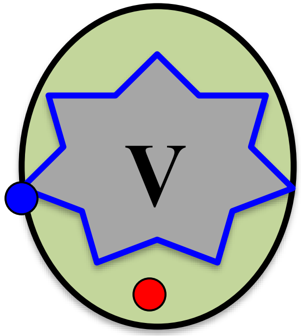
(quad constrained quad program)

Semidefinite relaxations of OPF

relaxation	model	first proposed	first analyzed
SOCP	BIM	Jabr 2006 TPS	
SDP	BIM	Bai et al 2008 EPES	Lavaei, Low 2012 TPS Bose et al 2011, 2015 Zhang, Tse 2011, 2013 Sojoudi, Lavaei 2012
Chordal	BIM	Bai, Wei 2011 EPES Jabr 2012 TPS	Molzahn et al 2013 TPS Bose et al 2014 TAC
SOCP	BFM	Farivar et al 2011 SGC Farivar, Low 2013 TPS	Farivar et al 2011 SGC Farivar, Low 2013 TPS Gan et al 2012, 2014
Chordal unbalanced	BFM	Gan, Low 2014 PSCC	Gan, Low 2014 PSCC

Tutorial with extensive refs:
Low. Convex relaxation of OPF (I, II), IEEE Trans Control of Network Systems, 2014

Basic idea



$$\begin{aligned} \min \quad & \operatorname{tr} CVV^H \\ \text{subject to} \quad & \underbrace{\underline{s}_j \le \operatorname{tr}\left(Y_j V V^H\right) \le \bar{s}_j \qquad \underline{v}_j \le |V_j|^2 \le \bar{v}_j}_{\mathbf{V}} \end{aligned}$$

Approach

1. Three equivalent characterizations of **V**
2. Each suggests a lift and relaxation

- What is the relation among different relaxations ?
- When will a relaxation be exact ?

Feasible set & SDP

$$\min \quad \operatorname{tr} CVV^H$$

$$\text{subject to} \quad \underline{s}_j \;\pounds\; \boxed{\operatorname{tr}\left(Y_j VV^H\right)} \;\pounds\; \bar{s}_j \qquad \underline{v}_j \;\pounds\; |V_j|^2 \;\pounds\; \bar{v}_j$$

quadratic in V
linear in W

Equivalent problem:

$$\min \quad \operatorname{tr} CW$$

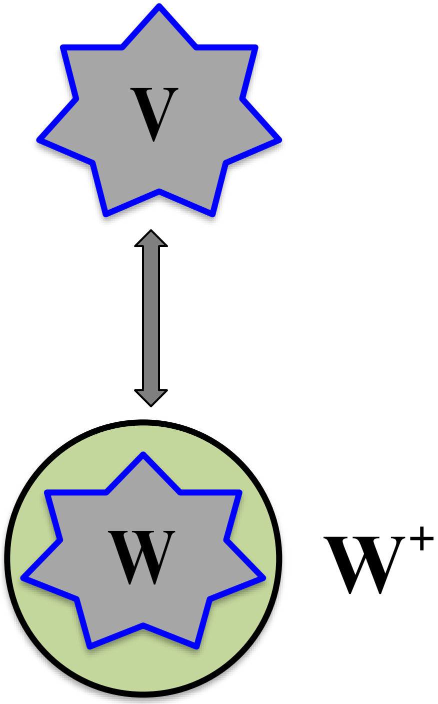
$$\text{subject to} \quad \boxed{\underline{s}_j \pounds \operatorname{tr}\left(Y_j W\right) \pounds \bar{s}_j \qquad \underline{v}_i \pounds W_{ii} \pounds \bar{v}_i}$$

$$W \;^3\; 0, \quad \operatorname{rank} W = 1$$

convex in W
except this constraint

Equivalent feasible sets

$$\mathbf{V} := \{ V : \underline{\text{quadratic}}\ \text{constraints} \}$$



QCQP: *n* variables

SDP: n^2 vars !

$$\mathbf{W} := \{ W : \underline{\text{linear}}\ \text{constraints} \} \cap \{ W \geq 0\ \cancel{\text{rank-1}} \}$$

idea: $W = VV^H$

Equivalent feasible sets

$$\mathbf{W}_{c(G)} := \left\{ W_{c(G)} : \ \underline{\text{linear}} \text{ constraints } \right\}$$

$$\text{idea: } \ W_{c(G)} = \left(VV^H \ \text{ on } c(G) \right)$$

$$\mathbf{W} := \left\{ W : \underline{\text{linear}} \text{ constraints } \right\} \cap \left\{ W \geq 0 \text{ rank-1} \right\}$$

$$\text{idea: } \ W = VV^H$$

Equivalent feasible sets

$$\mathbf{W}_{c(G)} := \left\{ W_{c(G)} : \ \underline{\text{linear}} \text{ constraints } \right\} \cap \left\{ W_{c(G)} \geq 0 \text{ rank-1} \right\}$$

$$\text{idea: } \ W_{c(G)} = \left(VV^H \text{ on } c(G) \right)$$

$$\mathbf{W} := \left\{ W : \underline{\text{linear}} \text{ constraints } \right\} \cap \left\{ W \geq 0 \text{ rank-1} \right\}$$

$$\text{idea: } \ W = VV^H$$

Equivalent feasible sets

$$\mathbf{W}_G := \left\{ W_G : \underline{\text{linear}} \text{ constraints } \right\}$$

$$\text{idea: } W_G = \left(VV^H \text{ only on } G \right)$$

$$\mathbf{W}_{c(G)} := \left\{ W_{c(G)} : \underline{\text{linear}} \text{ constraints } \right\} \cap \left\{ W_{c(G)} \geq 0 \text{ rank-1} \right\}$$

$$\text{idea: } W_{c(G)} = \left(VV^H \text{ on } c(G) \right)$$

$$\mathbf{W} := \left\{ W : \underline{\text{linear}} \text{ constraints } \right\} \cap \left\{ W \geq 0 \text{ rank-1} \right\}$$

$$\text{idea: } W = VV^H$$

Equivalent feasible sets

$$\mathbf{W}_G := \left\{W_G : \underline{\text{linear}} \text{ constraints } \right\} \cap \begin{Bmatrix} W(j,k) \geq 0 \text{ rank-1}, \\ \text{cycle cond on } \angle W_{jk} \end{Bmatrix}$$

$$\text{idea: } W_G = \left(VV^H \text{ only on } G\right)$$

$$\mathbf{W}_{c(G)} := \left\{W_{c(G)} : \underline{\text{linear}} \text{ constraints } \right\} \cap \left\{W_{c(G)} \geq 0 \text{ rank-1}\right\}$$

$$\text{idea: } W_{c(G)} = \left(VV^H \text{ on } c(G)\right)$$

$$\mathbf{W} := \left\{W : \underline{\text{linear}} \text{ constraints } \right\} \cap \left\{W \geq 0 \text{ rank-1}\right\}$$

$$\text{idea: } W = VV^H$$

Cycle condition

local

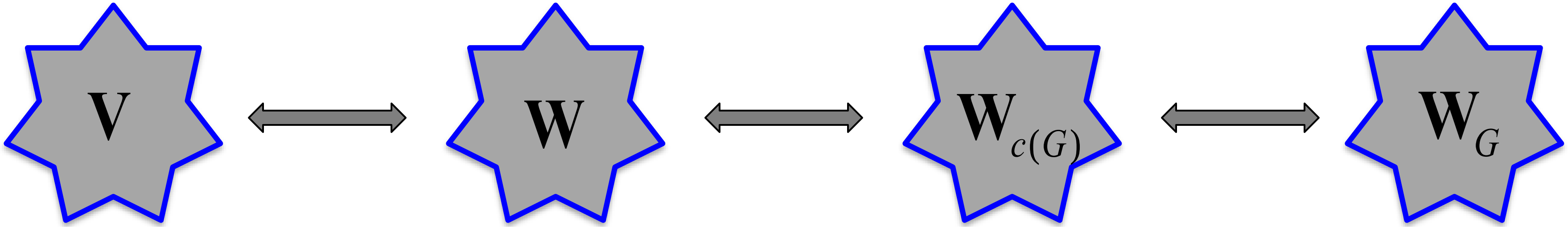
$$W_G(j,k) \succeq 0, \;\; \text{rank}\; W_G(j,k) = 1, \quad (j,k) \in E$$

global

$$\sum_{(j,k)\in c} \text{Đ}\left[W_G\right]_{jk} = \quad 0 \qquad \text{mod}\; 2\pi$$

← cycle cond

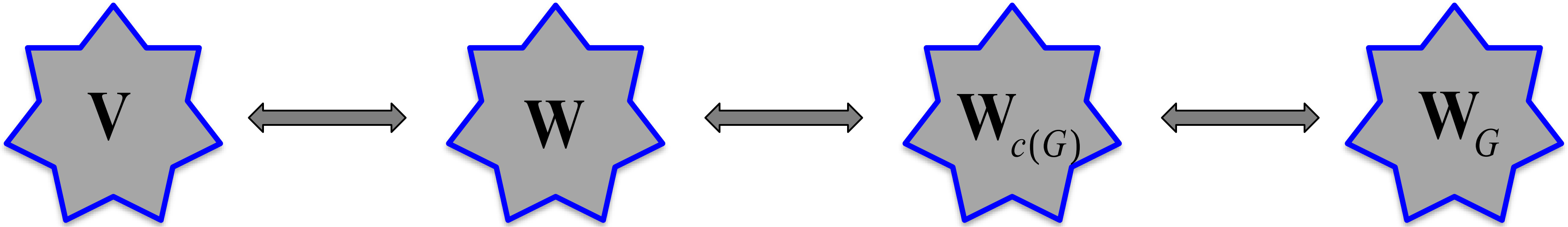
Equivalent feasible sets



Theorem: $\mathbf{V}\ ^{\mathrm{o}}\ \mathbf{W}\ ^{\mathrm{o}}\ \mathbf{W}_{c(G)}\ ^{\mathrm{o}}\ \mathbf{W}_G$

Bose, Low, Chandy Allerton 2012
Bose, Low, Teeraratkul, Hassibi TAC2014

Equivalent feasible sets



Theorem: $\mathbf{V}$ º $\mathbf{W}$ º $\mathbf{W}_{c(G)}$ º $\mathbf{W}_G$

Given W_G Î $\mathbf{W}_G$ or $W_{c(G)}$ Î $\mathbf{W}_{c(G)}$ there is unique completion W Î $\mathbf{W}$ and unique V Î $\mathbf{V}$

Can minimize cost over **any** of these sets, but …

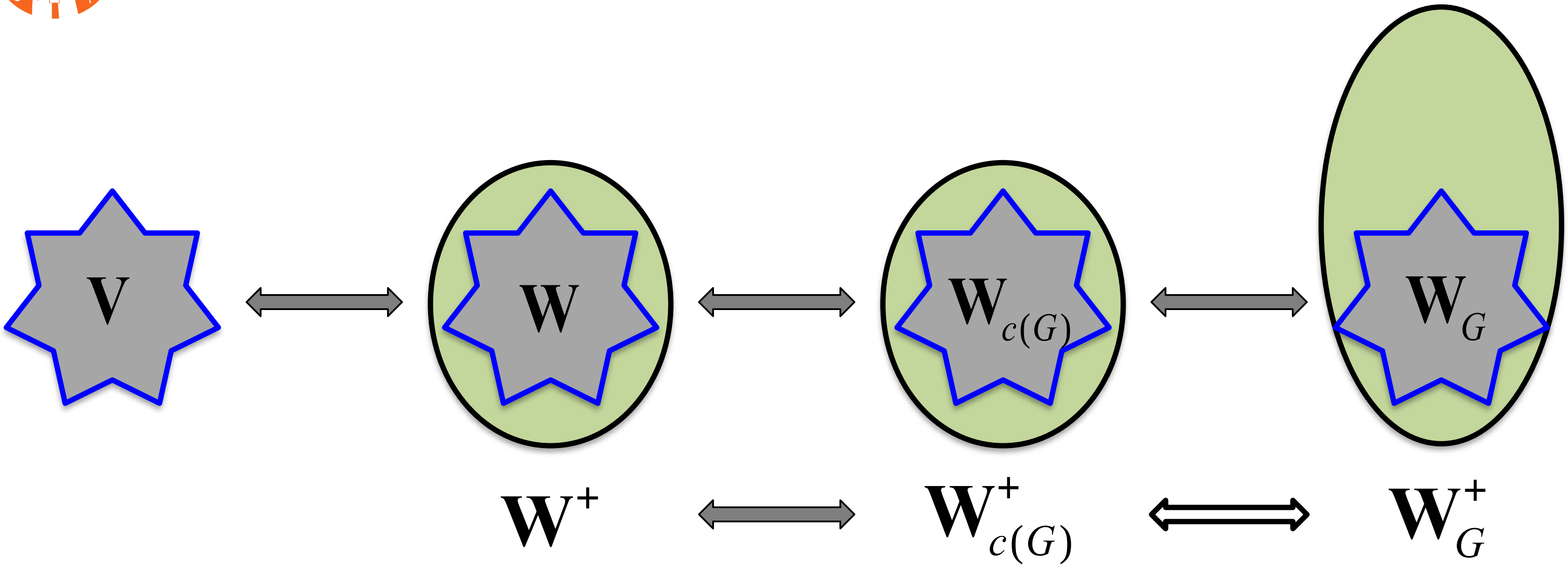
Equivalent feasible sets

$$\mathbf{W}_G := \left\{W_G : \underline{\text{linear}} \text{ constraints}\right\} \cap \left\{\begin{matrix} W(j,k) \geq 0 \ \cancel{\text{rank-1}}, \\ \cancel{\text{cycle cond on } \angle W_{jk}} \end{matrix}\right\}$$

$$\mathbf{W}_{c(G)} := \left\{W_{c(G)} : \underline{\text{linear}} \text{ constraints}\right\} \cap \left\{W_{c(G)} \geq 0 \ \cancel{\text{rank-1}}\right\}$$

$$\mathbf{W} := \left\{W : \underline{\text{linear}} \text{ constraints}\right\} \cap \left\{W \geq 0 \ \cancel{\text{rank-1}}\right\}$$

Relaxations

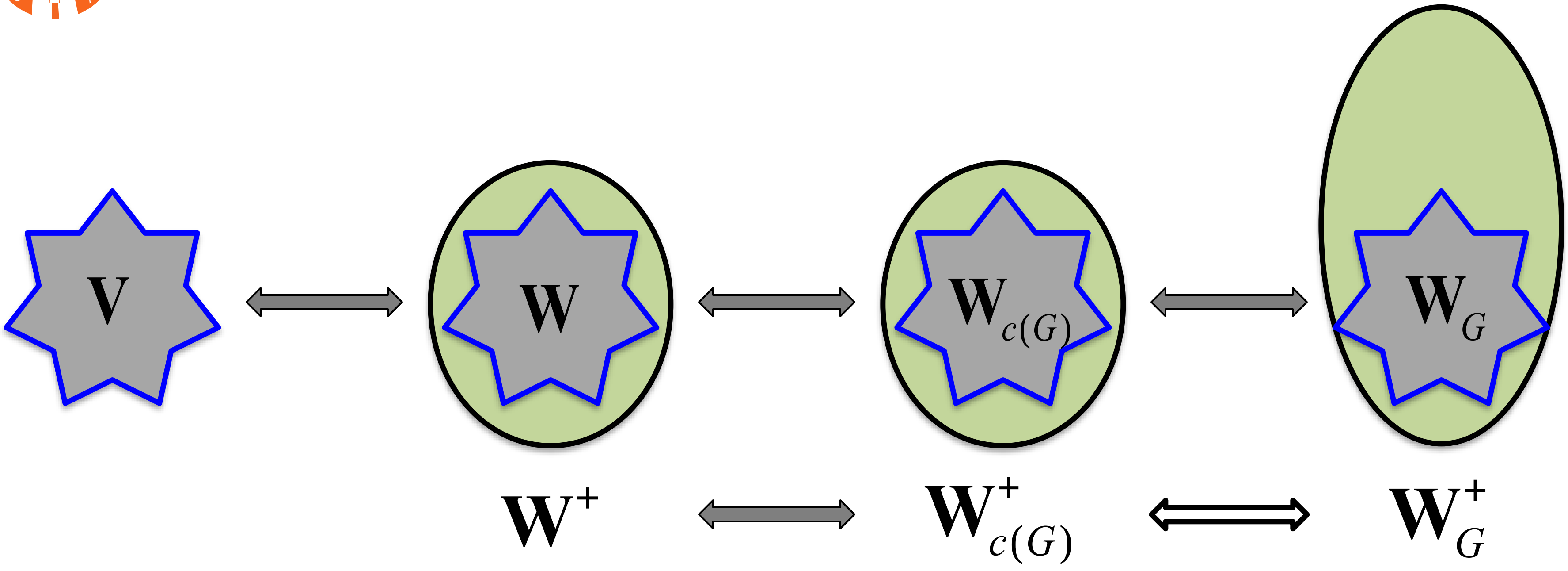


Theorem

- Radial G : $\mathbf{V} \subseteq \mathbf{W}^+ @ \mathbf{W}^+_{c(G)} @ \mathbf{W}^+_G$
- Mesh G : $\mathbf{V} \subseteq \mathbf{W}^+ @ \mathbf{W}^+_{c(G)} \subseteq \mathbf{W}^+_G$

Bose, Low, Chandy Allerton 2012
Bose, Low, Teeraratkul, Hassibi TAC2014

Relaxations



Theorem

- Radial G : $\mathbf{V} \subseteq \mathbf{W}^+ \simeq \mathbf{W}^+_{c(G)} \simeq \mathbf{W}^+_G$
- Mesh G : $\mathbf{V} \subseteq \mathbf{W}^+ \simeq \mathbf{W}^+_{c(G)} \subseteq \mathbf{W}^+_G$

For radial networks: always solve SOCP !

Recap: semidef relaxations

OPF

$$\min_{V} \; C(V) \quad \text{subject to} \quad V \in \mathbf{V}$$

OPF-sdp:

$$\min_{W} \; C(W_G) \quad \text{subject to} \quad W \in \mathbb{W}^+$$

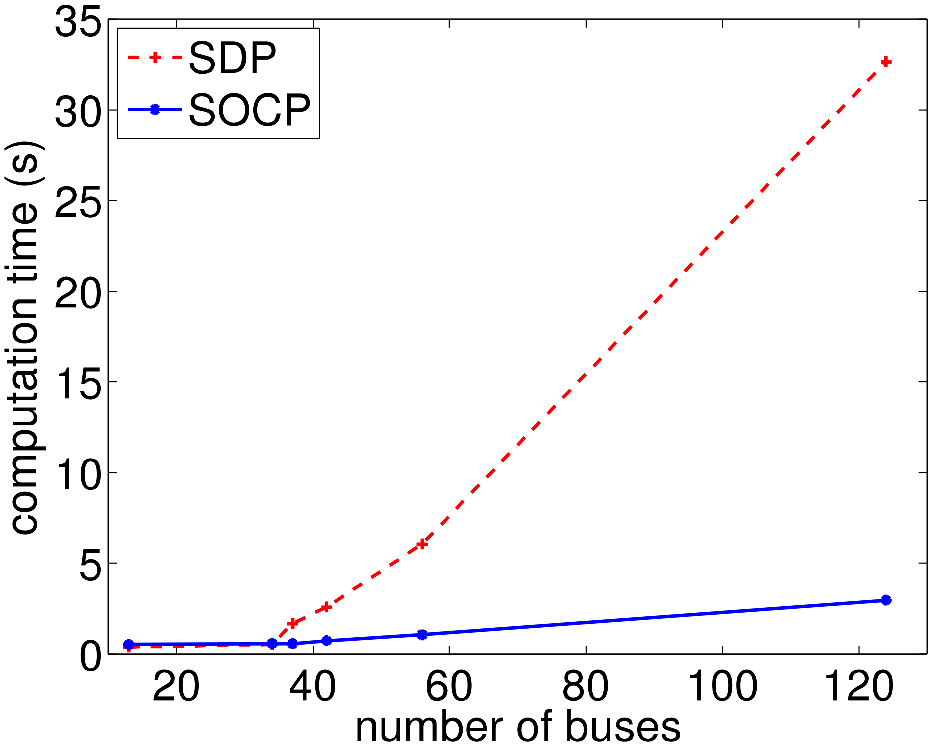
OPF-ch:

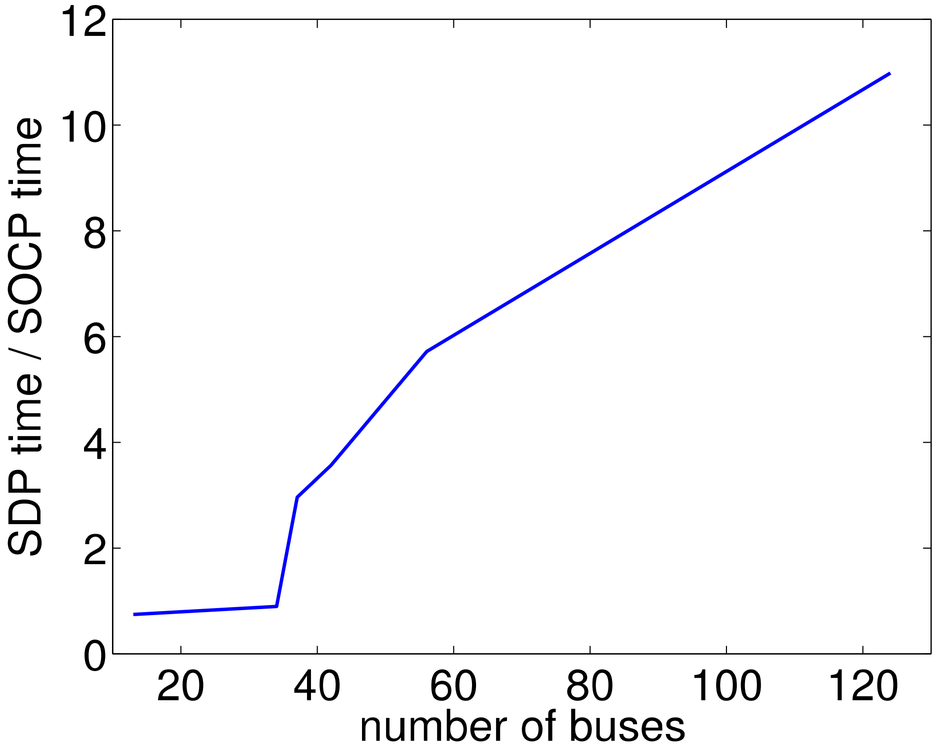
$$\min_{W_{c(G)}} \; C(W_G) \quad \text{subject to} \quad W_{c(G)} \in \mathbb{W}^+_{c(G)}$$

OPF-socp:

$$\min_{W_G} \; C(W_G) \quad \text{subject to} \quad W_G \in \mathbb{W}^+_G$$

SOCP more efficient than SDP

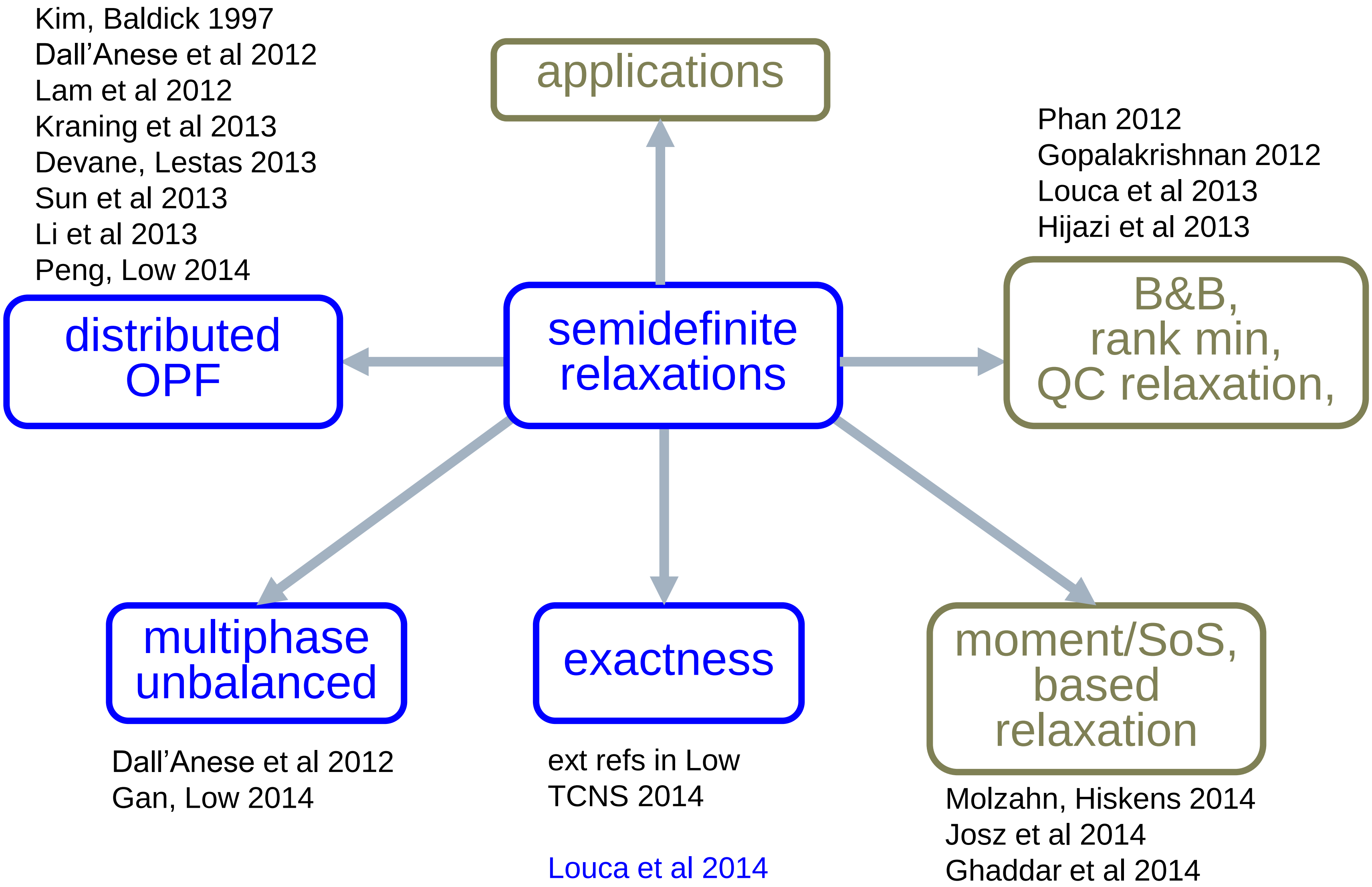




Relaxations are exact in all cases

- IEEE networks: IEEE 13, 34, 37, 123 buses (0% DG)
- SCE networks 47 buses (57% PV), 56 buses (130% PV)
- Single phase; SOCP using BFM
- Matlab 7.9.0.529 (64-bit) with CVX 1.21 on Mac OS X 10.7.5 with 2.66GHz Intel Core 2 Due CPU and 4GB 1067MHz DDR3 memory

OPF: extensions



semidefinite relaxations

applications

distributed OPF

Kim, Baldick 1997
Dall'Anese et al 2012
Lam et al 2012
Kraning et al 2013
Devane, Lestas 2013
Sun et al 2013
Li et al 2013
Peng, Low 2014

B&B, rank min, QC relaxation,

Phan 2012
Gopalakrishnan 2012
Louca et al 2013
Hijazi et al 2013

multiphase unbalanced

Dall'Anese et al 2012
Gan, Low 2014

exactness

ext refs in Low TCNS 2014

Louca et al 2014

moment/SoS, based relaxation

Molzahn, Hiskens 2014
Josz et al 2014
Ghaddar et al 2014

Outline

Overview & challenges

Optimal power flow (OPF)

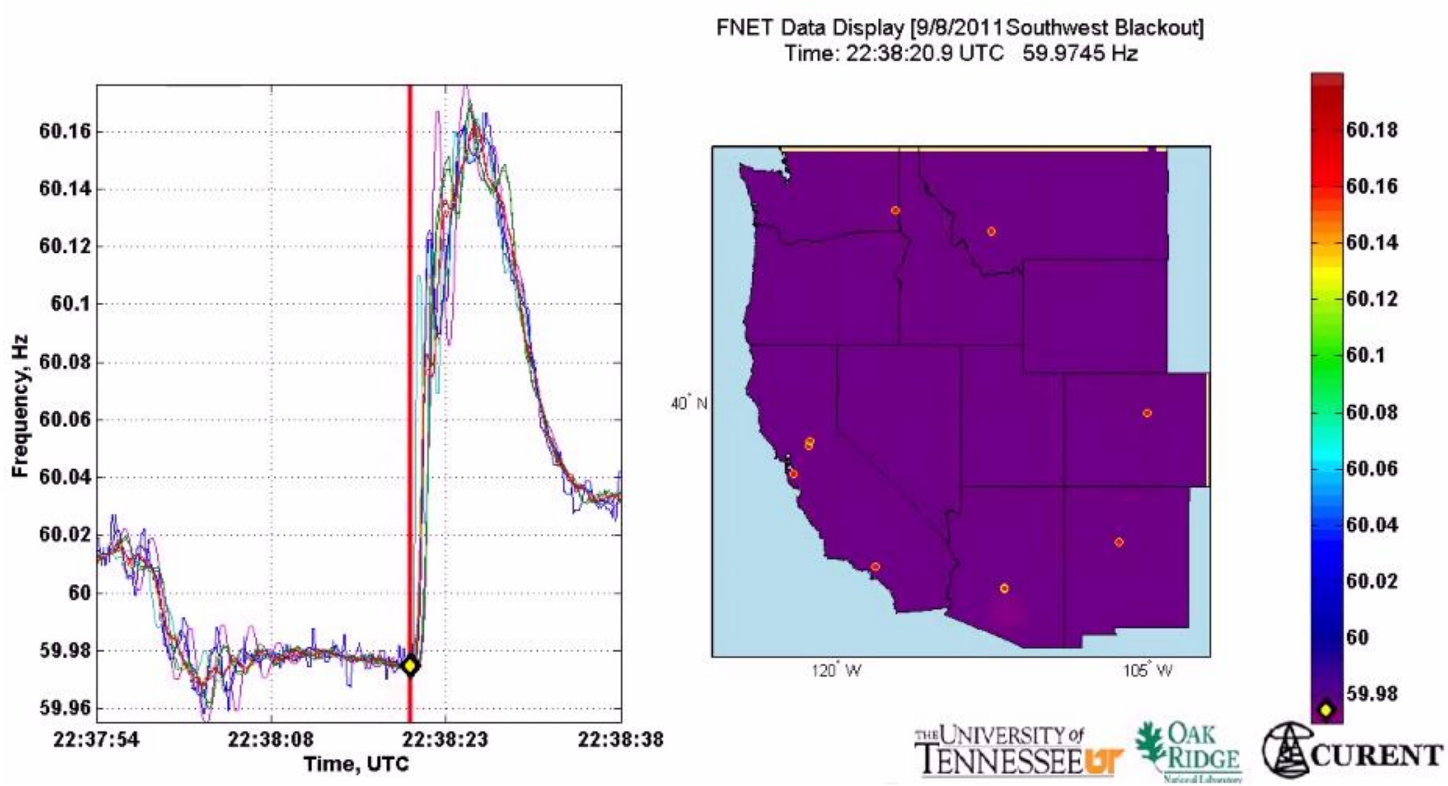
Frequency regulation

- load-side participation
- algorithm design and stability

Applications

Motivation

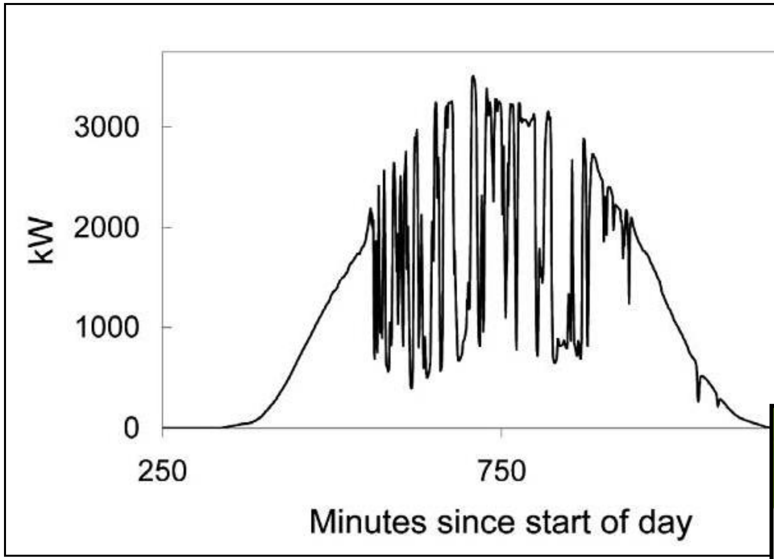
- All buses synchronized to same nominal frequency (US: 60 Hz; Europe: 50 Hz)
- Supply-demand imbalance ➔ frequency fluctuation



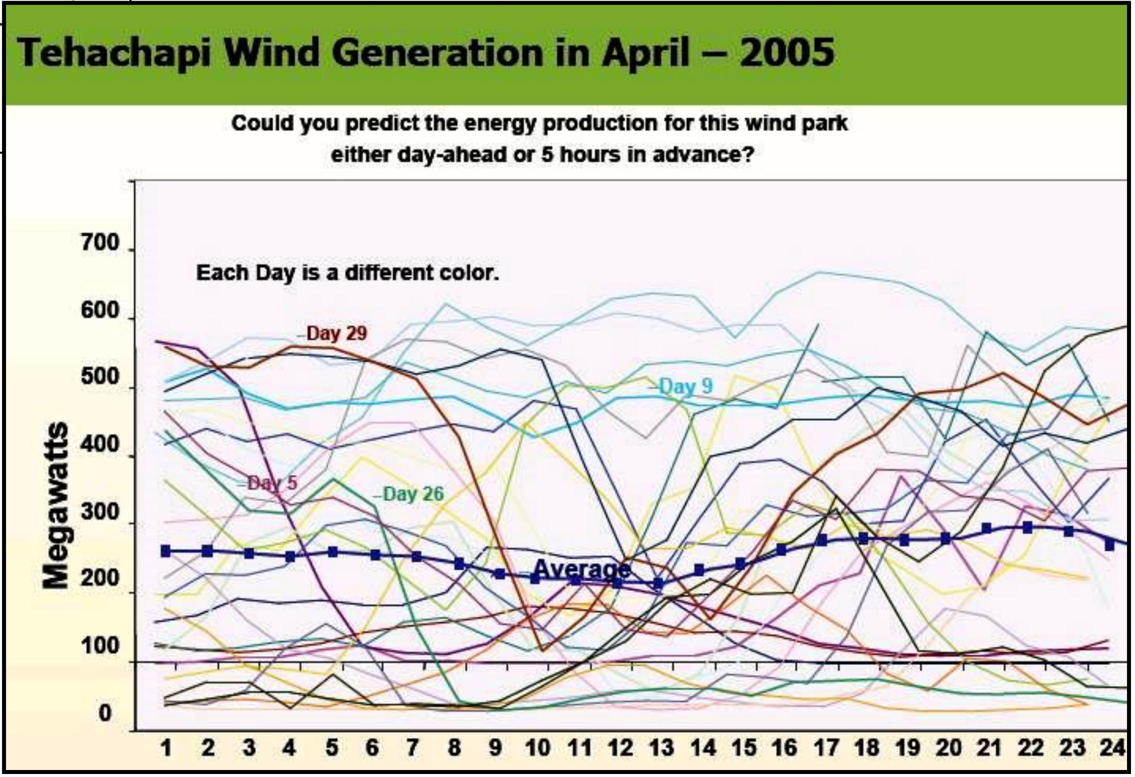
in)

2011 Southwest blackout

Motivation



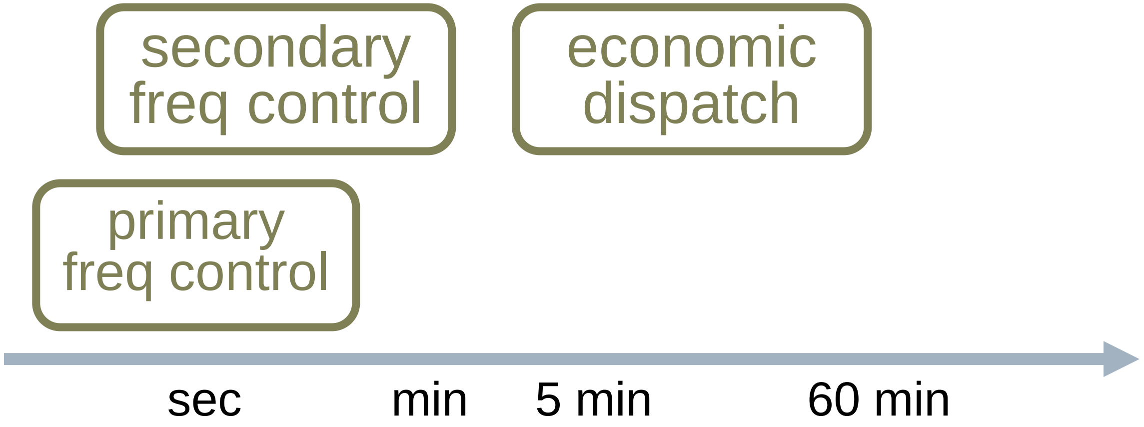
Imagine when we have 33%+ renewable generation …



Frequency control

Traditionally done on generator-side

- primary: rebalance power, resynchronize freq
- secondary: restore nominal freq & inter-area flows
- tertiary (EC): maximize economic efficiency



secondary freq control

economic dispatch

primary freq control

sec

min

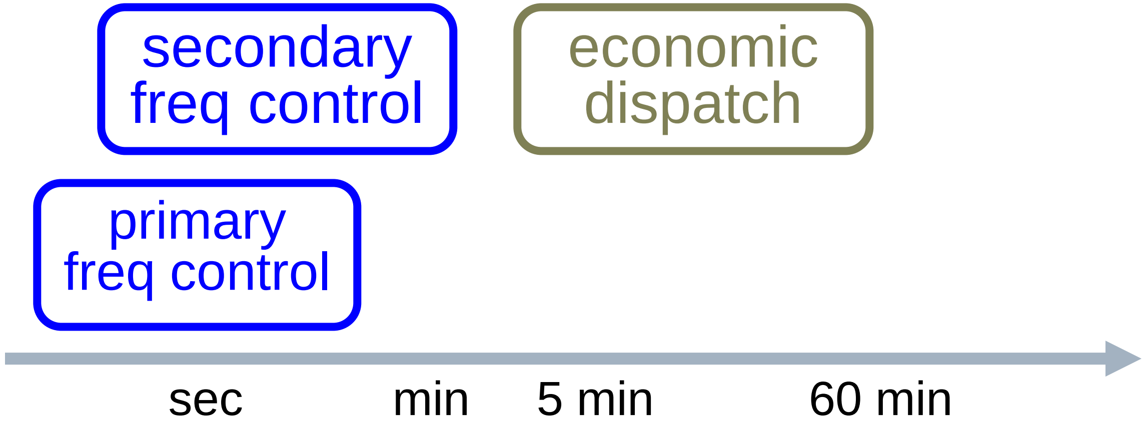
5 min

60 min

Why load-side participation

Ubiquitous continuous load-side control can supplement generator-side control

- faster (no/low inertia)
- no extra waste or emission
- more reliable (large #)
- better localize disturbances
- reducing generator-side control capacity



secondary freq control

economic dispatch

primary freq control

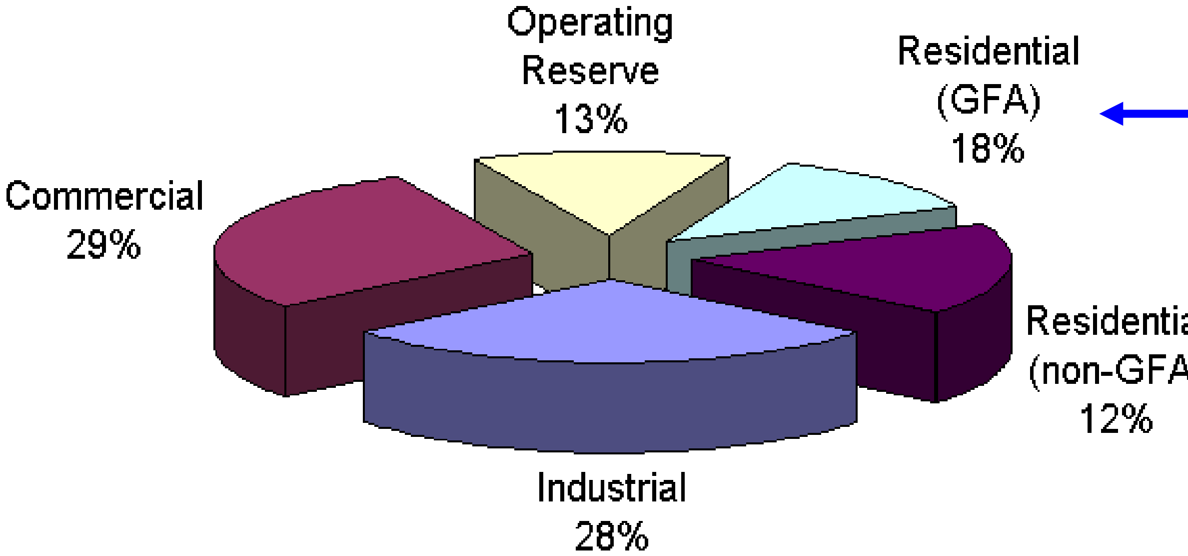
sec

min

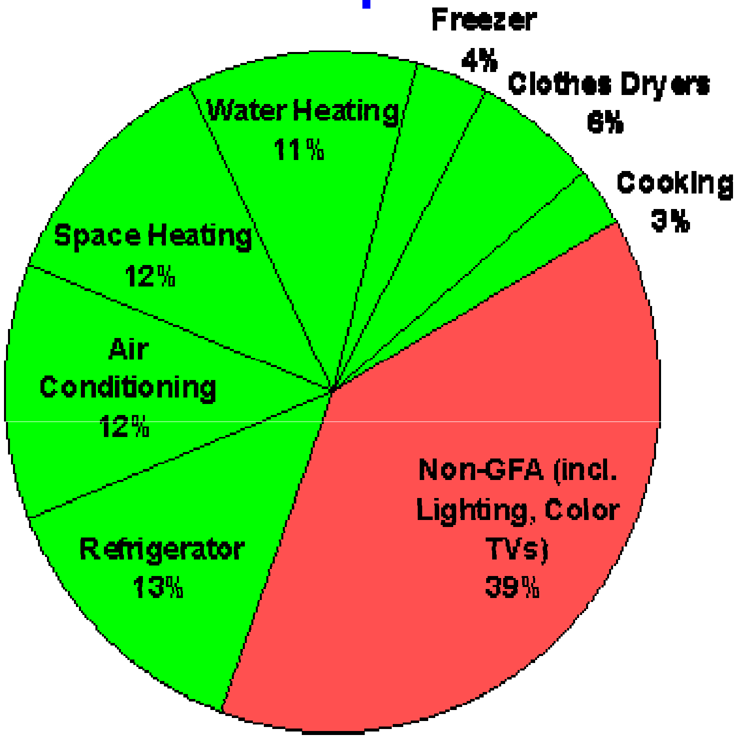
5 min

60 min

What is the potential



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



<u>US:</u>
operating reserve: 13% of peak
total GFA capacity: 18%

Lu & Hammerstrom (2006), PNNL

How

How to design load-side frequency control ?

How does it interact with generator-side control ?

Literature: load-side control

Original idea

- Schweppe et al 1979, 1980

Small scale trials around the world

- D.Hammerstrom et al 2007, UK Market Transform Programme 2008

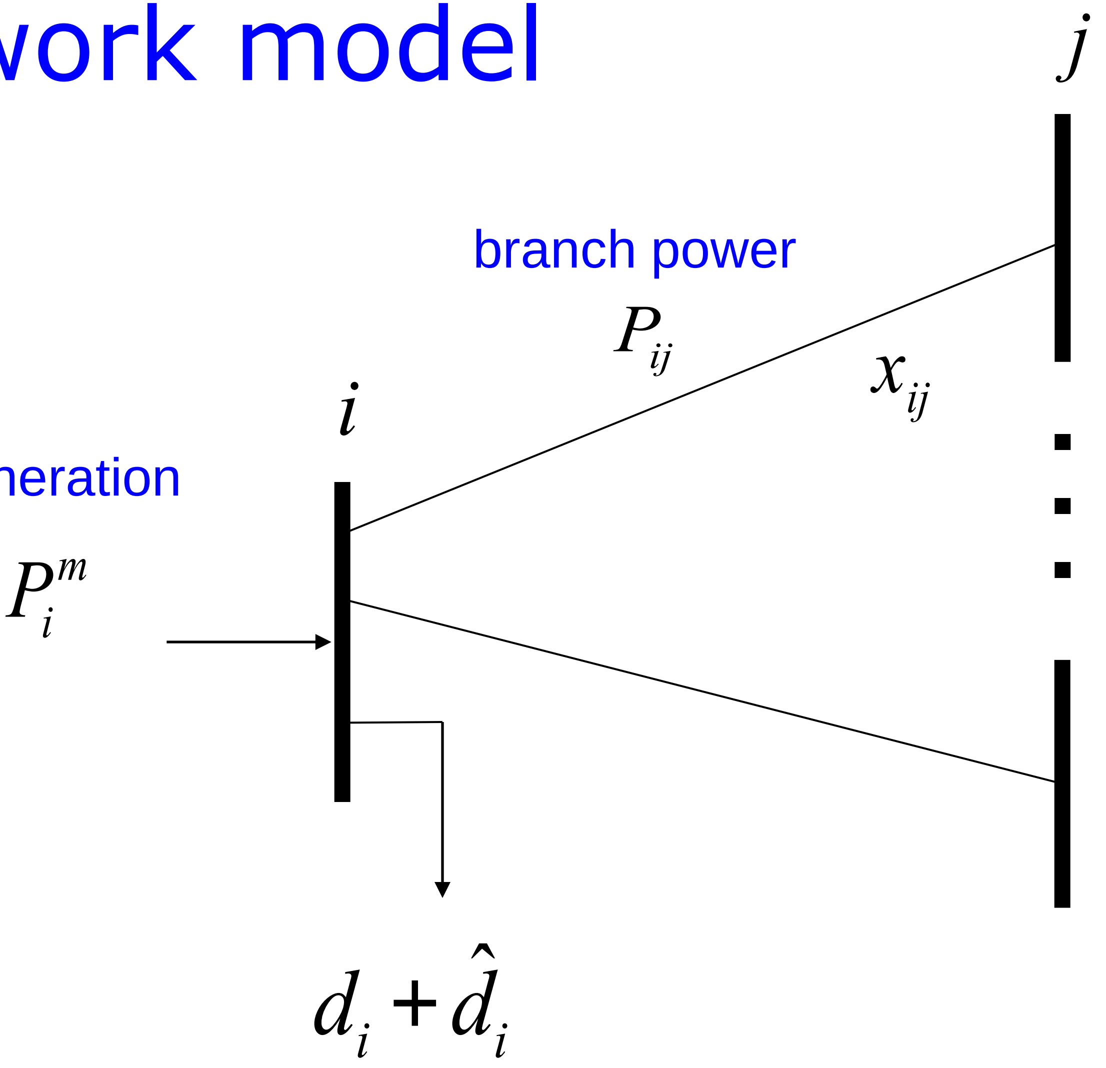
Numerical studies

- Trudnowski et al 2006, Lu and Hammerstrom 2006, Short et al 2007, Donnelly et al 2010, Brooks et al 2010, Callaway and I. A. Hiskens, 2011, Molina-Garcia et al 2011

Analytical studies

- Zhao et al (2012/2014), Mallada et al (2014), Zhao and Low (2014)
- Simpson-Porco et al 2013, You and Chen 2014, Zhang and Papachristodoulou (2014), Zhao, et al (2014)

Network model



j

branch power

P_{ij}

x_{ij}

i

generation

P_i^m

$d_i + \hat{d}_i$

loads:
controllable + uncontrollable

i : region/control area/balancing authority

Dynamic model

$$\dot{\theta}_i = \omega_i$$

$$M_i\dot{\omega}_i = -D_i\omega_i + p_i - \sum_e C_{ie}P_e$$

$$P_{ij} = b_{ij}\sin\left(\theta_i - \theta_j\right) \qquad \forall\ i \to j$$

generator bus: real power injection

Dynamic model

$$\dot{\theta}_i = \omega_i$$

$$M_i \dot{\omega}_i = -D_i \omega_i + p_i - \sum_e C_{ie} P_e$$

$$P_{ij} = b_{ij} \sin\left(\theta_i - \theta_j\right) \qquad \forall\ i \rightarrow j$$

generator buses:

$$\dot{p}_i = -\frac{1}{\tau_{bi}}\left(p_i + a_i\right)$$

$$\dot{a}_i = -\frac{1}{\tau_{gi}}\left(a_i + p_i^c\right)$$

primary control $p_i^c(t) = p_i^c\left(w_i(t)\right)$

e.g. freq droop $p_i^c\left(w_i\right) = - b_i w_i$

Dynamic model

$$\dot{\theta}_i = \omega_i$$

$$0 = -D_i\omega_i + d_i - \sum_e C_{ie} P_e$$

$$P_{ij} = b_{ij}\sin\left(\theta_i - \theta_j\right) \qquad \forall\ i \rightarrow j$$

load bus: controllable load

how to design controller $d_i(t)$?

Proposed approach

- formalize control goals as OLC
- derive distributed control as primal-dual alg

Load-side controller design

$$\dot{\theta}_i = \omega_i$$

$$0 = -D_i\omega_i + d_i - \sum_e C_{ie} P_e$$

$$P_{ij} = b_{ij} \sin\left(\theta_i - \theta_j\right) \qquad \forall\ i \to j$$

Control goals

- Rebalance power
- Stabilize frequency
- Restore nominal frequency
- Restore scheduled inter-area flows

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

Optimal load control (OLC)

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

$$\text{s. t.} \qquad P^m - (d + \hat{d}) = CP$$

demand = supply

key idea: “virtual flows”

$$BC^T v$$

in steady state: virtual = real flows

$$BC^T v = P$$

Optimal load control (OLC)

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

$$\text{s. t.} \quad P^m - (d + \hat{d}) = CP \qquad \text{demand = supply}$$

$$P^m - d = CBC^T v \qquad \text{restore nominal freq}$$

in steady state: virtual = real flows

$$BC^T v = P$$

Optimal load control (OLC)

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

s. t.

$$P^m - (d + \hat{d}) = CP$$ demand = supply

$$P^m - d = CBC^T v$$ restore nominal freq

$$\hat{C}BC^T v = \hat{P}$$ restore inter-area flow

$$\underline{P} \le BC^T v \le \overline{P}$$ respect line limit

in steady state: virtual = real flows

$$BC^T v = P$$

Distributed load control

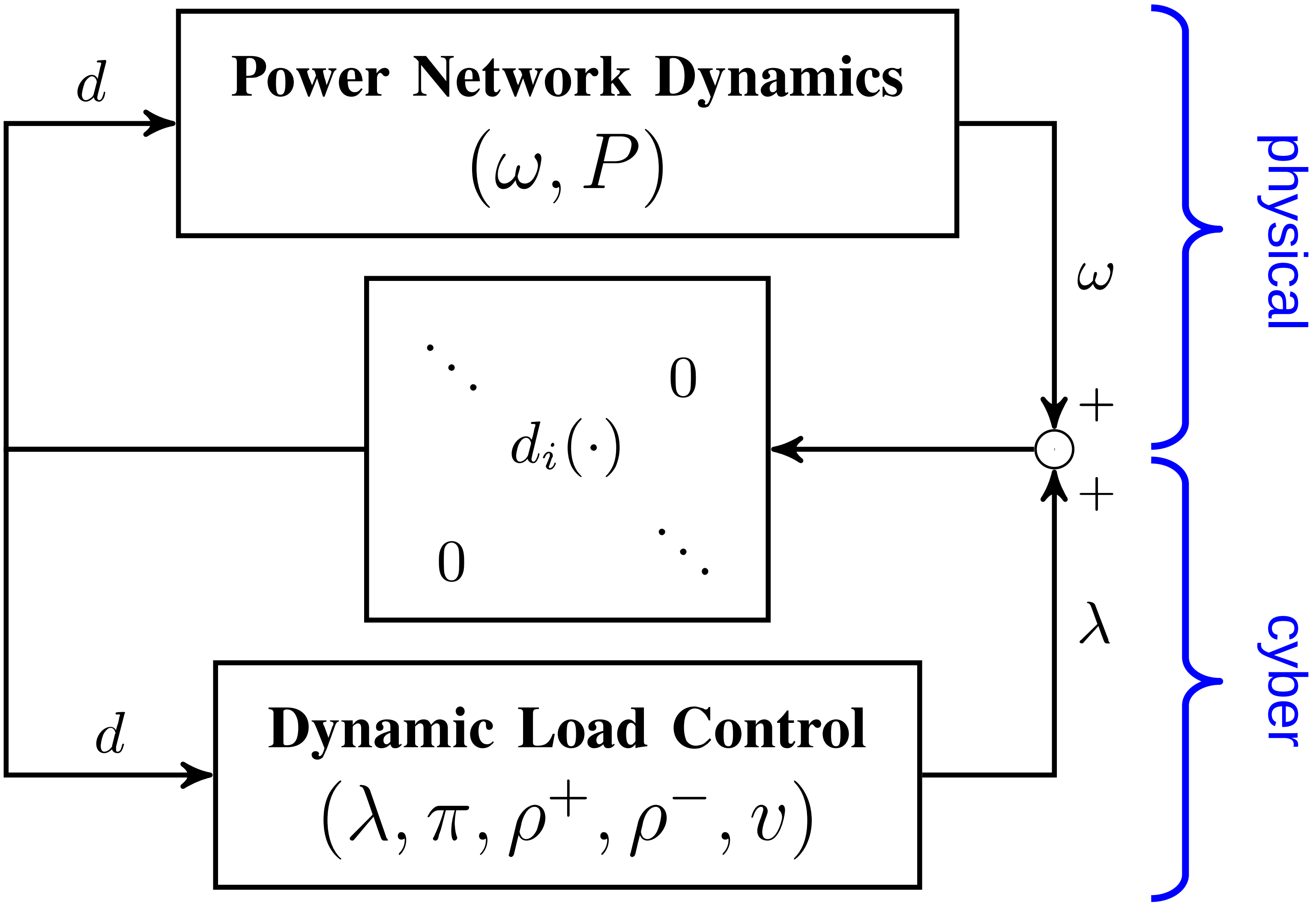
load control: $d_i(t) := \left[c_i'^{-1}\left(\omega_i(t) + \lambda_i(t)\right) \right]_{\underline{d}_i}^{\overline{d}_i}$

local frequency deviation
measured locally at load

virtual frequency
computed locally based
on neighborhood comm

network dynamics + active load control
= first-order primal-dual algorithm for OLC

Distributed control architecture



Power Network Dynamics

(ω, P)

$d_i(\cdot)$

Dynamic Load Control

$(\lambda, \pi, \rho^+, \rho^-, v)$

Load-side control works

Theorem

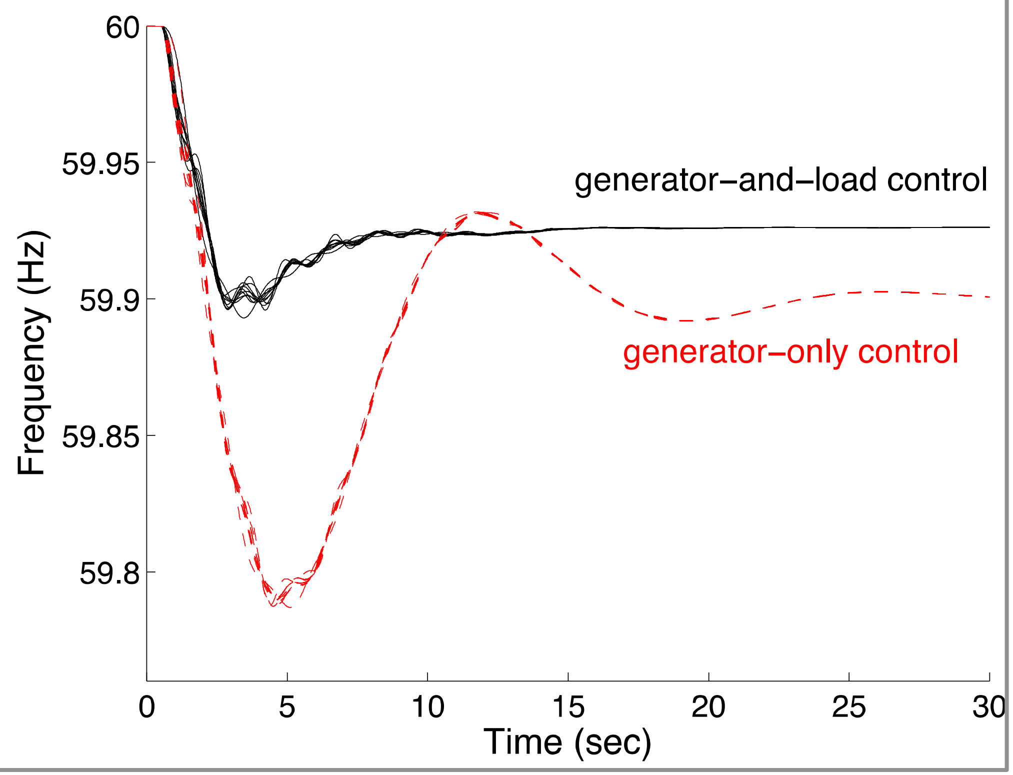
- Every closed-loop equilibrium solves OLC and its dual

Suppose $\left|p_i^c(\omega) - p_i^c(\omega^*)\right| \leq L_i \left|\omega - \omega^*\right|$

$$\text{near } \omega^* \text{ for some } L_i < D_i$$

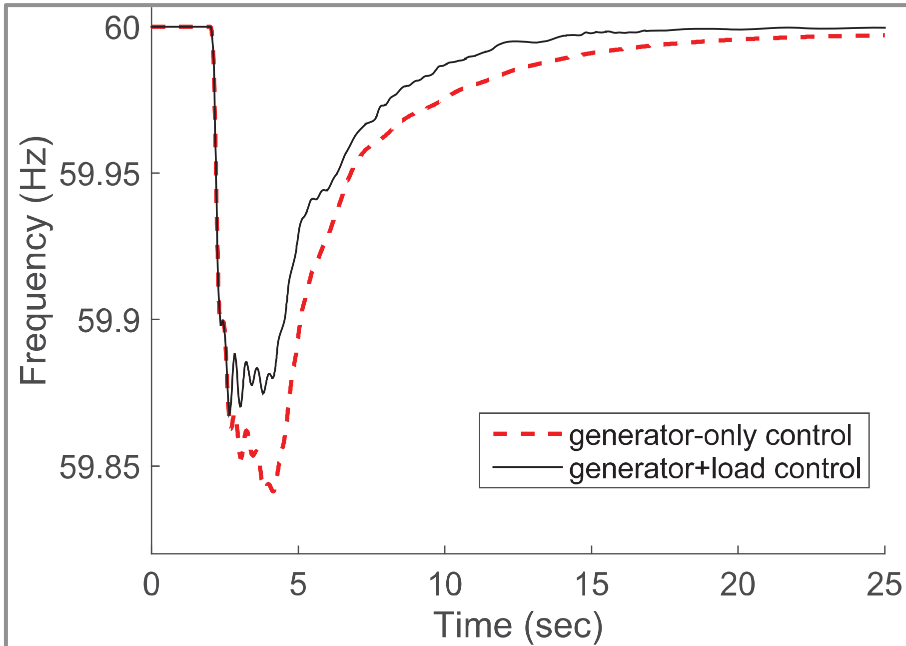
- Any closed-loop equilibrium is (locally) asymptotically stable provided

$$\left|\theta_i^* - \theta_j^*\right| < \frac{\pi}{2}$$



- Can replacing gen-side control with load-side control
- Load-side participation improves transient and steady state

PSS 39-bus, same control capacity
Primary frqueny control



PSS 14-bus, same control capacity
Secondary frequency control

Recap

Forward-engineering design facilitates

- explicit control goals
- distributed algorithms
- stability analysis

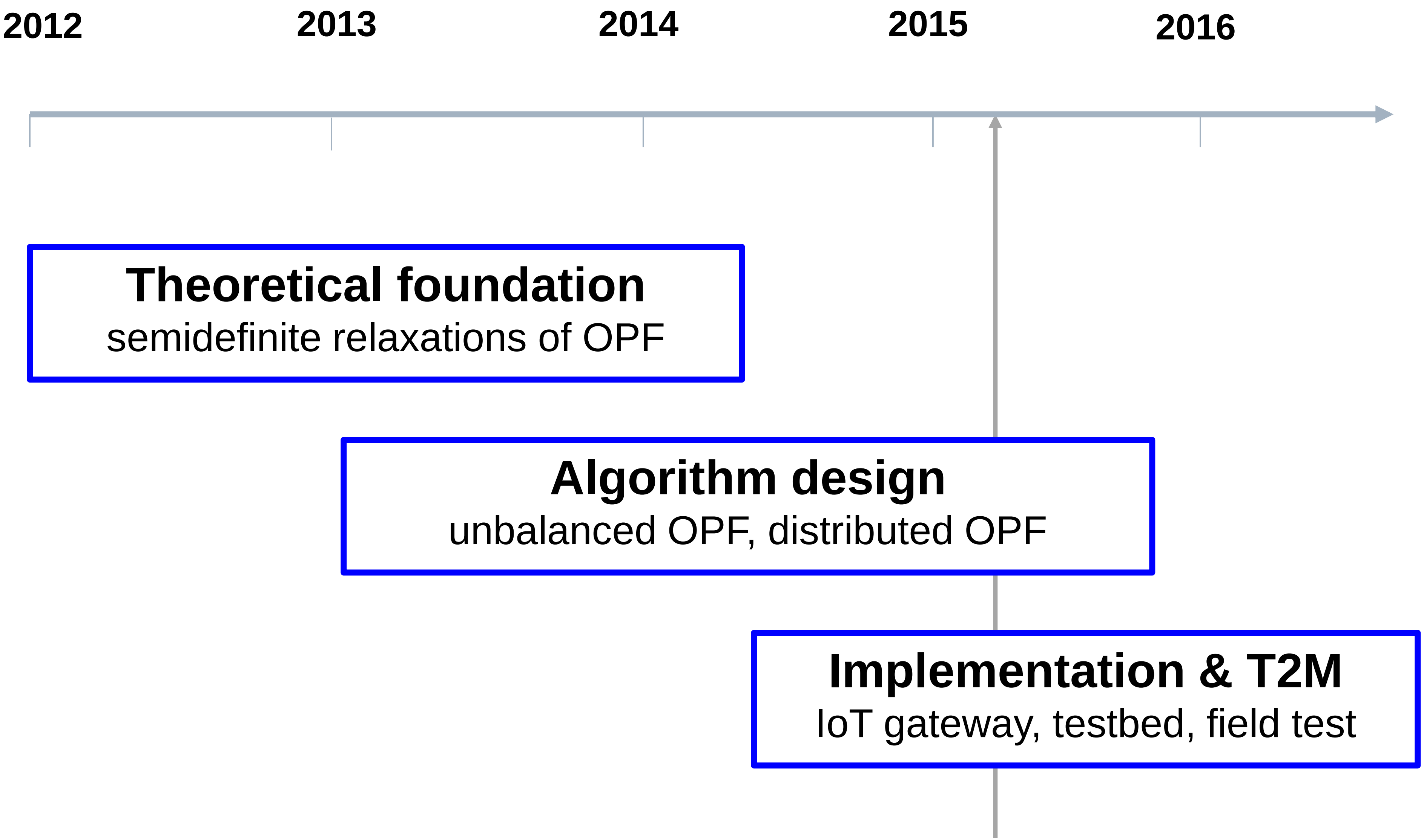
Load-side frequency regulation

- essential as renewable replaces thermal gen
- improves generator-side control

Outline

- Overview
- Optimal power flow (OPF)
- Frequency regulation
    - problem formulation
    - semidefinite relaxations
    - exact relaxation
- Applications

OPF research



2012

2013

2014

2015

2016

Theoretical foundation

semidefinite relaxations of OPF

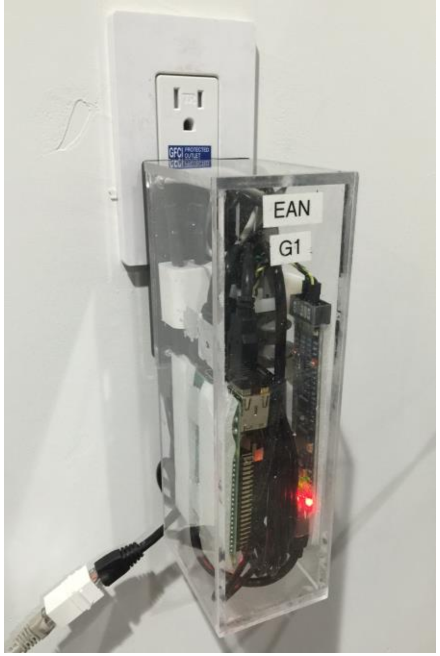
Algorithm design

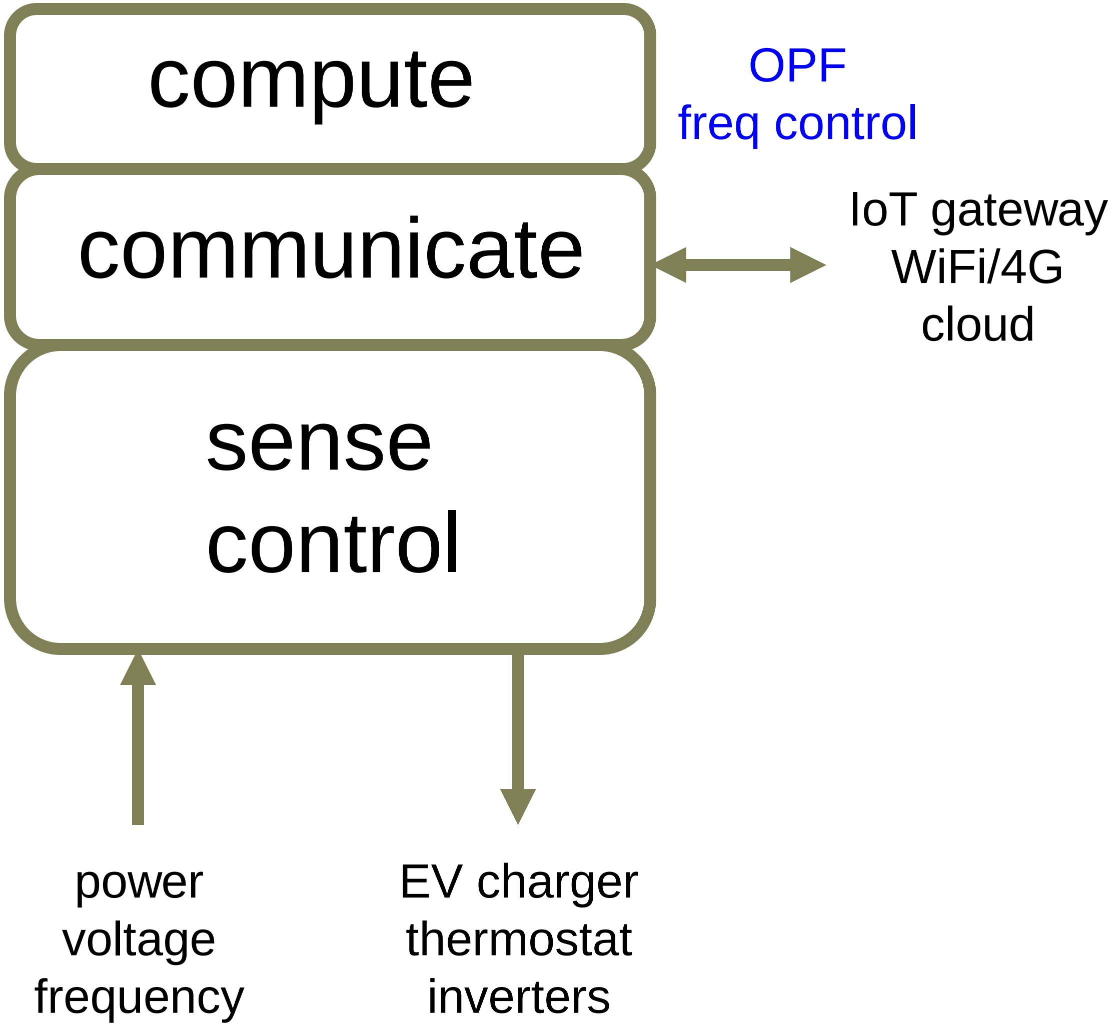
unbalanced OPF, distributed OPF

Implementation & T2M

IoT gateway, testbed, field test

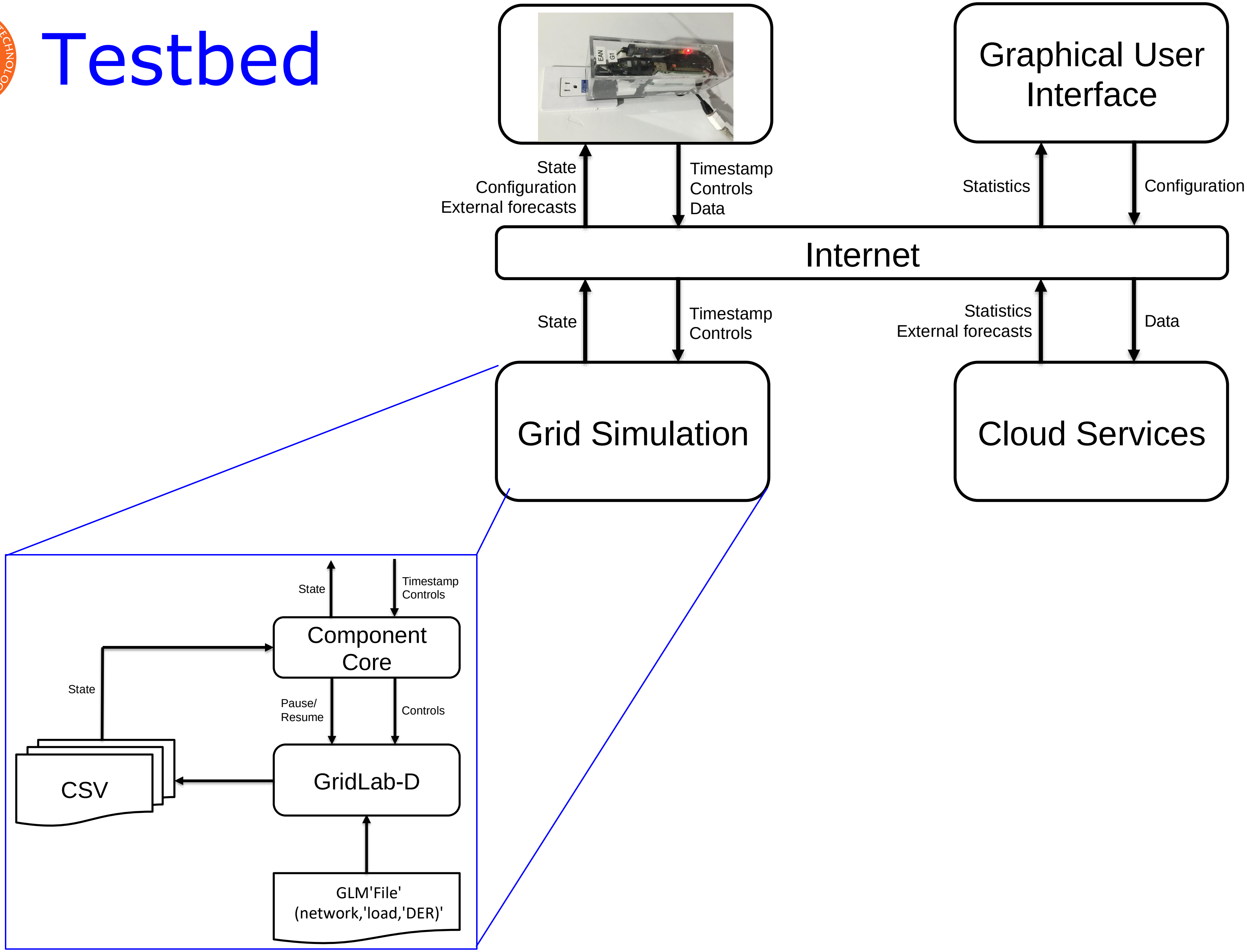
IoT gateway prototype





George Lee

Testbed



Graphical User Interface

State
Configuration
External forecasts

Timestamp
Controls
Data

Statistics

Configuration

Internet

State

Timestamp
Controls

Statistics
External forecasts

Data

Grid Simulation

Cloud Services

State

Timestamp
Controls

Component Core

State

Pause/
Resume

Controls

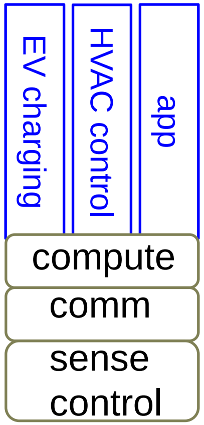
CSV

GridLab-D

GLM'File'
(network,'load,'DER)'

Field test

George Lee



EV charging

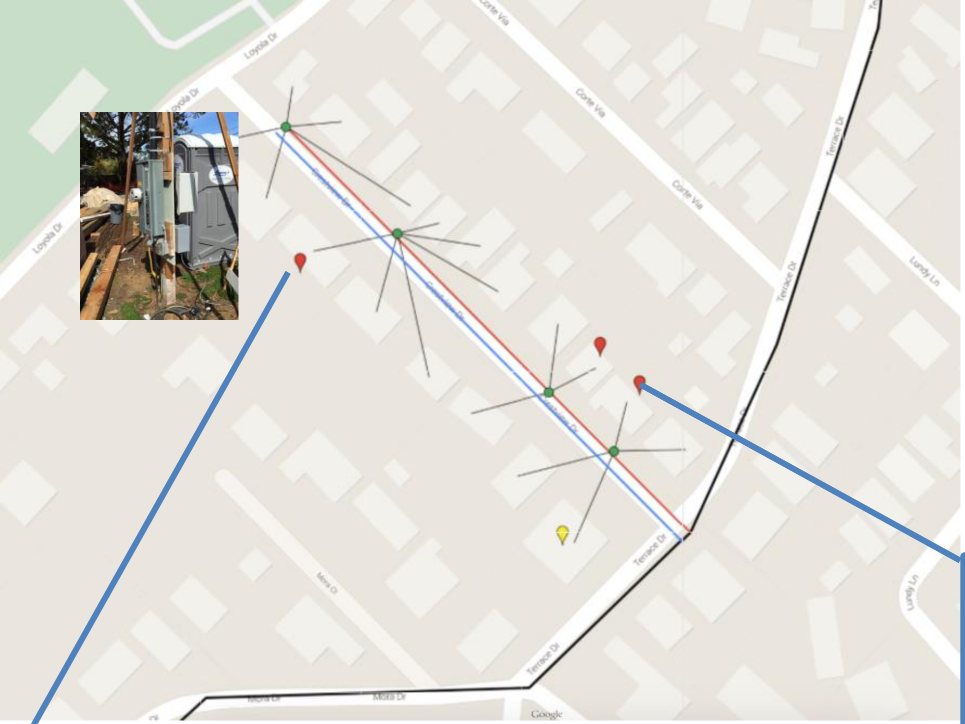
HVAC control

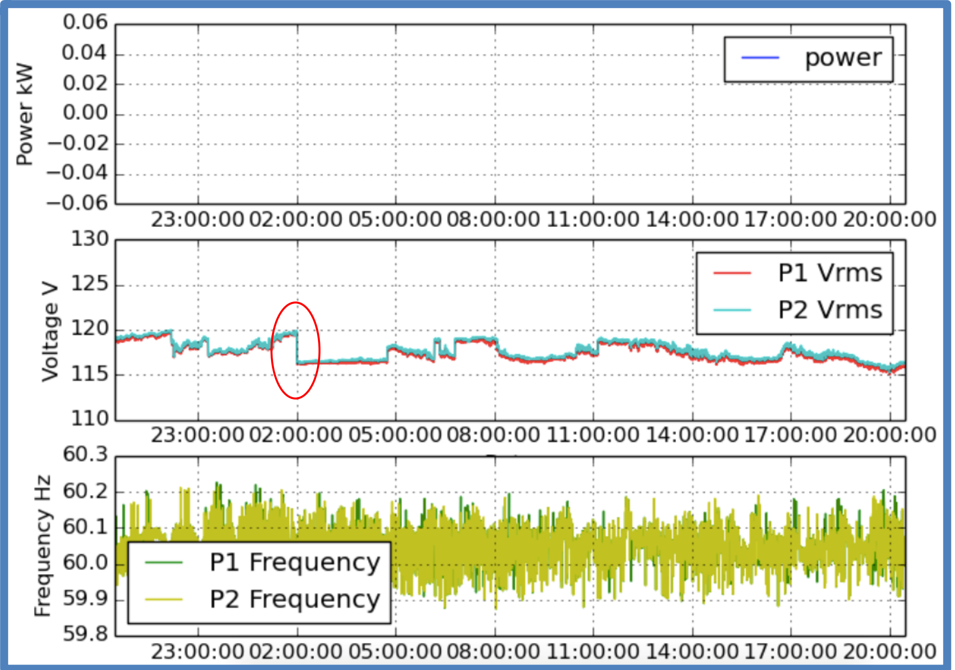
app

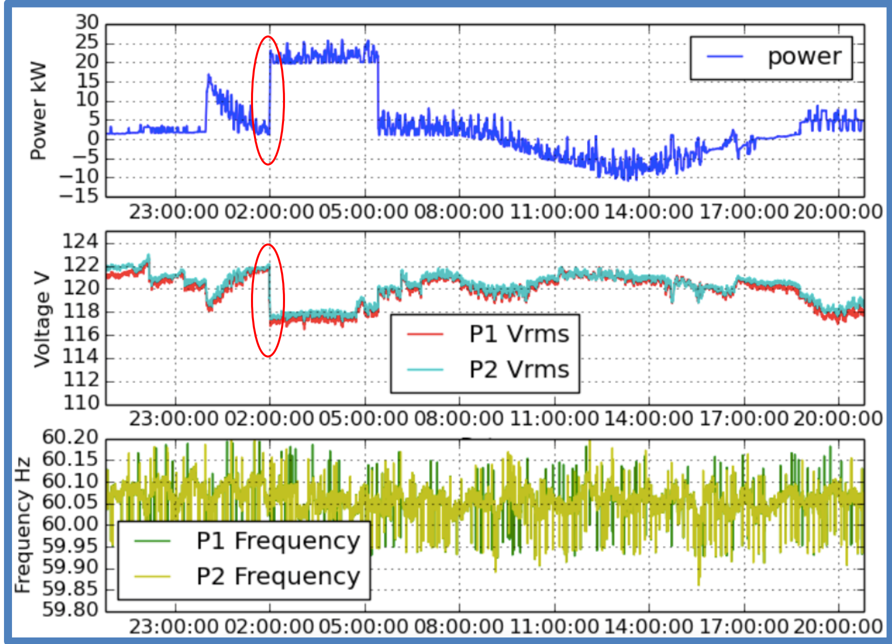
compute

comm

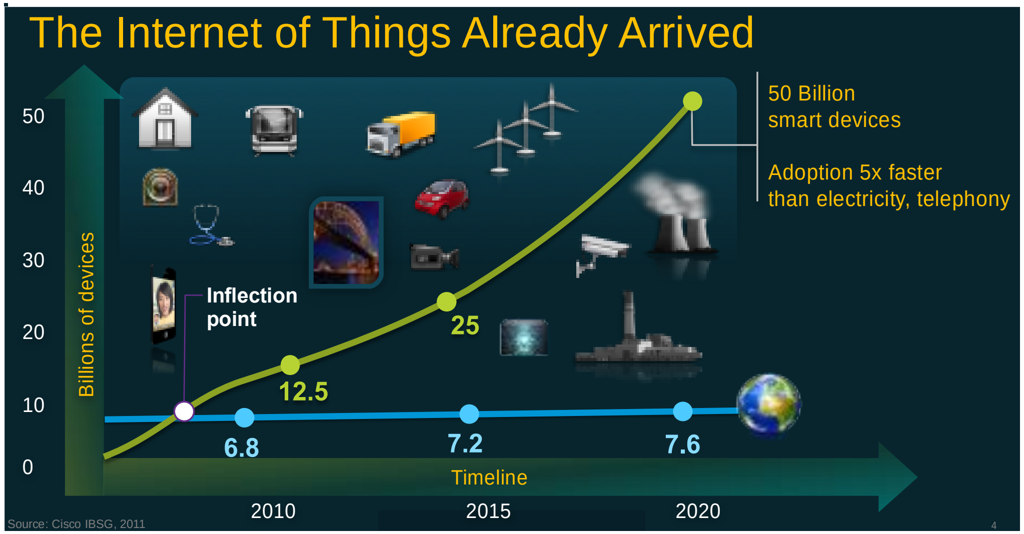
sense control







Tech-to-market



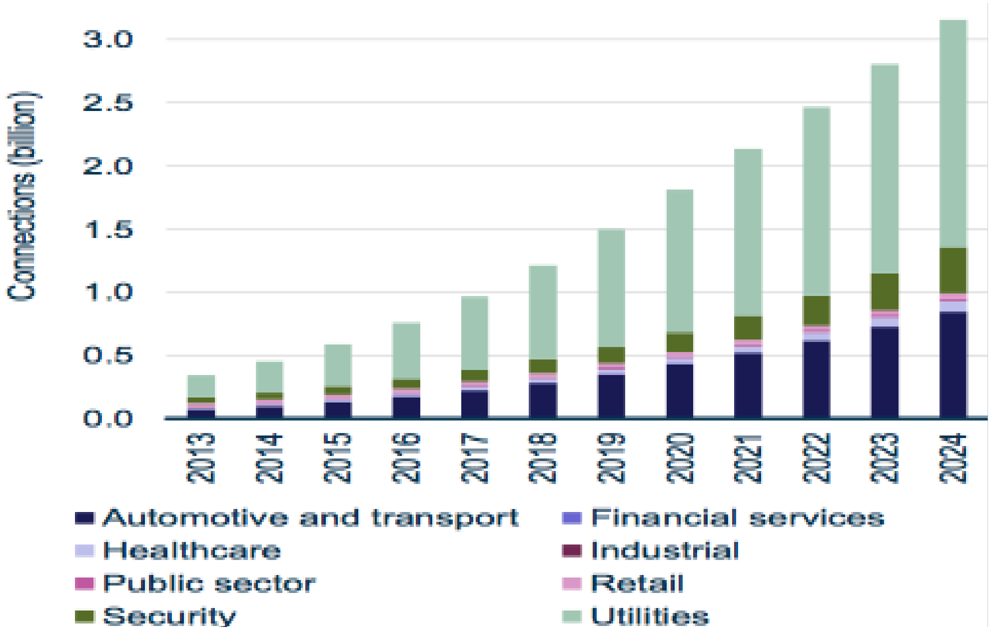
The Internet of Things Already Arrived

50 Billion smart devices

Adoption 5x faster than electricity, telephony

Source: Cisco IBSG, 2011

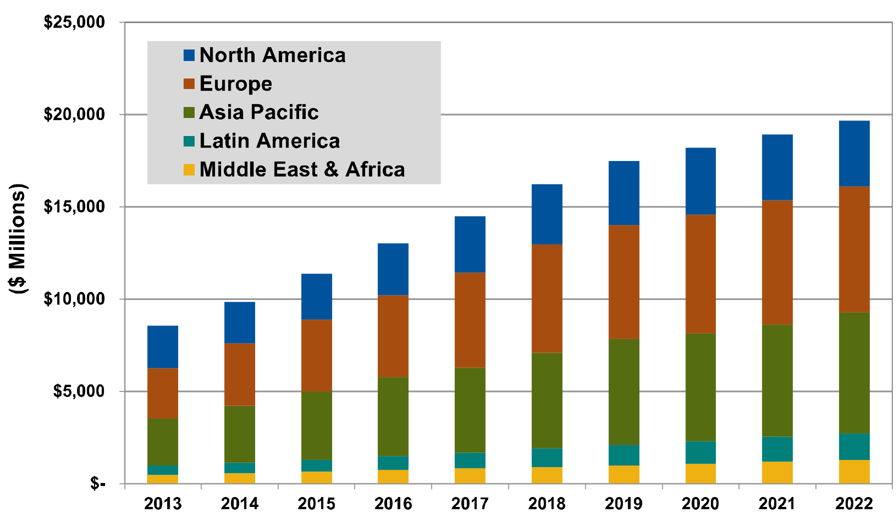
IoT has been growing at unprecedented rate



Energy is the largest application for IoT

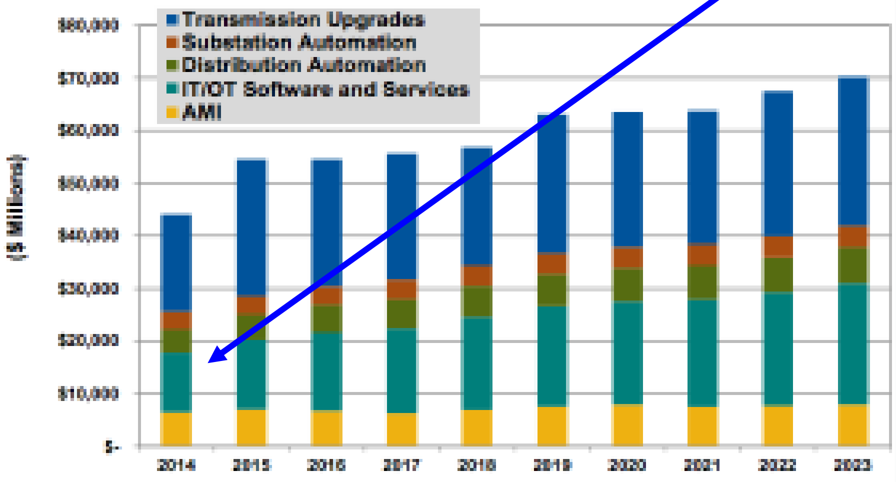
Tech-to-market

2.2 *Smart Grid IT Software and Services Spending by Region, World Markets: 2013-2022*



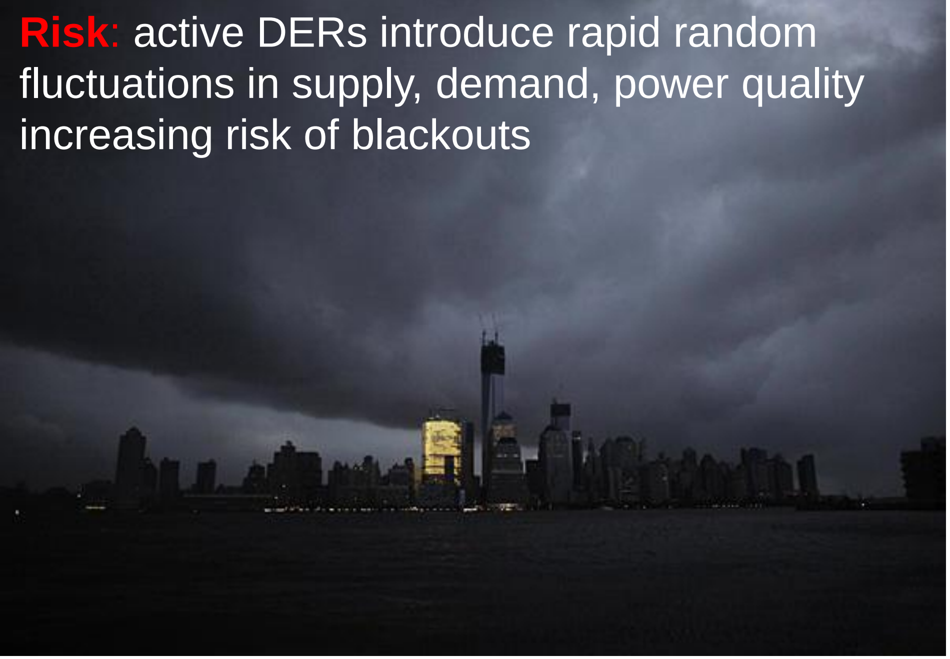
(Source: Navigant Research)

6.2 *Smart Grid Technology Revenue by Application, World Markets: 2014-2023*



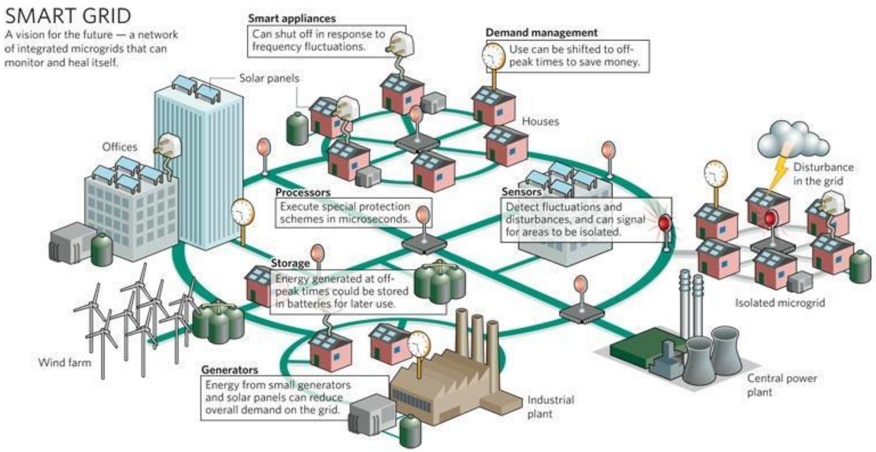
(Source: Navigant Research)

SG IT software is already a multi-B market

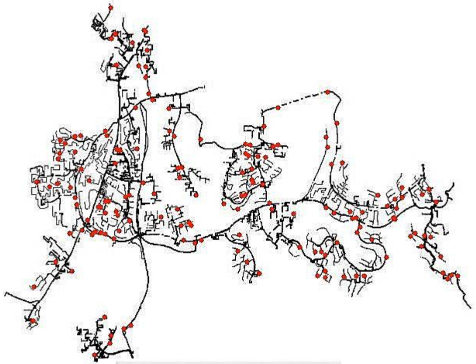


Risk: active DERs introduce rapid random fluctuations in supply, demand, power quality increasing risk of blackouts

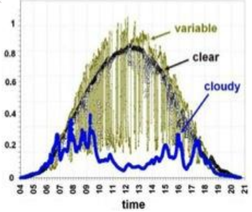
Opportunity: active DERs enables realtime dynamic network-wide feedback control, improving robustness, security, efficiency



Caltech research: distributed control of networked DERs



- Foundational theory, practical algorithms, concrete applications
- Integrate engineering and economics
- Active collaboration with industry



NSF arpa·e SOUTHERN CALIFORNIA EDISON RESNICKINSTITUTE science + energy + sustainability CISCO SYSTEMS