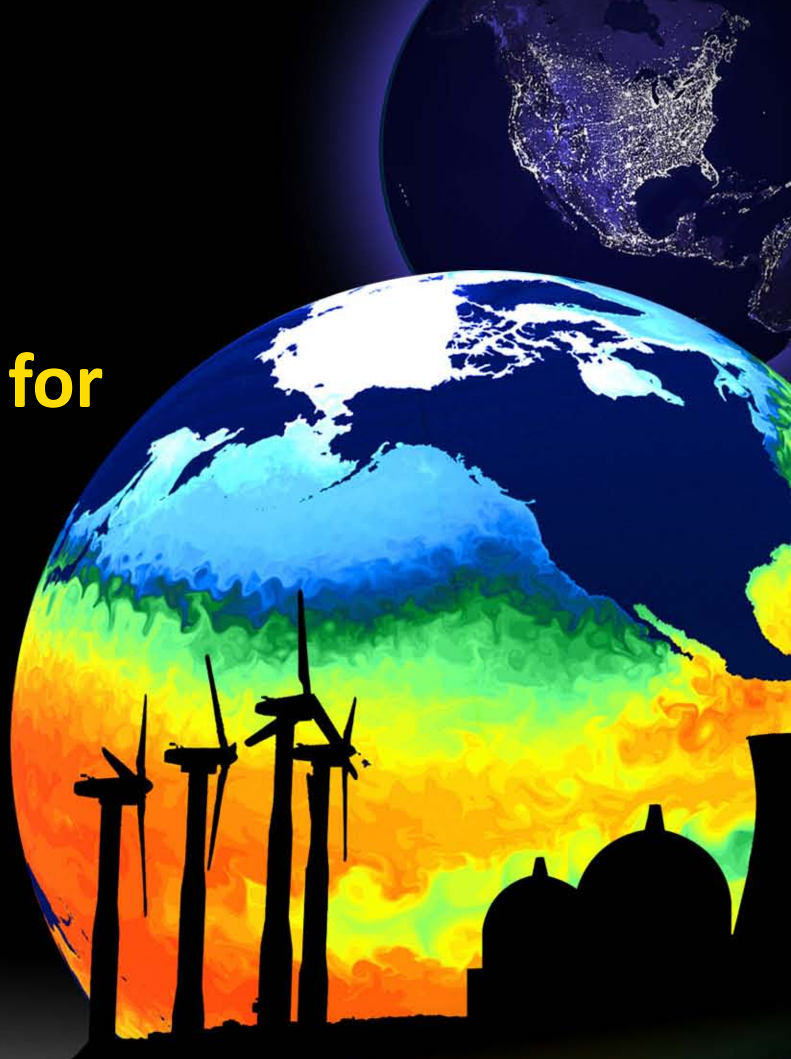
LANL/LDRD DR, FY10-FY12, Review: 08/22/2011



Optimization and Control Theory for Smart (Power) Grids

LA-UR 11-05087

M. Chertkov (PI, T)
(stability)

R. Bent (co-PI, D)
(planning)

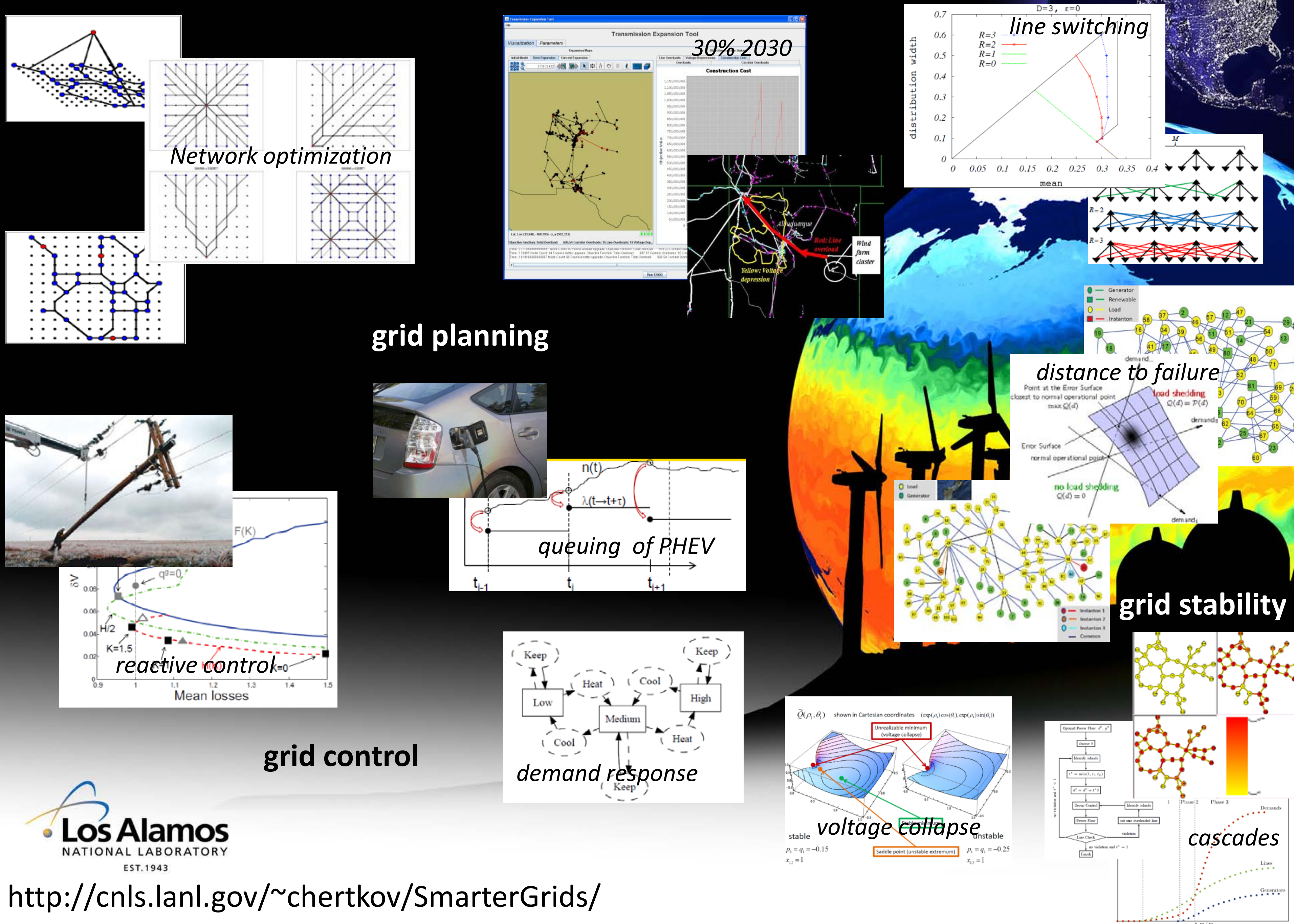
S. Backhaus (MPA)
(control)

http:/cnls.lanl.gov/~chertkov/SmarterGrids/

Los Alamos NATIONAL LABORATORY EST. 1943

NNSA

LANL LDRD DR (FY09-11): Optimization & Control Theory for Smart Grids



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EST. 1943

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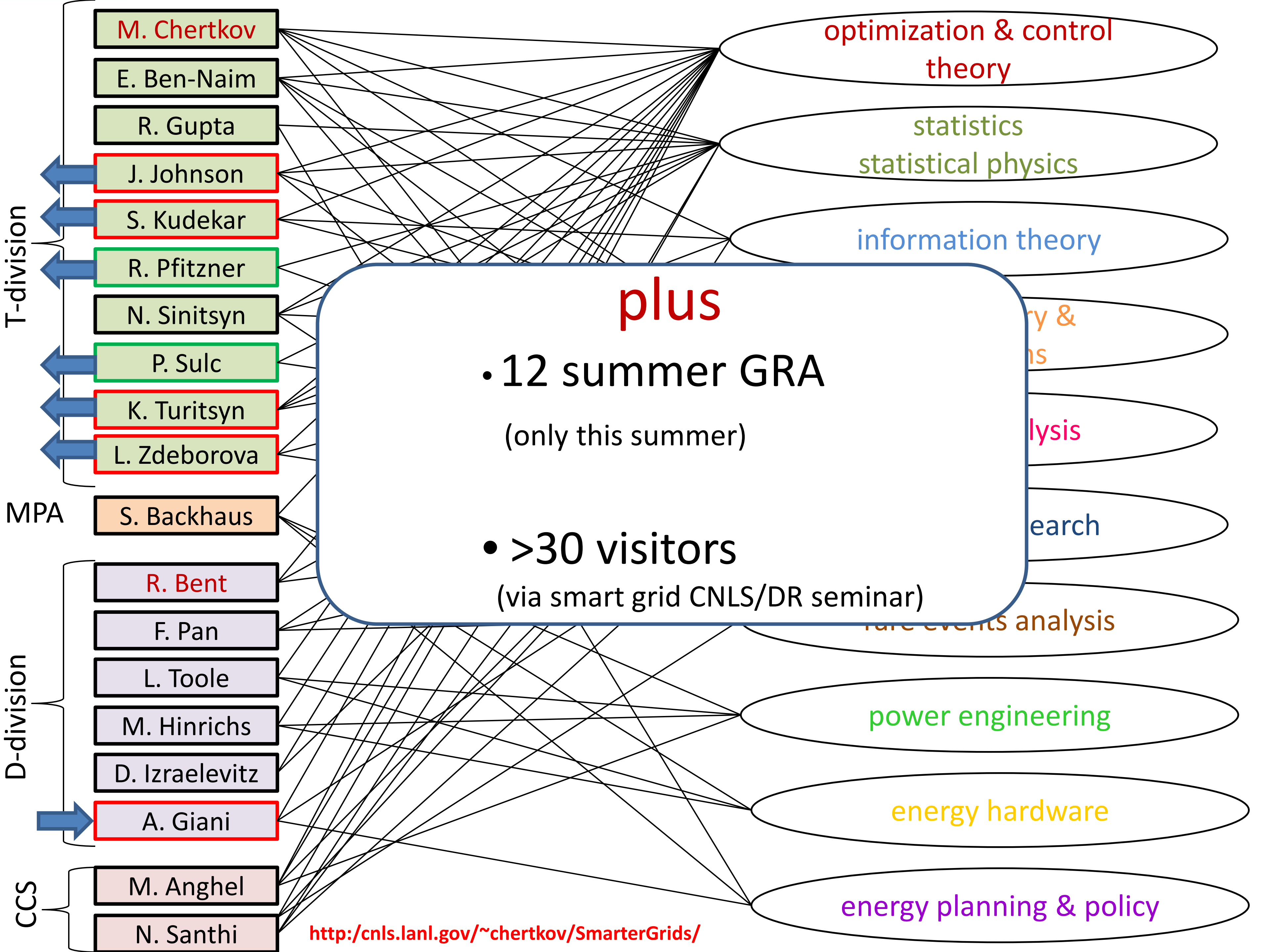

T-division
M. Chertkov
E. Ben-Naim
R. Gupta
J. Johnson
S. Kudekar
R. Pfitzner
N. Sinitsyn
P. Sulc
K. Turitsyn
L. Zdeborova
MPA
S. Backhaus
D-division
R. Bent
F. Pan
L. Toole
M. Hinrichs
D. Izraelevitz
A. Giani
CCS
M. Anghel
N. Santhi
optimization & control theory
statistics
statistical physics
information theory
ry &
ns
lysis
earch
events analysis
power engineering
energy hardware
energy planning & policy
plus
• 12 summer GRA
(only this summer)
• >30 visitors
(via smart grid CNLS/DR seminar)
http:/cnls.lanl.gov/~chertkov/SmarterGrids/

Received external funding

- DTRA project on ``Cascading failures” FY11-FY13 (350K/year)

- Smart Grid Technology Test Bed (LANL+NEDA+LA county)
  FY12 funding: 320K-400K
  will likely continue at a similar level in FY13

- NSF/NMC project on ``Grid Spectroscopy” with MIT, UIUC
  (in approval status) FY12-FY14 (180K/year)

29+ papers

- Proceedings of IEEE
- IEEE Transactions on Smart Grids
- Multiple Invited Presentations (e.g. plenary at SIAM/DS)
- Super Session Presentaton at IEEE/PES
- IEEE SmartGridComm, DIMACS, CDC +++

Conferences/workshops organized

- CNLS Workshop, August 2010 (last year review)
- CNLS Annual Conference, May 2012
- Two Special Sessions at SIAM/DS, May 2011

Today's presentation

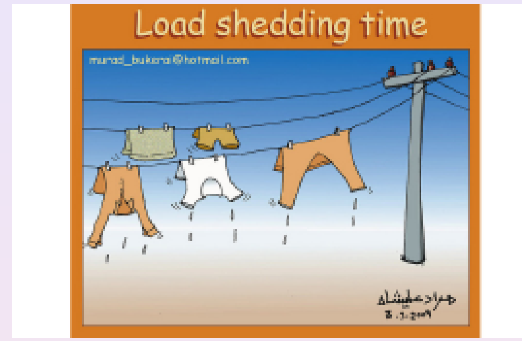
mainly new (last year) stuff

- M. Chertkov (40+ min)
  - Distance to failure (better then N-1)
  - Cascading failures (size distribution)
  - Voltage Collapse (effect of disorder)
  - Phase Stability & Synchronization
  - Robust Optimization (OPF)
- S. Backhaus (40+ min)
  - Demand Response (Thermostat Control)
  - Combined Optimization & Control
  - Cyber-Physical (Game Theory)
  - EM waves, detection, PMUs and Green functions
  - Grid Expansion/Planning
- Discussions (20+ min)
  - What else do we need to do to get SERIOUS programmatic funding in a year?

Distance to Failure (better then N-1)

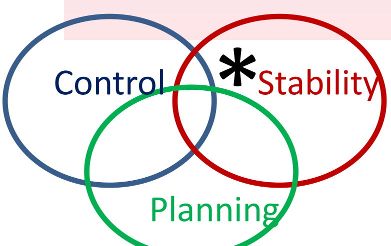
MC, F. Pan (LANL) and M. Stepanov (UA Tucson)

- Predicting Failures in Power Grids: The Case of Static Overloads, IEEE Transactions on Smart Grids **2**, 150 (2010).



MC, FP, MS & R. Baldick (UT Austin)

- Exact and Efficient Algorithm to Discover Extreme Stochastic Events in Wind Generation over Transmission Power Grids, invited session on Smart Grid Integration of Renewable Energy at CDC/ECC 2011.



Extreme Statistics of Failures

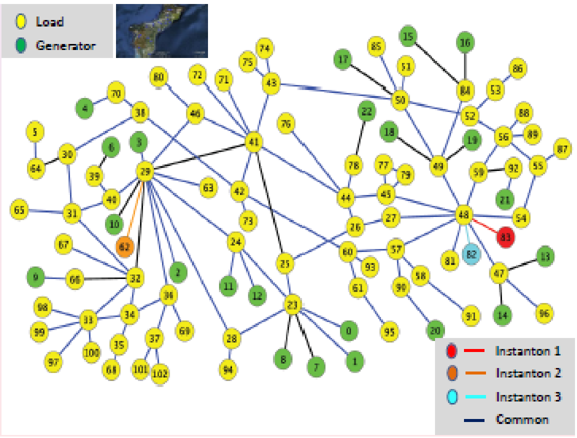
- Statistics of loads/demands is assumed given: $\mathcal{P}(\mathbf{d})$
- $\mathbf{d} \in$ SAT=No Shedding; $\mathbf{d} \in$ UNSAT =Shedding

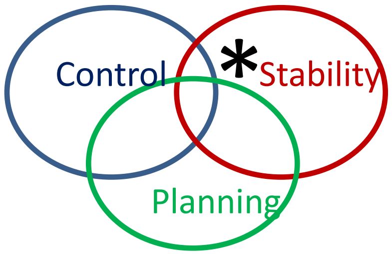
Most Dangerous Configuration of the demand = the Instanton

- $\arg\max_{\mathbf{d}} \mathcal{P}(\mathbf{d})|_{\mathbf{d} \notin SAT}$ - most probable instanton
- SAT is a polytope (finding min-shedding solution is an LP); $-\log(\mathcal{P}(\mathbf{d}))$ is (typically) convex

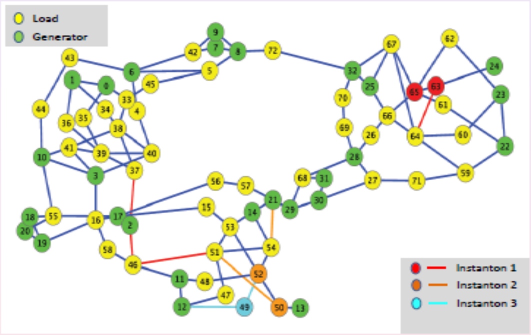
The task: to find the (rated) list of (local) instantons

- The most probable instanton represents the large deviation asymptotic of the failure probability
- Use an efficient heuristics to find candidate instantons (technique was borrowed from our previous "rare events" studies of a similar problem in error-correction '04-'11)





Example of IEEE RTS96 system



- The instantons are well localized (but still not sparse)
- The troubled nodes and structures are repetitive in multiple-instantons
- Violated constraints (edges) can be far from the troubled nodes: long correlations
- Instanton structure is not sensitive to small changes in statistics of demands

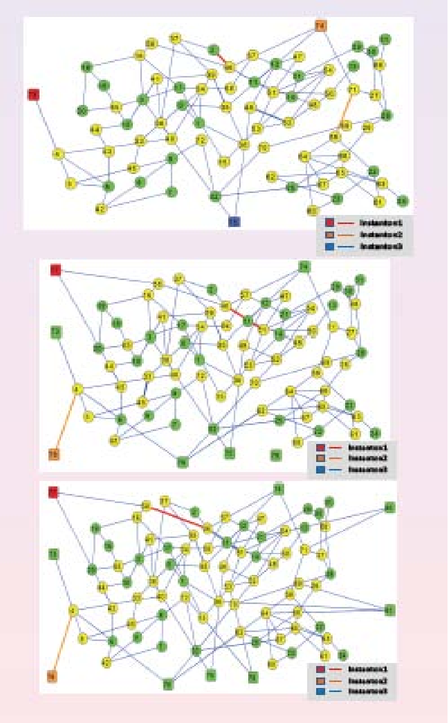
Instantons for Wind Generation

Setting

- Renewables is the source of fluctuations
- Loads are fixed (5 min scale)
- Standard generation is adjusted according to a droop control (low-parametric, linear)

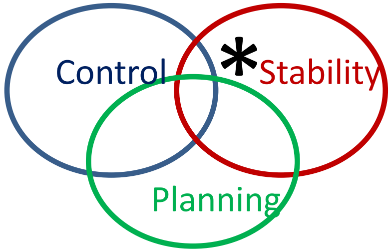
Results

- The instanton algorithm discovers most probable UNSAT events
- The algorithm is EXACT and EFFICIENT (polynomial)
- Illustrate utility and performance on IEEE RTS-96 example extended with additions of 10%, 20% and 30% of renewable generation.



Path Forward

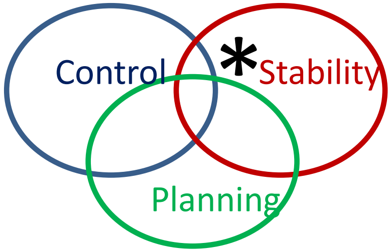
- Many large-scale practical tests, e.g. ERCOT wind integration, WECC, Eastern Interconnect
- The instanton-amoeba allows upgrade to other (than LP_{DC}) network stability testers, e.g. for AC flows and transients. Synchronization. Voltage Collapse.
- Instanton-search can be accelerated, utilizing LP-structure of the tester (exact & efficient for example of renewables, go beyond the example)
- Robust Instanton ("second order" uncertainty - in statistics)
- Other models of external fluctuations (attacks)
- Instantons in more difficult settings (Interdiction, Games, etc)



Analysis of Cascading Failures in Power Grids

R. Pfitzner (LANL/NMC -> ETH)
K. Turitsyn (LANL-> MIT, ME)
MC

- Statistical Classification of Cascading Failures in Power Grids, IEEE PES 2011, http://arxiv.org/abs/1012.0815
- Controlled Tripping of Overheated Lines Mitigates Power Outages, http://arxiv.org/abs/1104.4558



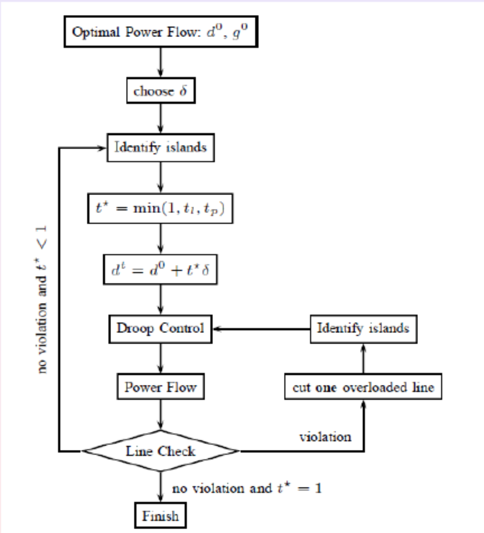
Objectives:

- Have a realistic microscopic model of a cascade [not (!!) a "disease-spread" like phenomenological model]
- Resolve discrete events dynamics (lines tripping, overloads, islanding) explicitly
- Address (first) the current reality of the transmission grid operation, e.g. automatic control on the sub-minute scale
- Consider (first) fluctuations in demand as a source of cascade in the overloaded (modern) grid
- Analyze the results, e.g. in terms of phases observed, on available power grid models [IEEE test beds]

Building on

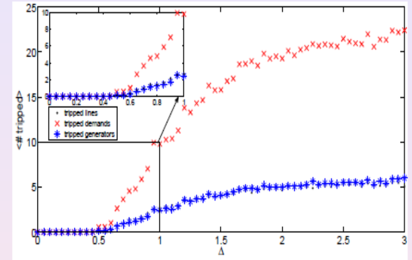
- I. Dobson, B. Carreras, V. Lynch, and D. Newman, *An initial model for complex dynamics in electric power system blackouts*, HICSS-34, 2001

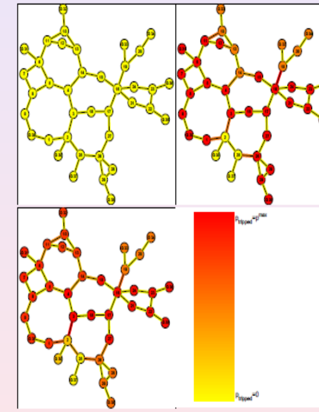
Algorithm of the Cascade



- *Optimum Power Flow* finds (cost) optimal distribution of generation (decided once for $\sim$ 15 min - in between state estimations)
- *DC power flow* is our (simplest) choice
- *Droop Control* = equivalent (pre set for 15 min) response of all the generators to change in loads
- *Identify islands* with a proper connected component algorithm(s)
- *Discrete time Evolution of Loads* = (a) generate configuration of demand from given distribution (our enabling example = Gaussian, White); (b) assume that the configuration "grow" from the typical one (center of the distribution) in continuous time, $t \in [0;1]$; (c) project next discrete event (failure of a line or saturation of a generator) and jump there

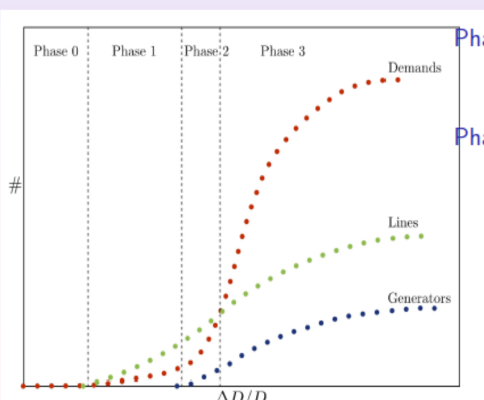
Tests on IEEE 39 buses





- Average # vs level of fluctuations.
- Stress Diagram. Average # of failures per edge/node. $\Delta = 0.3, 0.4, 0.6 \Rightarrow$

General Conclusions (3 phases)



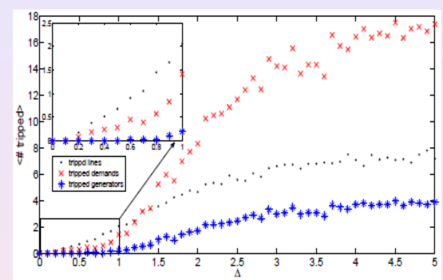
Phase #0 The grid is resilient against fluctuations in demand.

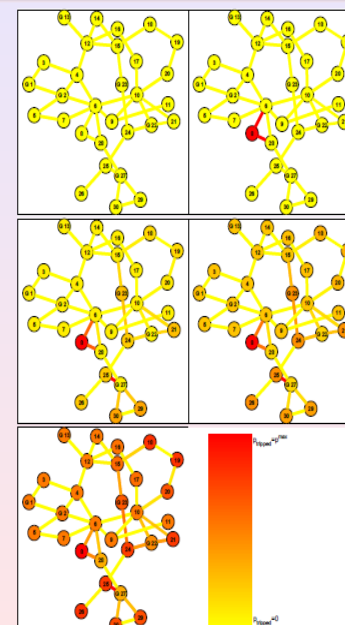
Phase #1 shows tripping of demands due to tripping of overloaded lines. This has a overall "de-stressing" effect on the grid.

Phase #2 Generator nodes start to become tripped, mainly due to islanding of individual generators. With the early tripping of generators the system becomes stressed and cascade evolves much faster (with increase in the level of demand fluctuations) when compared with a relatively modest increase observed in Phase #1.

Phase #3 Significant outages are observed. They are associated with removal from the grid of complex islands, containing both generators and demands.

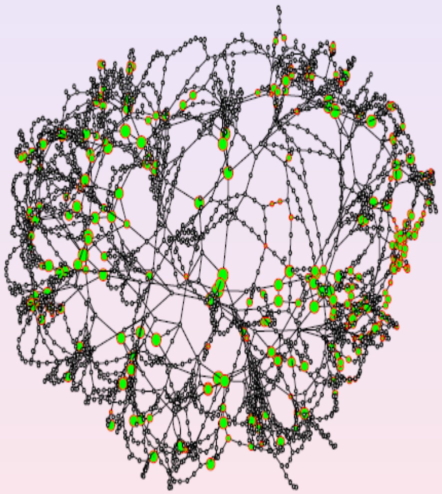
Tests on IEEE 30 system





- Average # vs level of fluctuations.
- Stress Diagram. Average # of failures per edge/node. $\Delta = 0.1, 0.2, 0.9, 1.2, 2.0 \Rightarrow$

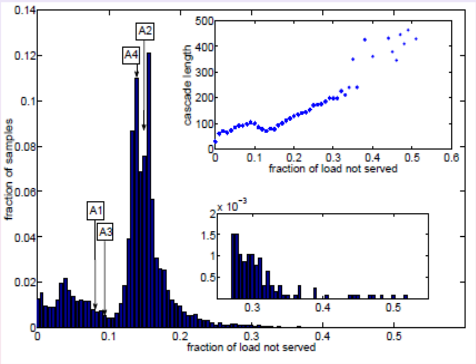
Study Cascade ... and Mitigate ...



Polish Grid (MATPOWER)

- For sufficiently large initiation (failure), many lines becomes overloaded
- If let to develop as is, tripping is "arbitrary"
- Order of tripping can lead to very different results (size of resulting outage)!
- Use it ... and pre-trip smartly!

Experiments with Trippings (I)



Histogram of different outage sizes of 12.000 samples, initiated by tripping line *44*. This line is from the top 1% of the most stressed lines (graded in power flows). Every instance was initiated i.i.d.

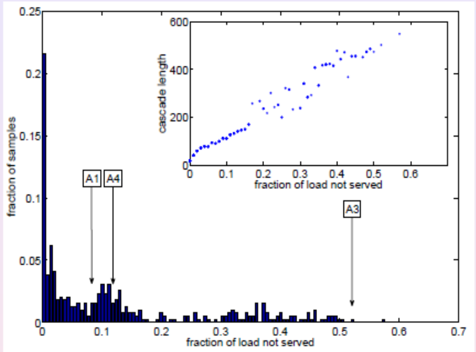
Tripping Strategies

- A1 Trip the line, (i,j), with the minimal current power flow, $P_{ij} = \min\{P_{\mathcal{O}}\}$ ... tree/hierarchical inspired
- A2 Trip the line, (i,j), with the maximal current power flow, $P_{ij} = \max\{P_{\mathcal{O}}\}$ ... anti [A1]
- A3 Trip the line, (i,j), with the minimal current relative overload, $p_{ij} = \min\{p_{\mathcal{O}}\}$ ... similar to [A1]
- A4 Trip line, (i,j), with the maximal current relative overload, $p_{ij} = \max\{p_{\mathcal{O}}\}$ ... anti [A3] also "natural"

Path Forward (Cascades)

- More realistic modeling (load shedding, generator re-dispatch)
- From DC solver to AC solver
- Mixed models - combining fluctuations in demands and incidental line tripping
- More detailed study of effect of capacity inhomogeneity (e.g. on islanding)
- Better algorithms for tripping (global, local, optimal, heuristics)
- Control via tripping + other control options, also at the Unit Commitment and Optimum Power Flow (longer time span) levels
- Towards validated (derived from micro-) phenomenological model and theory of cascades [power tails, scaling, dynamic mechanisms]

Experiments with Trippings (IV)



Histogram of different outage sizes of 400 samples, initiated by tripping lines *3* and *29*.

Intentional tripping of lines according to a good tripping heuristic can become a practical tool for cascade control

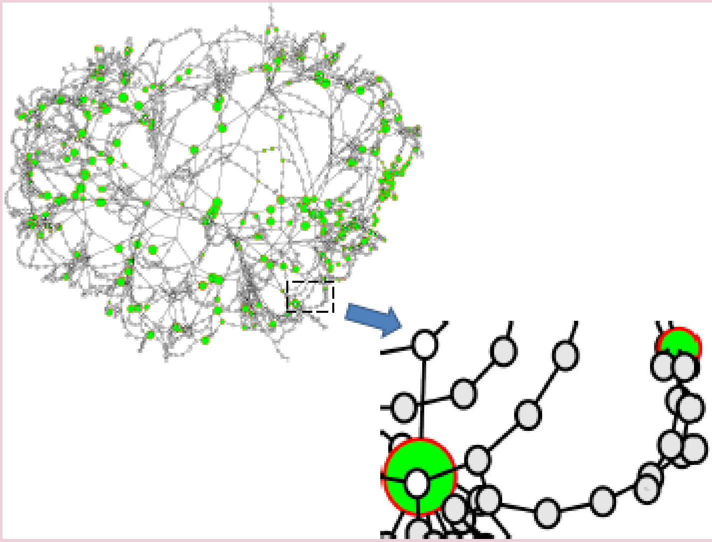
Tripping Strategies

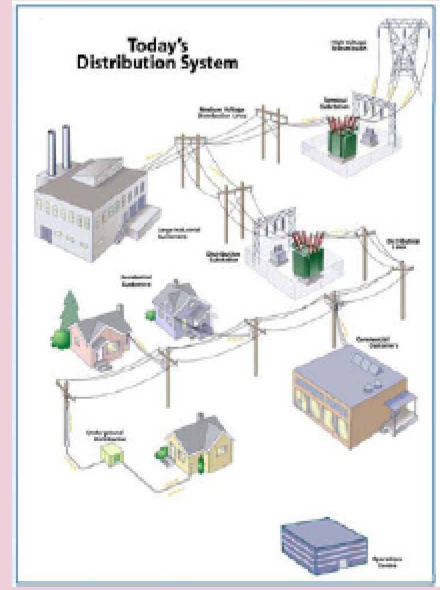
- A1 Trip the line, (i,j), with the minimal current power flow, $P_{ij} = \min\{P_{\mathcal{O}}\}$
- A2 Trip the line, (i,j), with the maximal current power flow, $P_{ij} = \max\{P_{\mathcal{O}}\}$
- A3 Trip the line, (i,j), with the minimal current relative overload, $p_{ij} = \min\{p_{\mathcal{O}}\}$
- A4 Trip line, (i,j), with the maximal current relative overload, $p_{ij} = \max\{p_{\mathcal{O}}\}$

$$p_{ij} = (P_{ij} - P_{ij}^{max})/P_{ij}^{max}$$

Voltage Collapse/Stability

Linear Segments in Transmission & Distribution



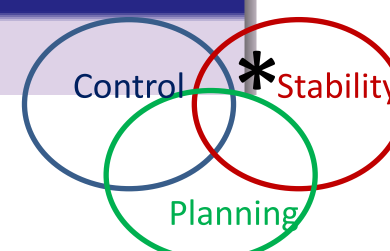


- Spatially Continuous (ODE) Model of a Linear Segment
- Dynamics & Control of Loads
- Critical Slow Down & Voltage Collapse
- Structural and Dynamic (PDE) Stability

Applied Math/Physics Prospective (to appear soon)

- MC, S. Backhaus, K. Turitsyn, V. Chernyak, V. Lebedev

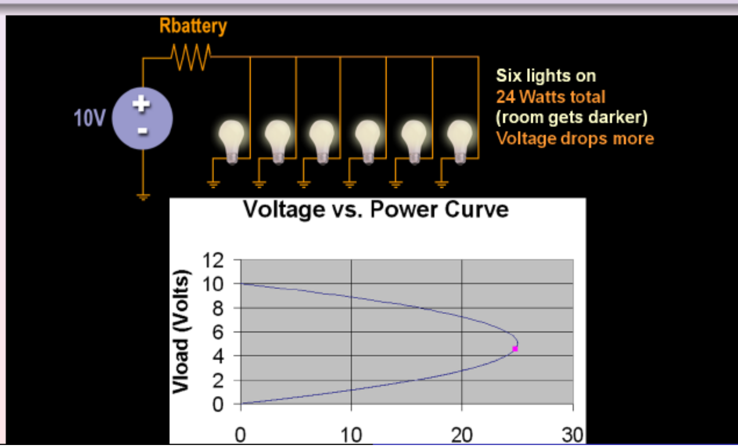
(LANL + MIT, Wayne State, Landau Inst.)



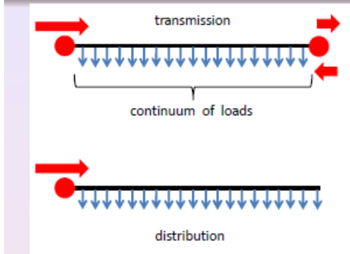
Voltage Collapse

- **Voltage Collapse=** Power Flow Eqs. have no solution(s)

Animation of Voltage Collapse (by P.W. Sauer)



Continuum (one dimensional) power flows



Boundary Conditions: $v(0) = 1,\ \theta(0) = 0 +$

- $P(0)$ and $v(L)$ are fixed
- $P(L) = Q(L) = 0$

From Algebraic Eqs. on a (linear) Graph to Power Flow ODEs

$$\underbrace{0 = p + \beta\partial_r\left(v^2\partial_r\theta\right) + gv\left(\partial_r^2 v - v\left(\partial_r\theta\right)^2\right)}_{\text{balance of real power}}, \quad \underbrace{0 = q + \beta v\left(\partial_r^2 v - v\left(\partial_r\theta\right)^2\right) - g\partial_r\left(v^2\partial_r\theta\right)}_{\text{balance of reactive power}}$$

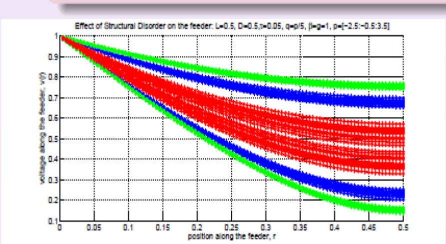
$$P = \underbrace{-\beta v^2\partial_r\theta - gv\partial_r v}_{\text{real power flowing through the segment}}, \quad Q = \underbrace{-\beta v\partial_r v + gv^2\partial_r\theta}_{\text{reactive power flowing though the segment}}$$

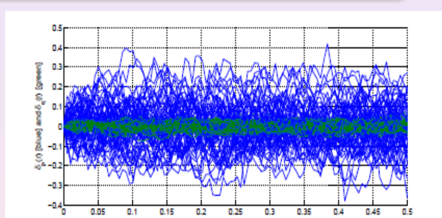
$$0 = \underbrace{p}_{\text{real consumption}} - \overbrace{\partial_r P}^{\text{real transport}} - \underbrace{r\frac{P^2+Q^2}{v^2}}_{\text{real dissipation}}, \quad 0 = \underbrace{q}_{\text{reactive consumption}} - \overbrace{\partial_r Q}^{\text{reactive transport}} - \underbrace{x\frac{P^2+Q^2}{v^2}}_{\text{reactive dissipation}}$$

Effects of Structural Disorder

Amplification and Spread of Disorder

The same feeder ... with quenched disorder in p, q





- In spite of the the fact that the amount of disorder in p and q added was identical in all the three cases, the spread in voltage was significantly stronger close to criticality (the point of voltage collapse).
- The disorder is smoothed out (distributed) in voltage profiles.

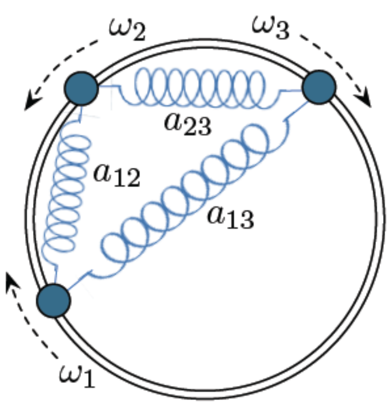
- ODE-PDE approach is a useful tool of model reduction (coarse-graining)
- Approaching voltage collapse is similar to spinodal/bifurcation point (allows interpretation in terms of the energy landscape)
- Critical slowdown precedes voltage collapse (and possibly cascades)
- Disorder is amplified close to collapse

Plans:

- other nonlinear, dynamic and stochastic regimes
- extension to inhomogeneous 2d grids

Phase Stability and Synchronization

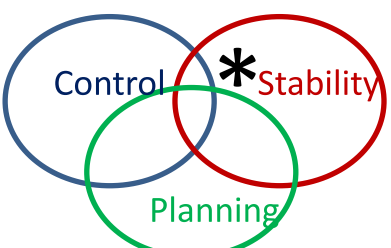
F. Dorfler, MC, F. Bullo [this summer + work in progress] (LANL & UCSB)

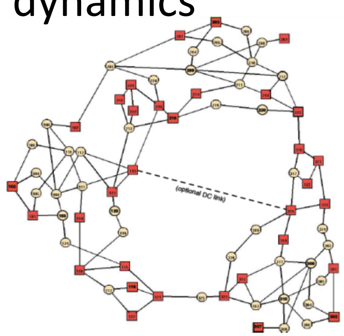


$$M_i\ddot{\theta}_i + D_i\dot{\theta}_i = \omega_i - \sum_{j\in\text{neighbors}(i)} a_{ij}\sin(\theta_i-\theta_j), \quad i\in\{1,\dots,m\},$$

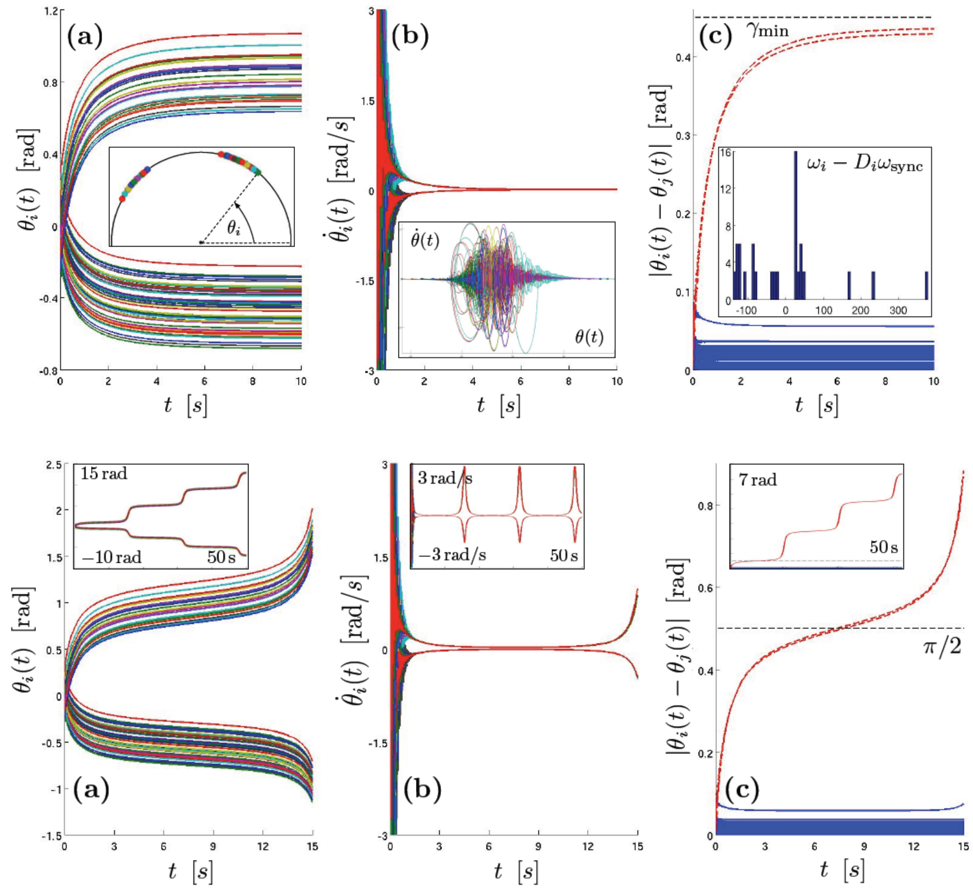
$$D_i\dot{\theta}_i = \omega_i - \sum_{j\in\text{neighbors}(i)} a_{ij}\sin(\theta_i-\theta_j), \quad i\in\{m+1,\dots,n\},$$

Kuromoto (phase) dynamics





• simple (linear and easy to test) and general (!!) synchronization conditions were formulated



Future Directions:

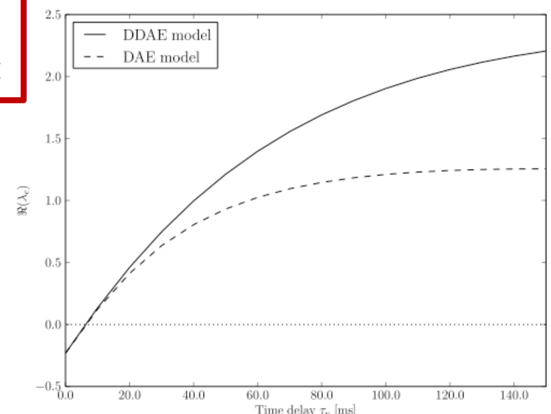
- Static Proxy for Stability (e.g. in distance to failure)
- Towards accounting for voltage (collapse) effects

Impact of Time Delays on Power System Stability

Marian Anghel + Federico Milano (Spain) submitted to IEEE Transactions on Circuits and Systems

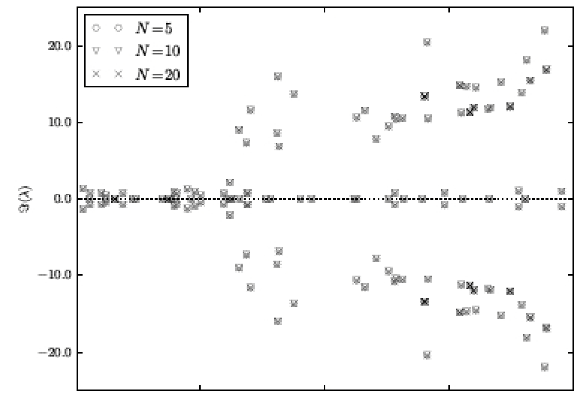
- Time delays are usually neglected
- While their effect on stability is significant

IEEE 14-bus $\mathrm{Re}(\lambda_c)$ vs time delay



1213-bus system for $\tau_v = 10$ ms

These simulations are the largest DDAE to day

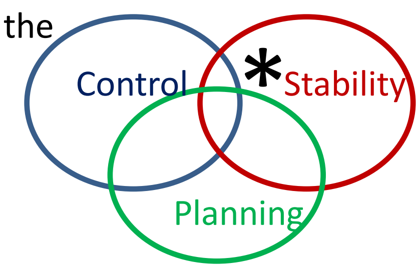


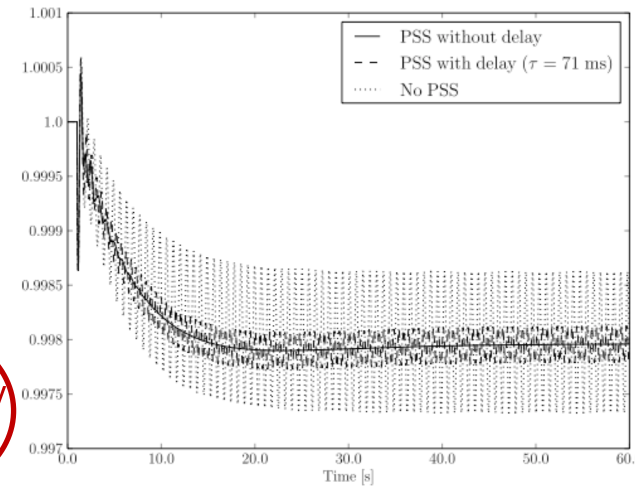
Results:

- General DDAE model was formulated
- Efficient method to analyze small signal stability of the model (rightmost part of the spectrum) was developed
- Analyzed effect of time delays (due to control and stabilizers) on system stability (bifurcation analysis)
- Performed contingency analysis (time domain simulations) with the time-delay

Future Plans:

- Generalization to stochastic time delays.
- Generalization to include stochastic renewable and distributed energy sources.
- Introduce wide-area measurement & control and the associated communication network.





Time delay can be interpreted as a virtual load increase

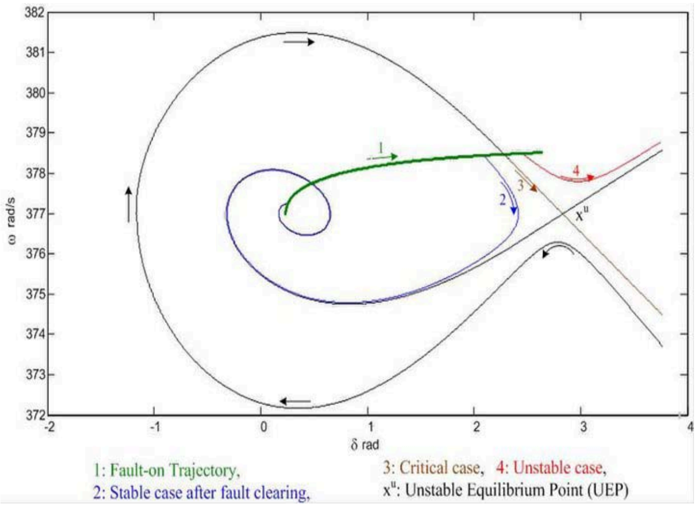
Robust Power Grid Stability Analysis [work in progress]

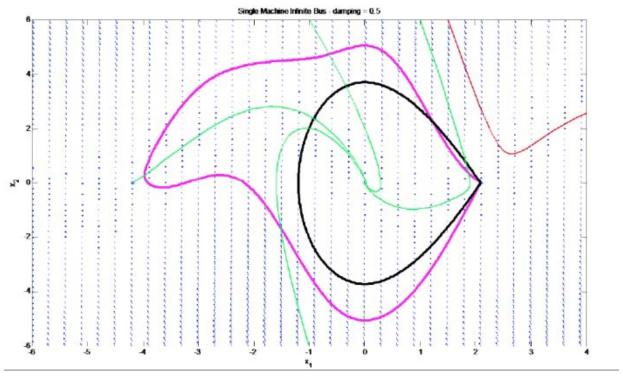
Marian Anghel (CCS-3) + Antonis Papachristodoulou (Oxford) and Federico Milano (Spain)

Main Idea:

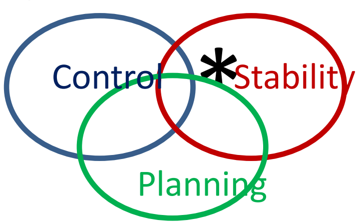
- Formulate Lyapunov stability (of power system with uncertainty in parameters, e.g. damping) problem as a Sum Of Squares (SOS) algebraic optimization, i.e. search for a SOS Lyapunov functional

- Solve the resulting SOS efficiently -> Semi-Definite Programming, estimate Region Of Attraction (ROA)



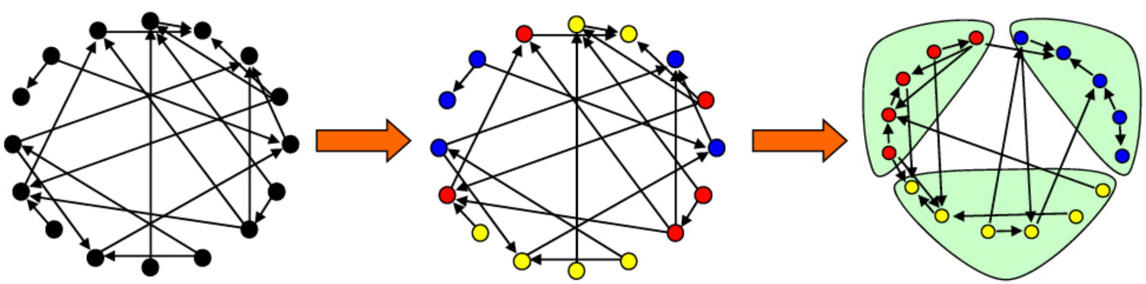


ROA estimated via SOS (magenta) vs energy functional estimate (black)



Future Plans:

- make SOS computations scalable
- e.g. with graph-partitioning and nonlinear system decomposition
- search for composite Lyapunov functions



Example: model reduction in 16 state nonlinear system with 2^{nd} order dynamics

Robust (DC) Optimum Power Flow under uncertain renewables

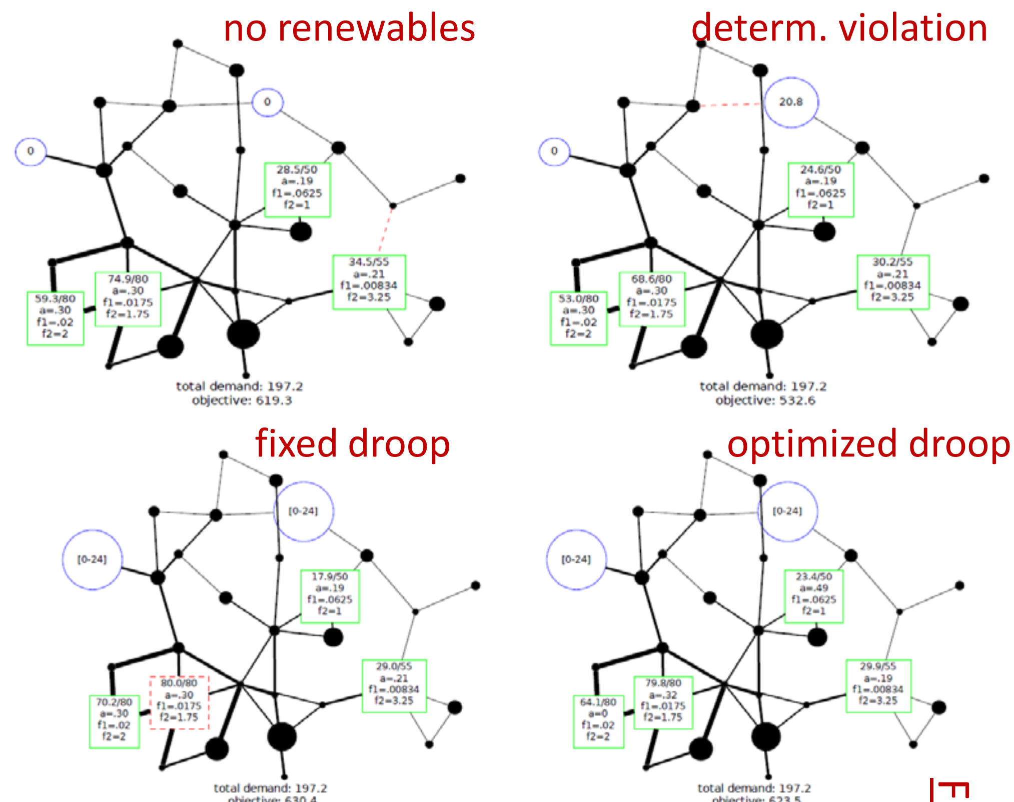
S. Harnett, MC, D. Bienstock[this summer + work in progress] (LANL & Columbia)

- Find optimum generation and droop dispatch (at the beginning of the market period) given uncertainty in renewables (conservative)

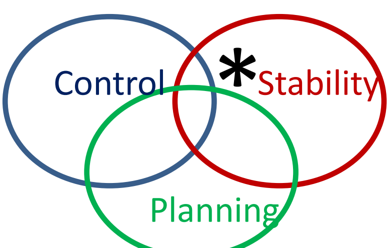
- Robust =worst case

$$\min_{\mathbf{p}_g^0,\vec{\alpha}} \left[\sup_{\mathbf{p}_r \in \mathcal{U}} \sum_{i \in I_r} f_i(p_g^i) : \mathbf{p}_g \in COND_{edge} \cup COND_{gen} \forall \mathbf{p}_r \in \mathcal{U} \right]$$

- $\mathbf{p}_g = \mathbf{p}_g^0 - (\sum \mathbf{p}_r) \cdot \vec{\alpha}$
- f_i are quadratic cost functions for the standard generators
- $COND_{edge} = \{\mathbf{p}_g : \mathbf{B}_{bus}\theta = [\mathbf{p}_g; \mathbf{p}_r; \mathbf{p}_l], |\mathbf{B}_f\theta| \leq \mathbf{F}_{max}\}$
- $COND_{gen} = \{\mathbf{p}_g : \underline{\mathbf{p}_g} \leq \mathbf{p}_g \leq \overline{\mathbf{p}_g}\}$



- Implementation=
ROME (Robust Optimization Made Easy)
+ MATHPOWER



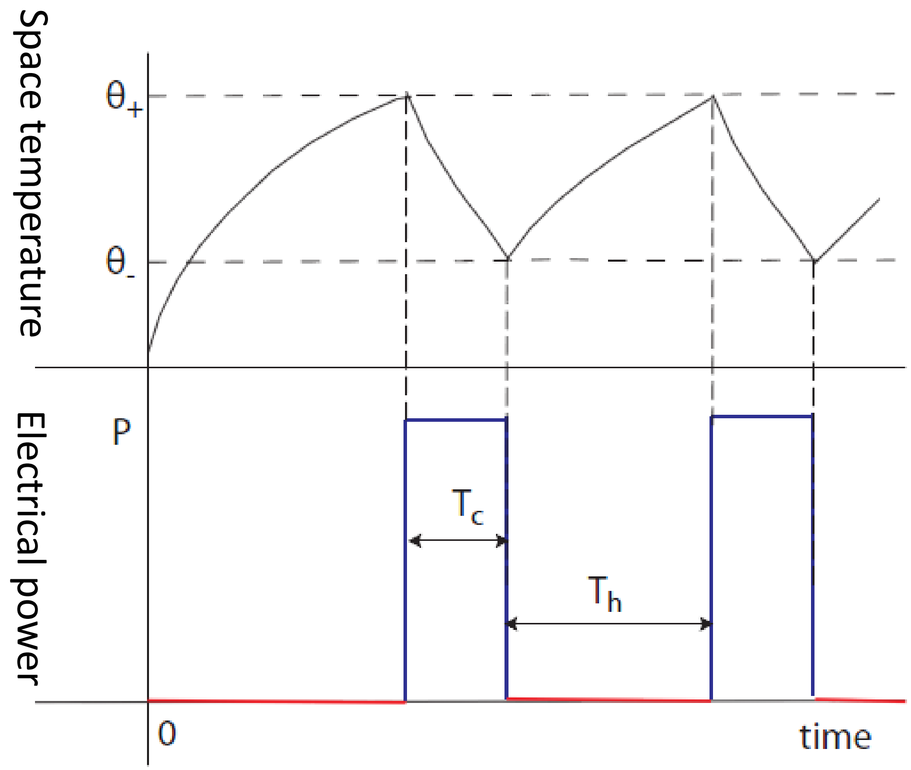
Future Directions:

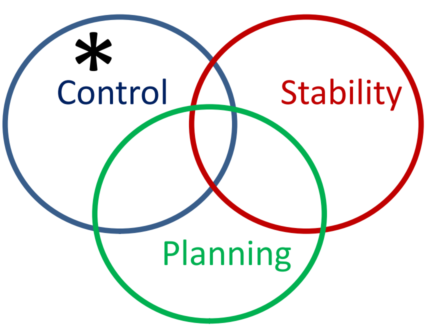
- Less conservative notion of robustness
- Large and more realistic tests (Polish +)
- ``Value at Risk" = generalization of the instanton approach
- Ambiguous Chance Constraint Instanton (uncertainty in modeling the wind distribution)

Demand Response (Thermostat Control)

Electrically-driven heating and cooling is perhaps the cheapest form of energy storage for the electrical grid

- Small changes in temperature set points can temporarily decrease or increase electrical load
- Set point control yields a quantifiable impact on end-use
- Aggregation over 1000's of thermostat loads provides a smooth response
- Individual loads are ~kW range
- Aggregation over 1,000's provides ~MW-scale resources

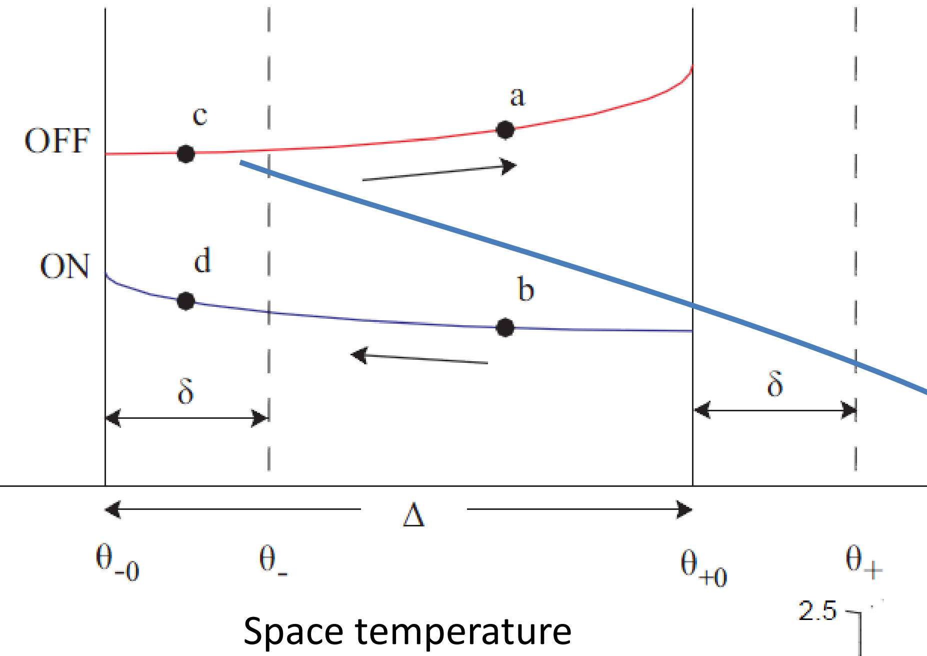


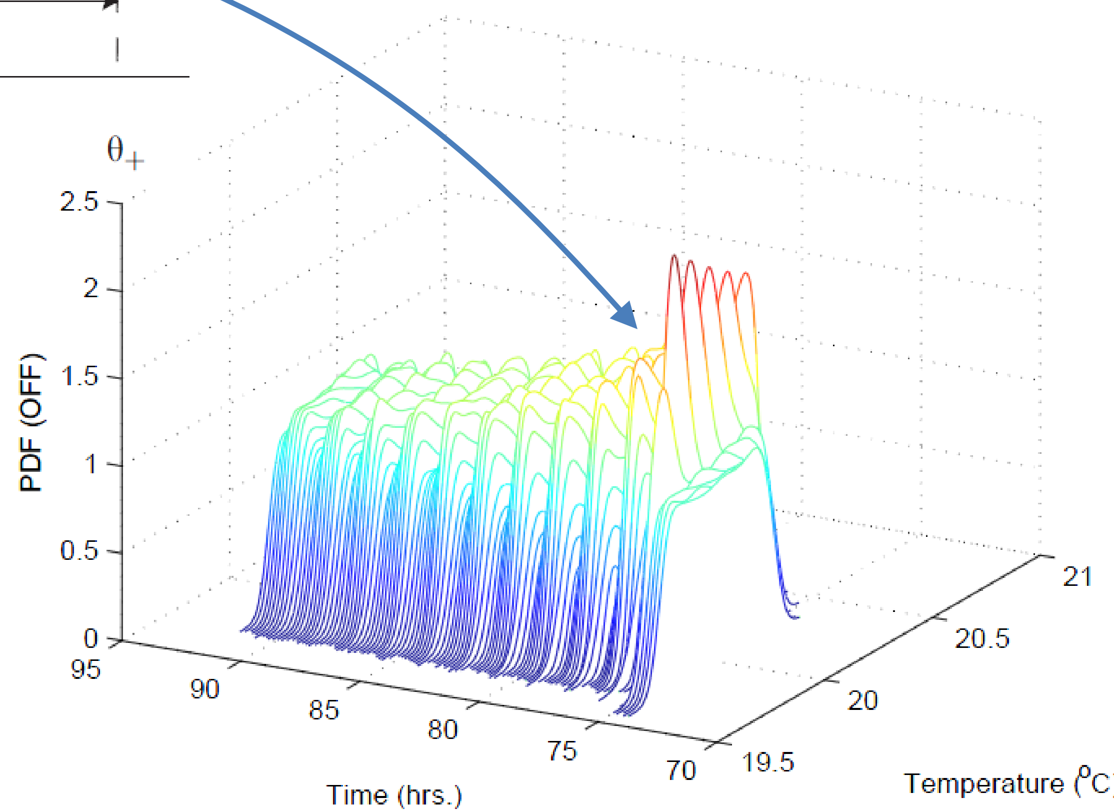


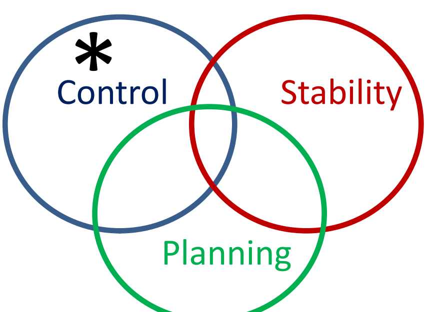
Aggregate control → 1000's of unobserved state variables. Requires a statistical treatment and integration over the unobserved states.

Demand Response (Thermostat Control)

- Use statistical mechanics methods to solve for time evolution of probability distributions
- Compute electrical power
- Dynamical response of <u>aggregate</u> electrical load to set point changes

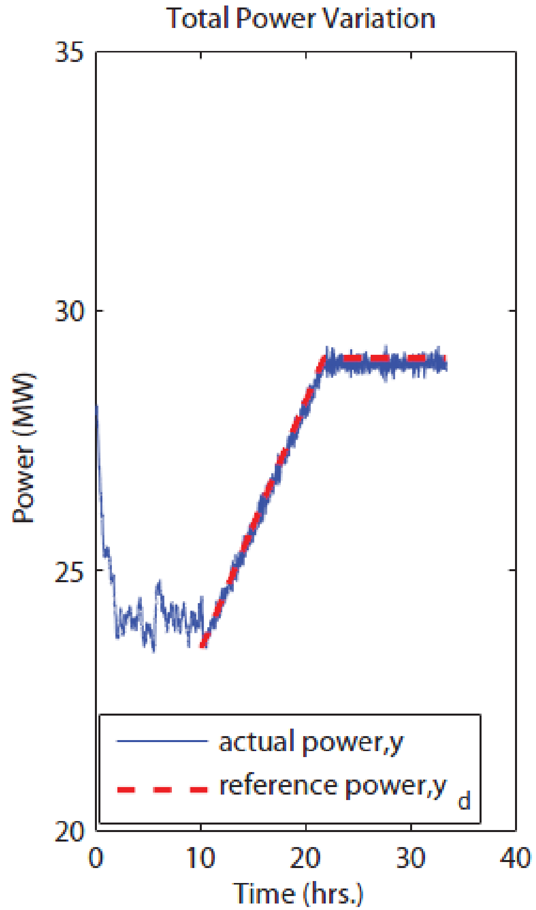


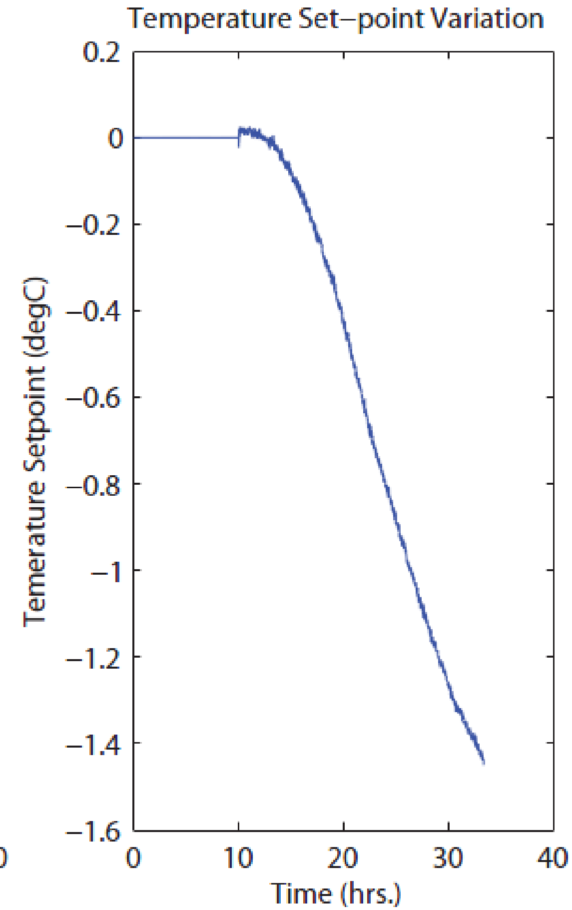


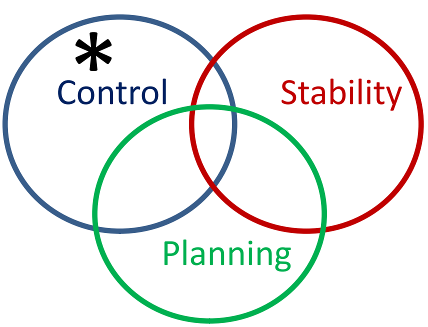


Demand Response (Thermostat Control)

- Dynamical response of aggregate electrical load → Design of feedback control laws
- Control laws validated in simulation environment







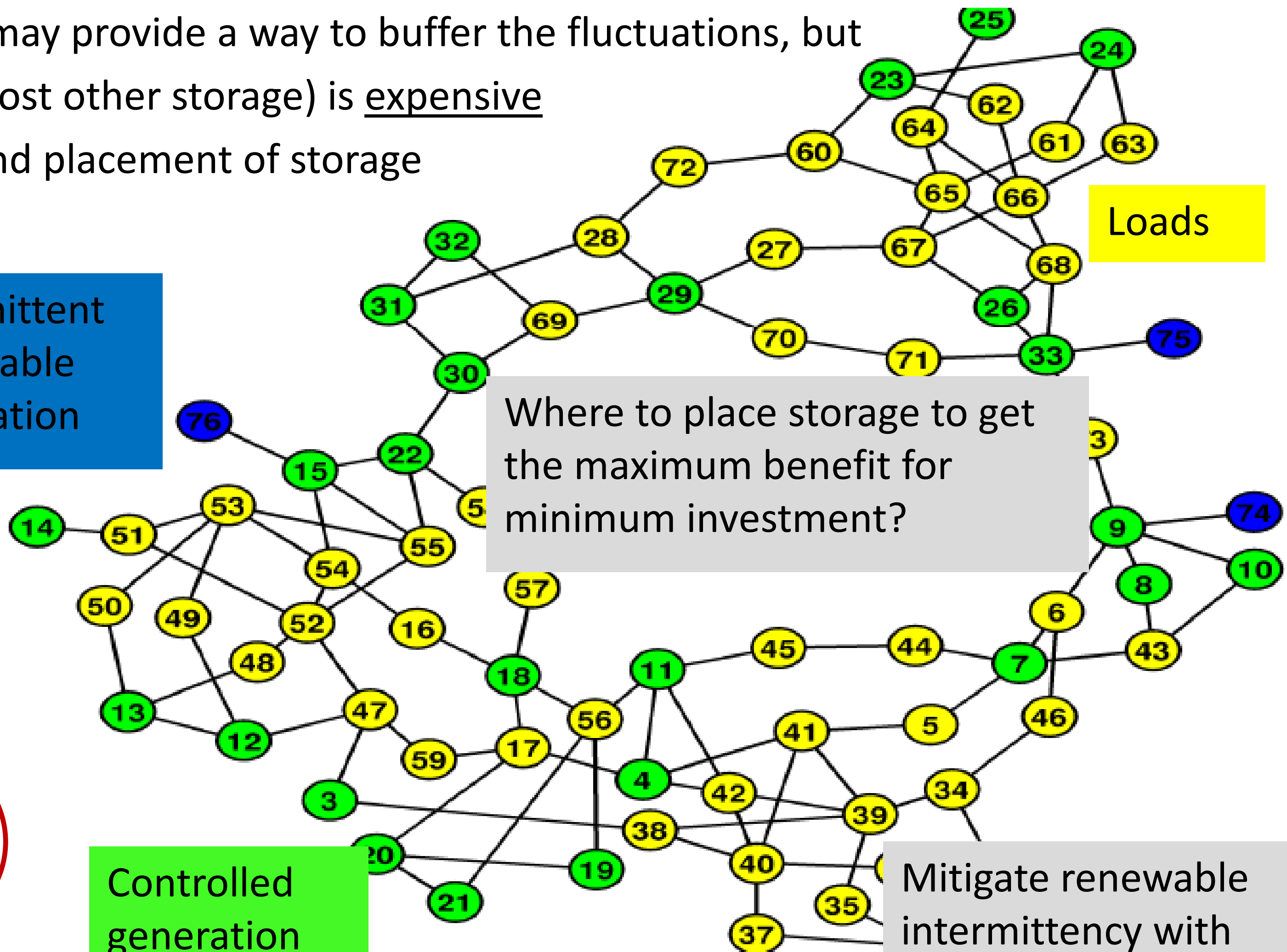
LANL + University of Michigan

S. Kundu, N. Sinitsyn, S. Backhaus, and I. Hiskens Modeling and control of thermostatically controlled loads , 17th Power Systems Computation Conference 2011, arXiv:1101.2157

Placement and sizing of storage in an existing grid

- Wind and photovoltaic generation fluctuate in time and space, but
- generation and load must stay in balance at all times
- Battery storage may provide a way to buffer the fluctuations, but
- batteries (and most other storage) is <u>expensive</u>
- Optimal sizing and placement of storage

RTS-96



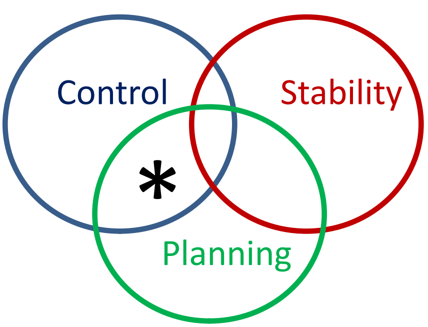
Loads

Intermittent renewable generation

Where to place storage to get the maximum benefit for minimum investment?

Controlled generation

Mitigate renewable intermittency with storage.



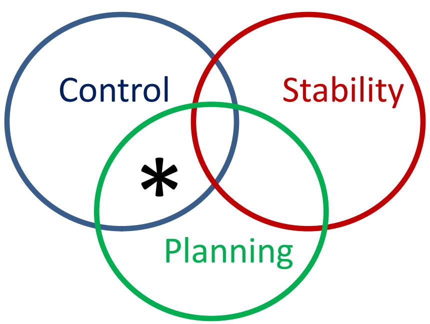
Placement and sizing of storage in an existing grid

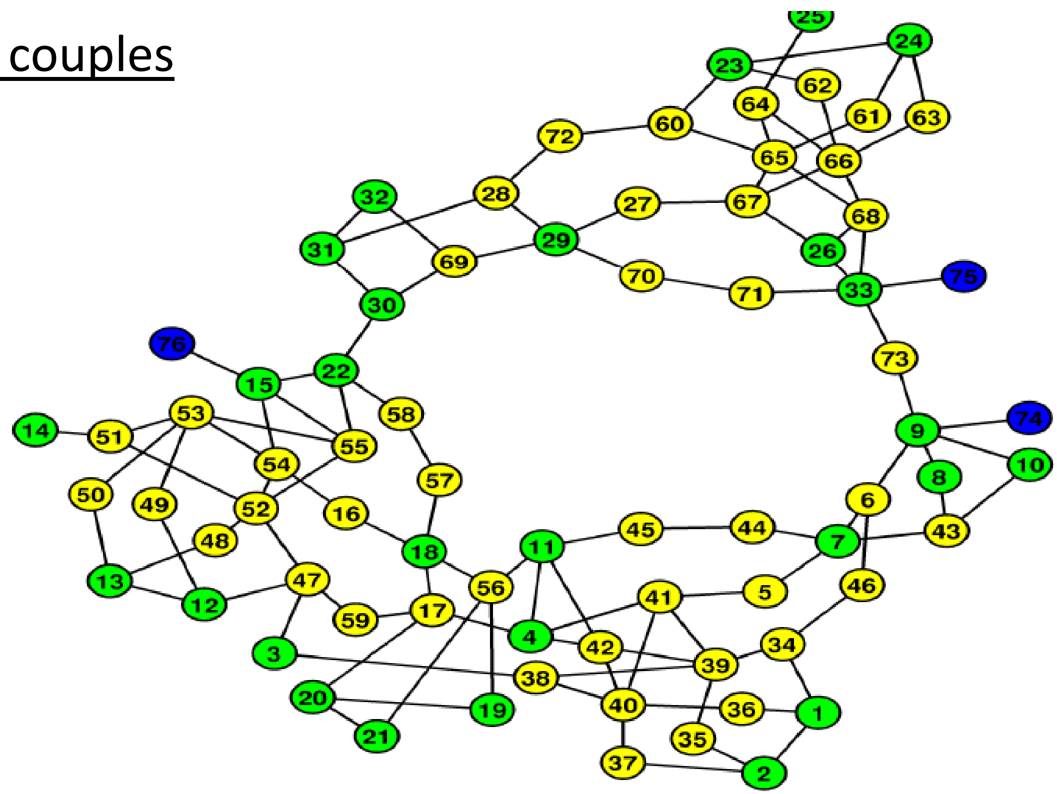
Some “intuitive” design choices

- Place storage at the renewable sites and fix the total output?
- Place storage at the loads and absorb the excess generation for later delivery?
- Place the storage at the generation sites to provide more regulation capacity?
- Place a small amount of storage everywhere?

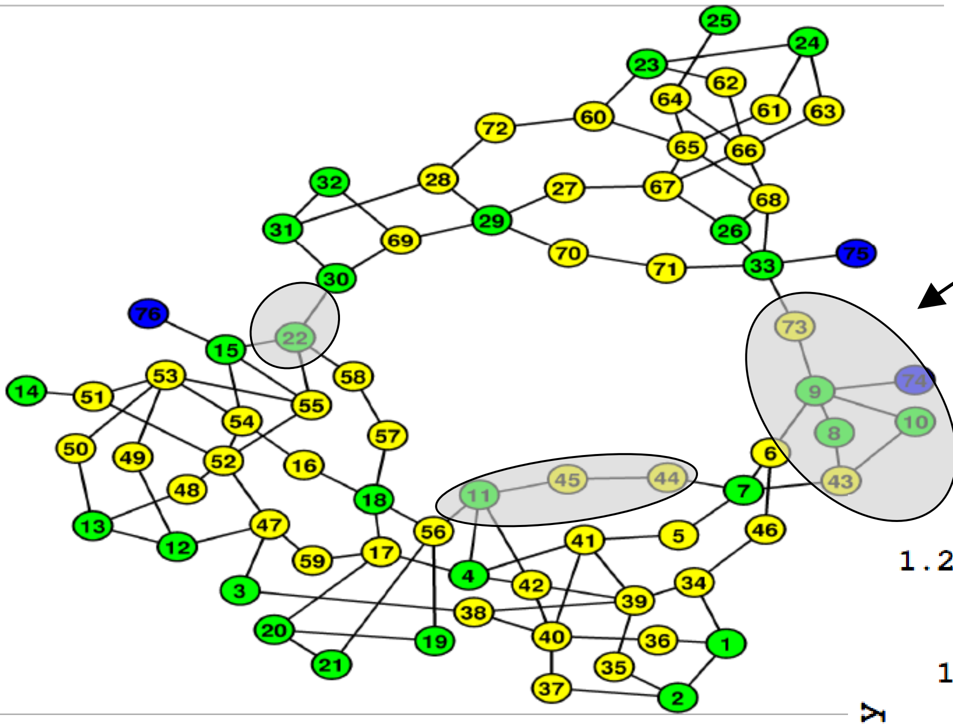
What’s needed is an method that couples operations and planning

- Power flow physics
- Generator controls
- Storage controls
- Planning heuristics

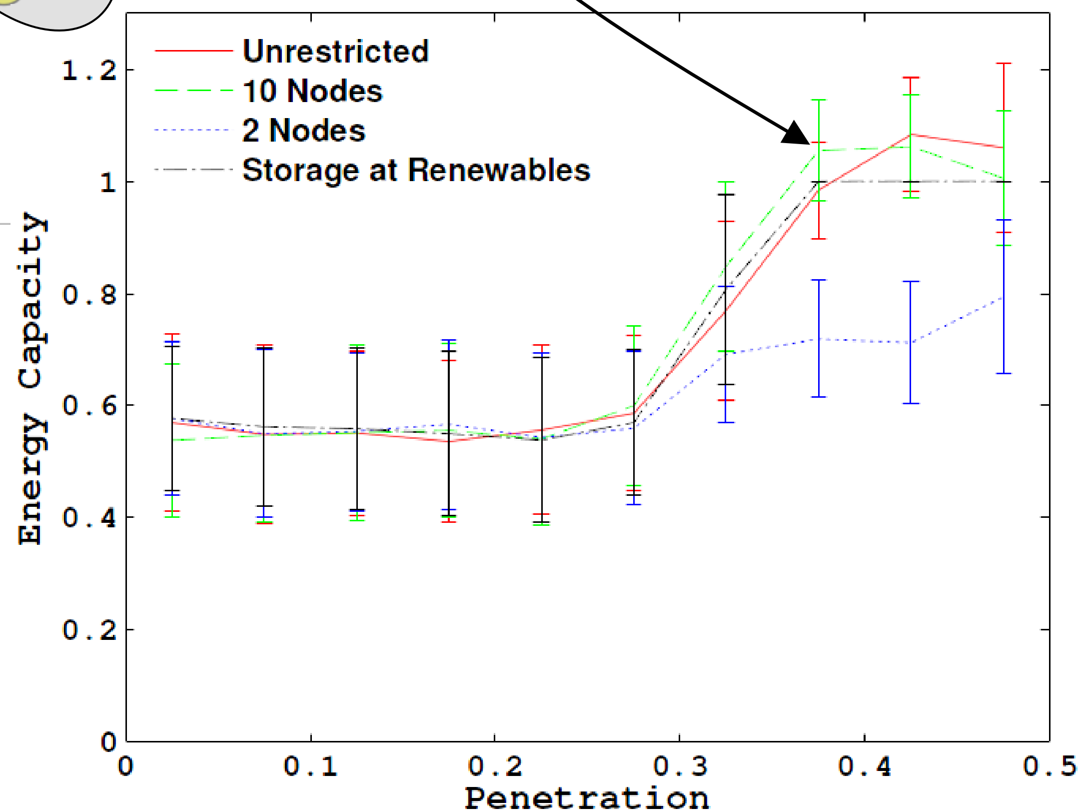


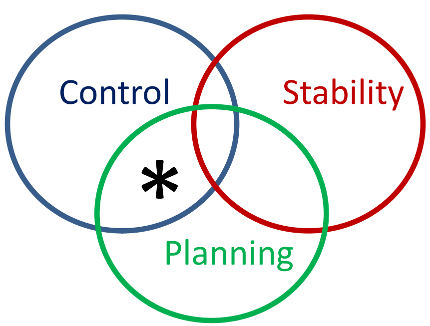


Placement and sizing of storage in an existing grid

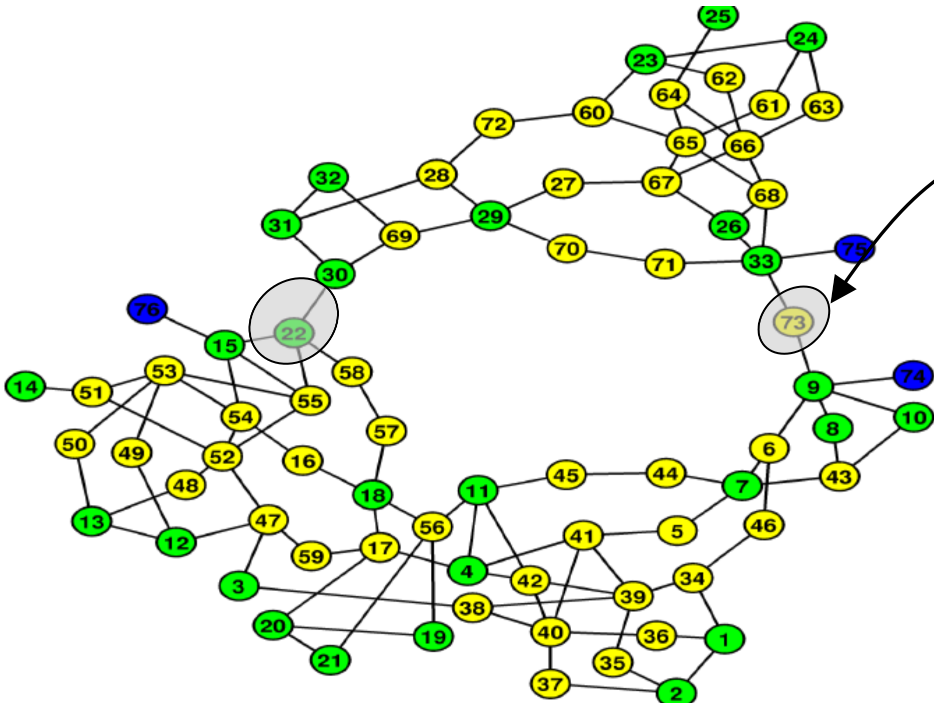


10 storage nodes



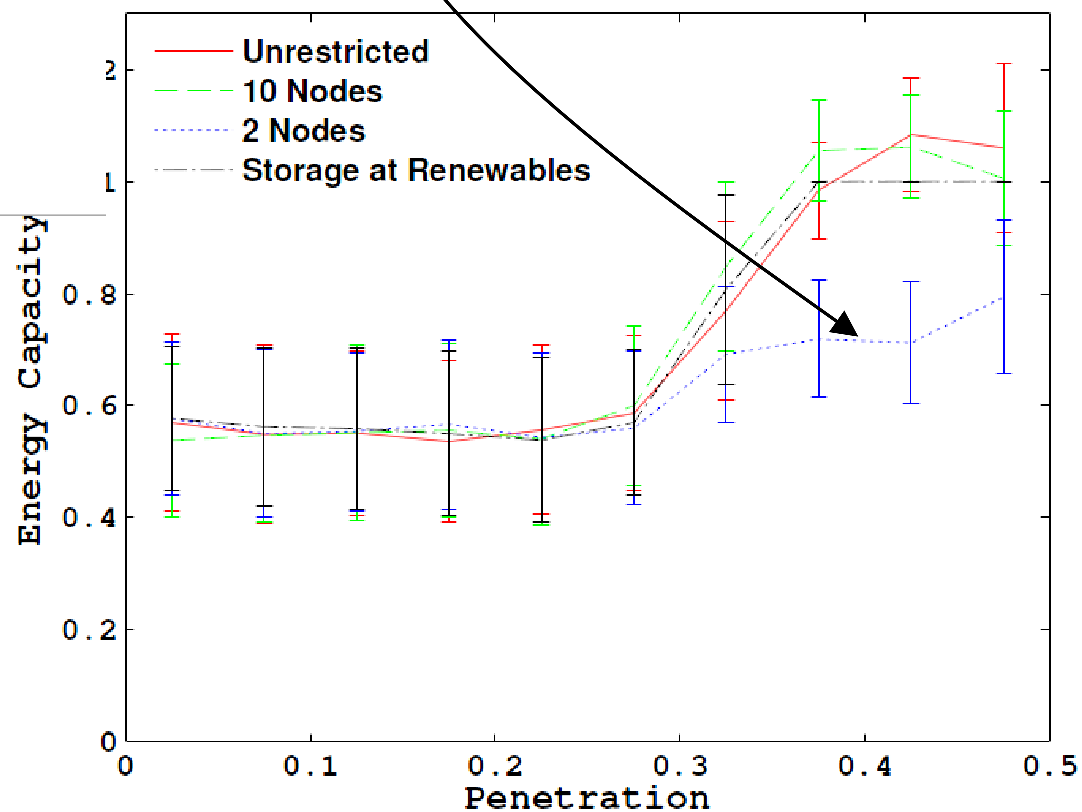


Placement and sizing of storage in an existing grid



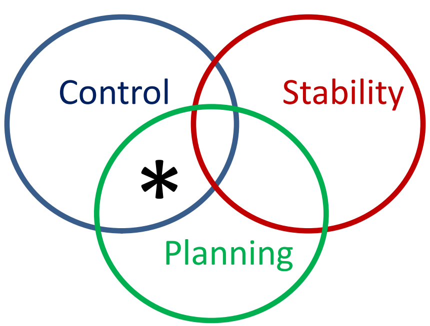
2 storage nodes

Imposing sparsity via planning heuristics yields better controllability from storage investment



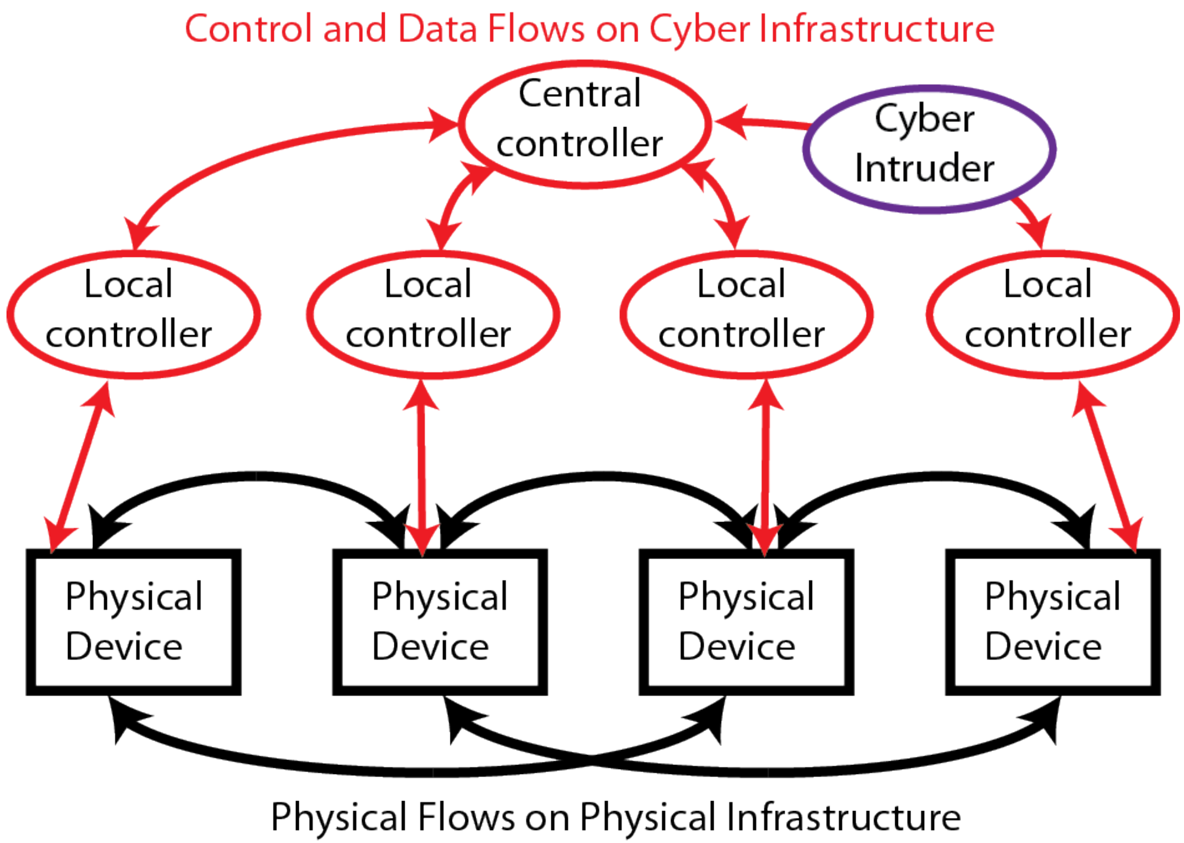
LANL + University of Washington

K. Dvijotham, S. Backhaus, and M. Chertkov, Operations-Based Planning for Placement and Sizing of Energy Storage in a Grid With a High Penetration of Renewables, arxiv:1107.1382.

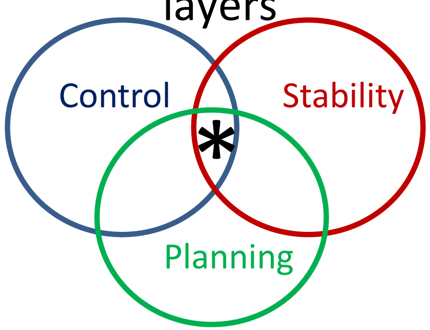


Cyber-Physical Security—Game Theory Approaches

- Cyber-physical system is an (often distributed) system the obeys known physical laws and is controlled in either a centralized or distributed fashion where control information is passed over a cyber infrastructure.
  - Electrical Grid
  - Water Systems
  - Chemical Plants
  - Gas and Oil Pipelines
  - etc…..

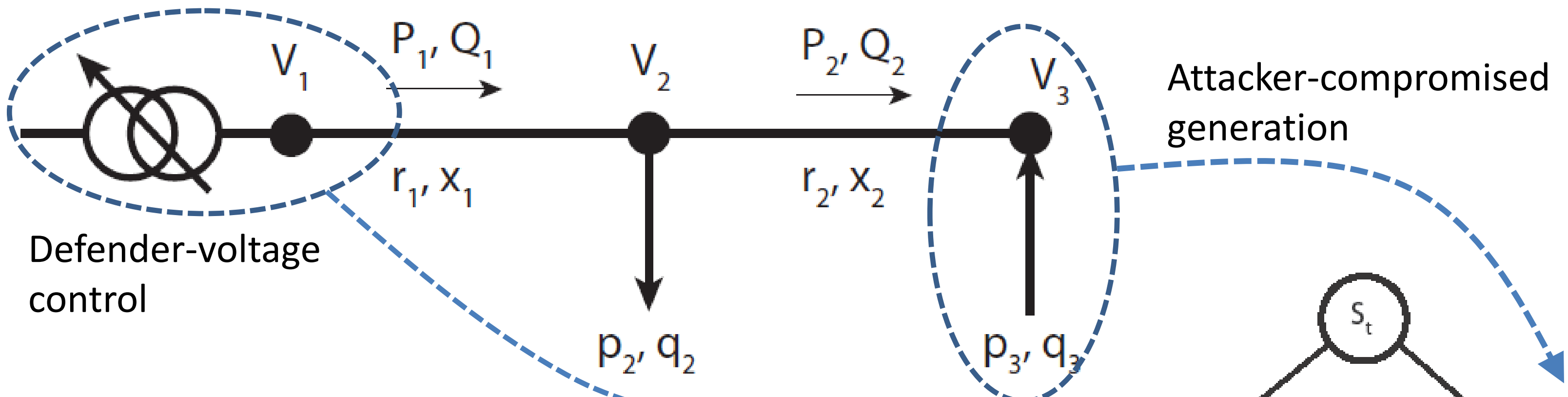


- Models exist for the physical devices and flows
- Often there are system models that integrate the control and physical layers

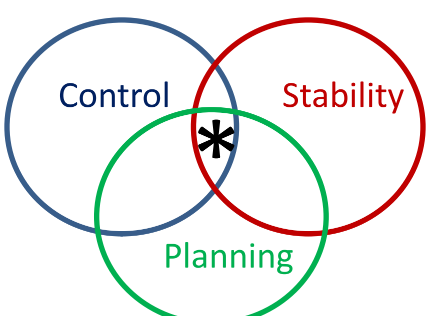


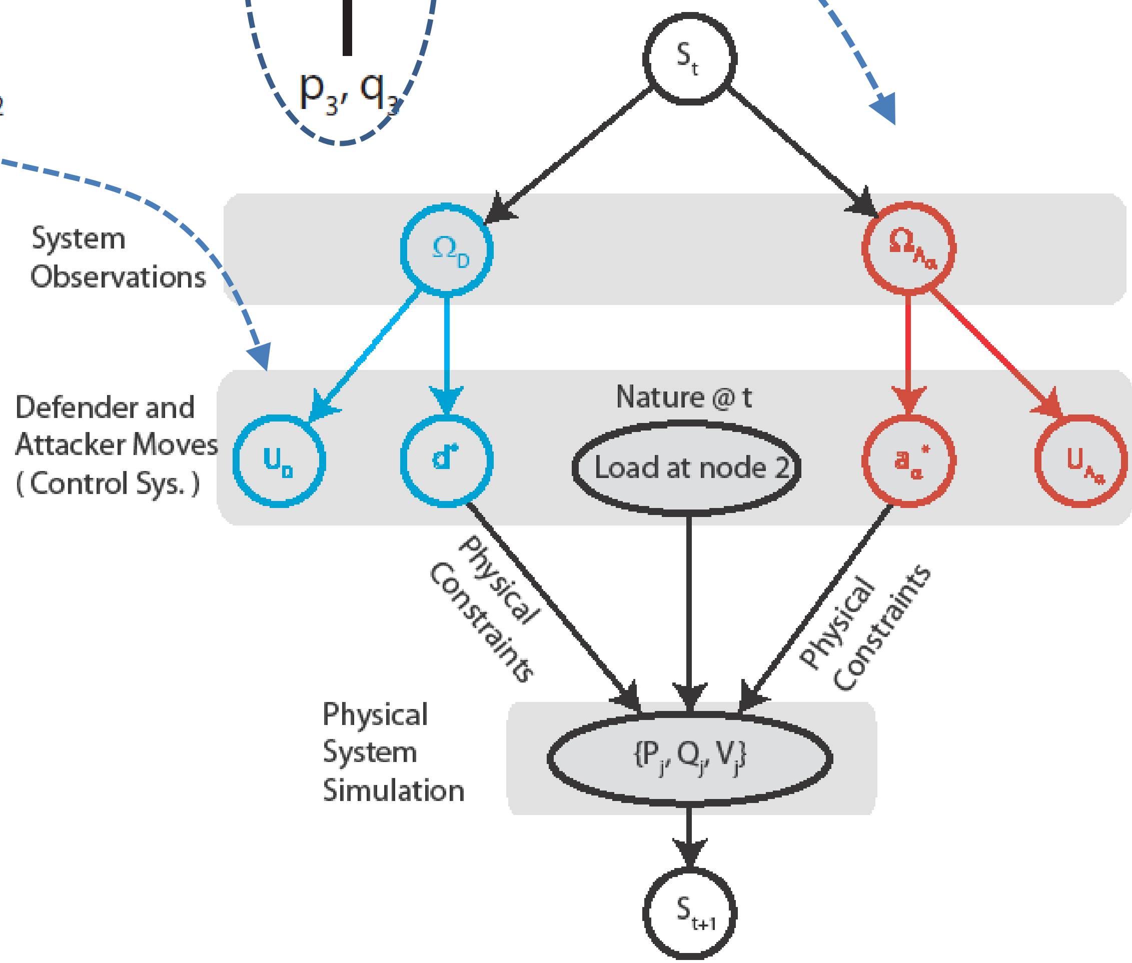
LANL + NASA Ames + American University + Carnegie Mellon (SV)

Cyber-Physical Security—Game Theory Approaches

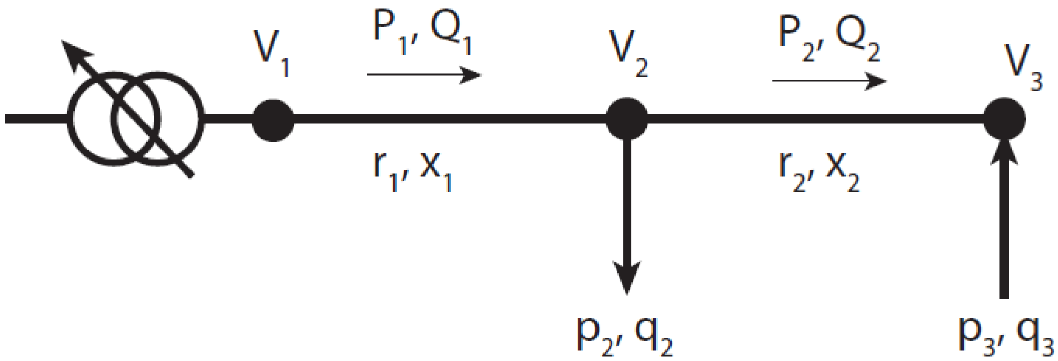


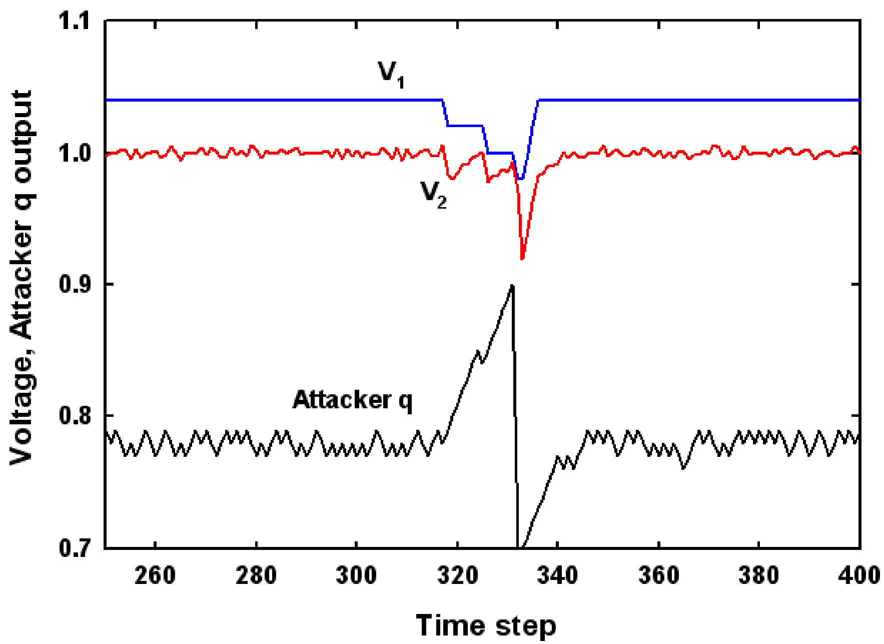
- Long-term attacker strategies can leverage power system limitations
- Strategy searches via enumeration are computationally intractable—not representative of human behavior
- Developing heuristics based on policy-driven behavior

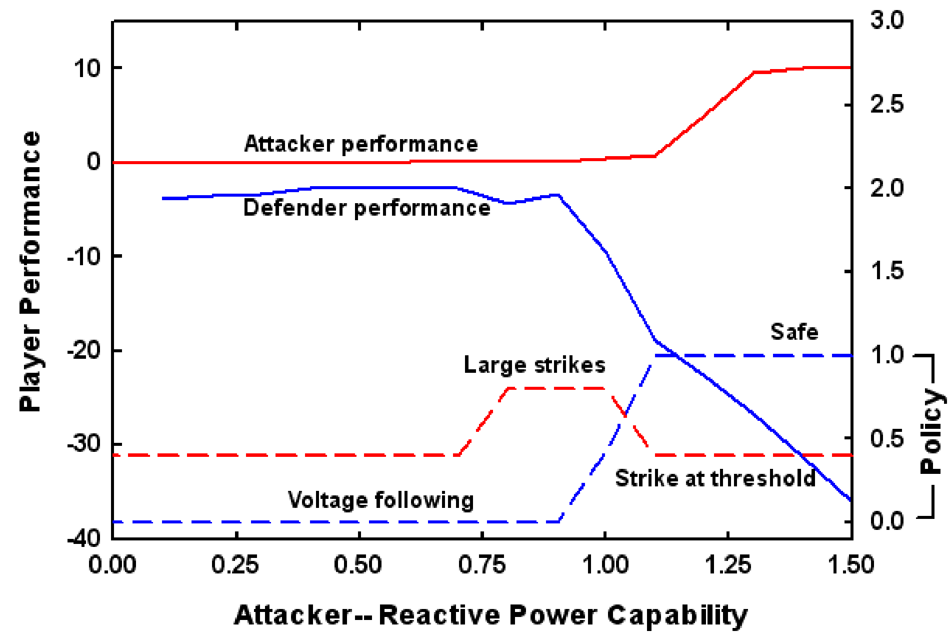


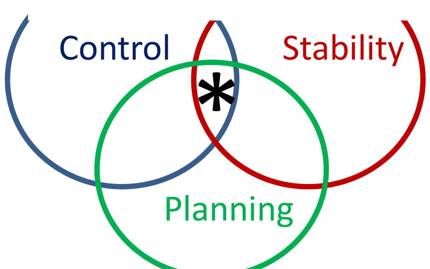


Cyber-Physical Security—Game Theory Approaches



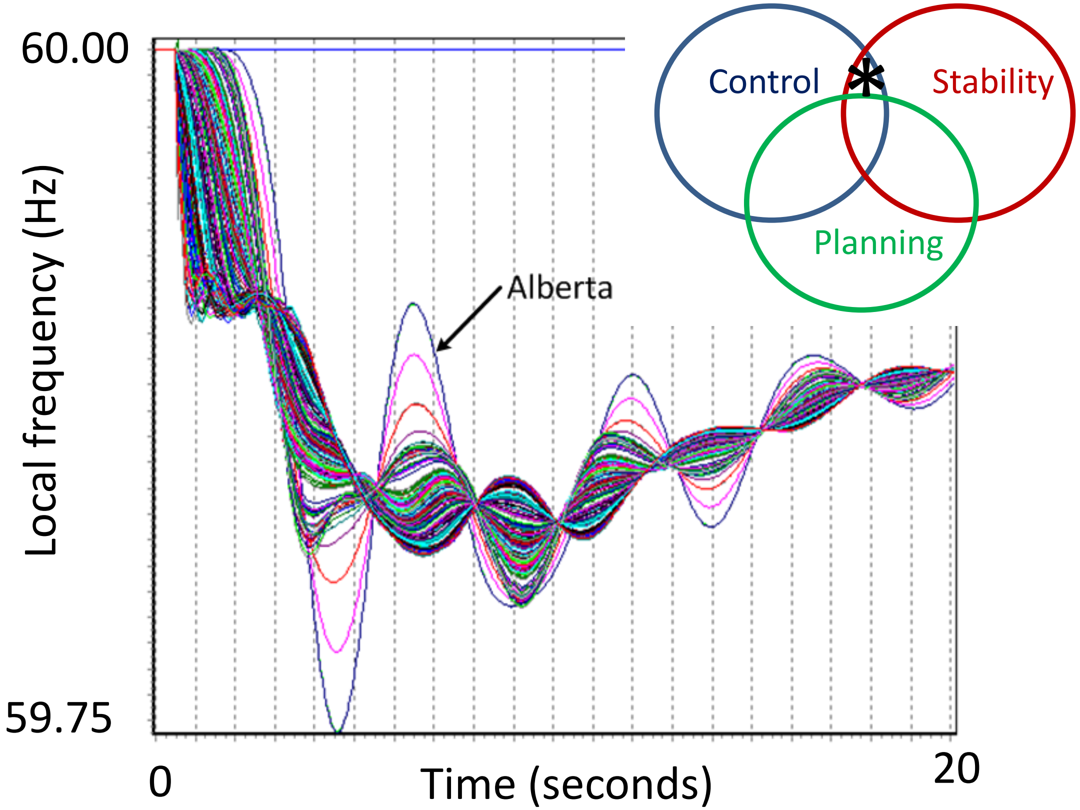


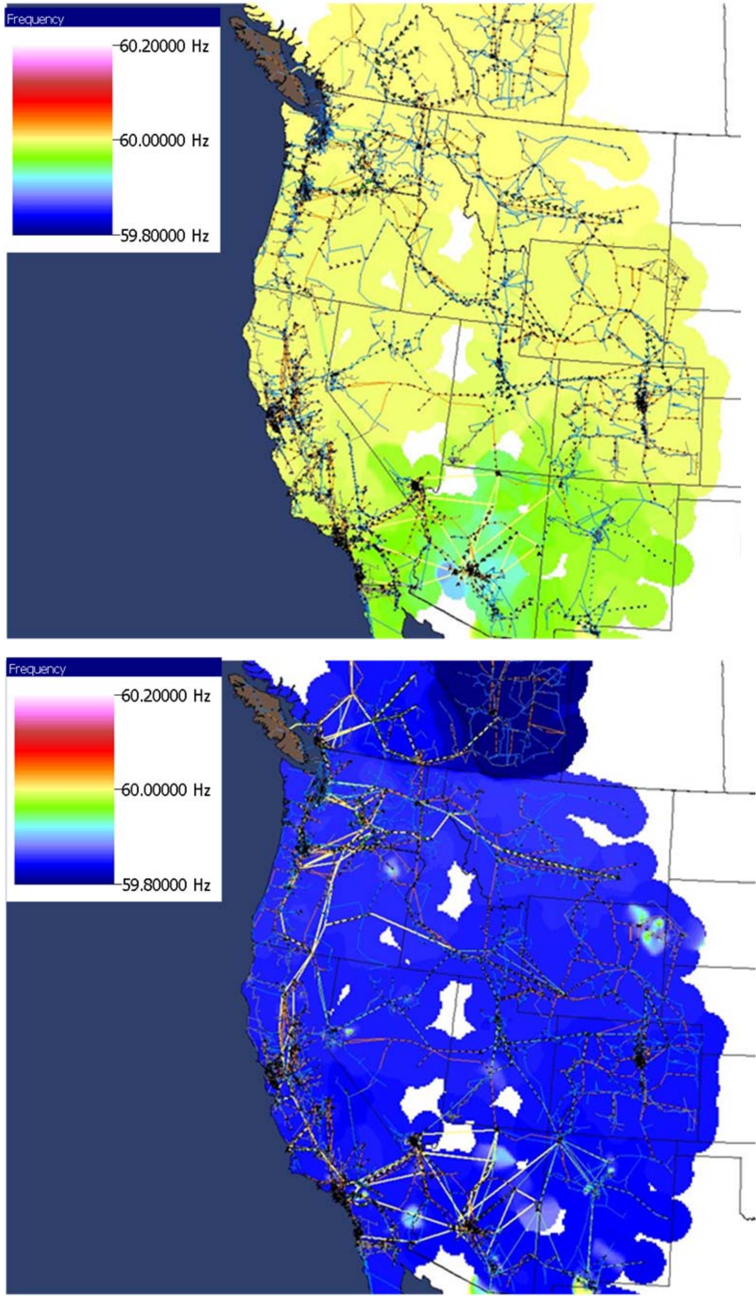




EM waves, detection, PMUs and Green functions

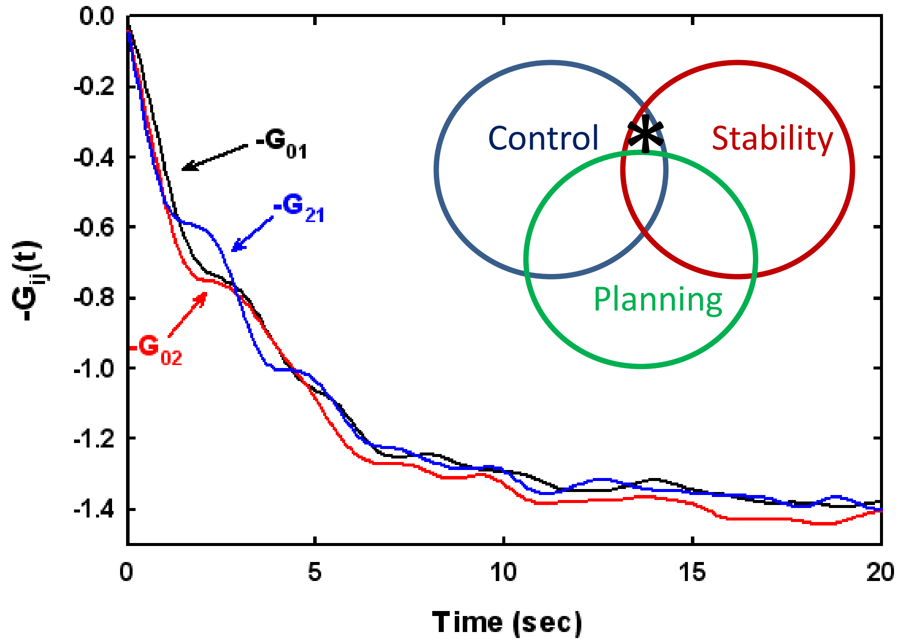
- Major system disturbances propagate at EM waves
- Detailed, computationally-intensive models can capture the system-wide response
- Not useful for real-time operation… two slow… grid evolves in time making accuracy hard to assure
- We need an <u>on-line, real-time monitoring system that can **forecast this behavior before it actually happens**</u>

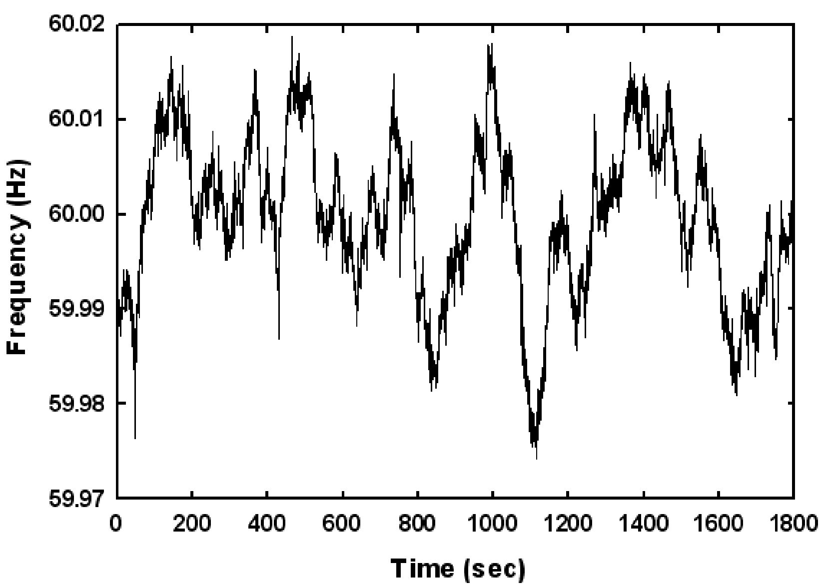


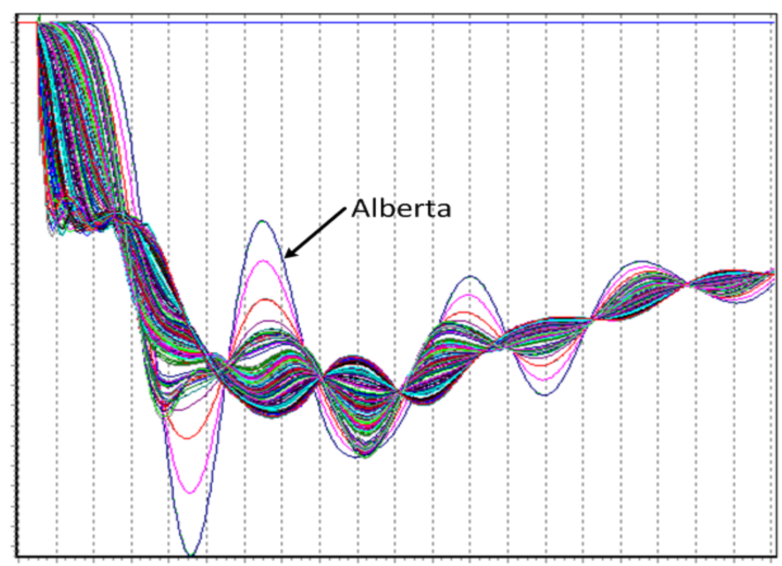


EM waves, detection, PMUs and Green functions

- Phasor Measurement Units (PMU) provide time-synchronized measurements of frequency at many locations in the grid
- Cross-correlations in time of "ambient frequency noise"
- Extract the Greens function for EM wave propagation—response to a loss in generation

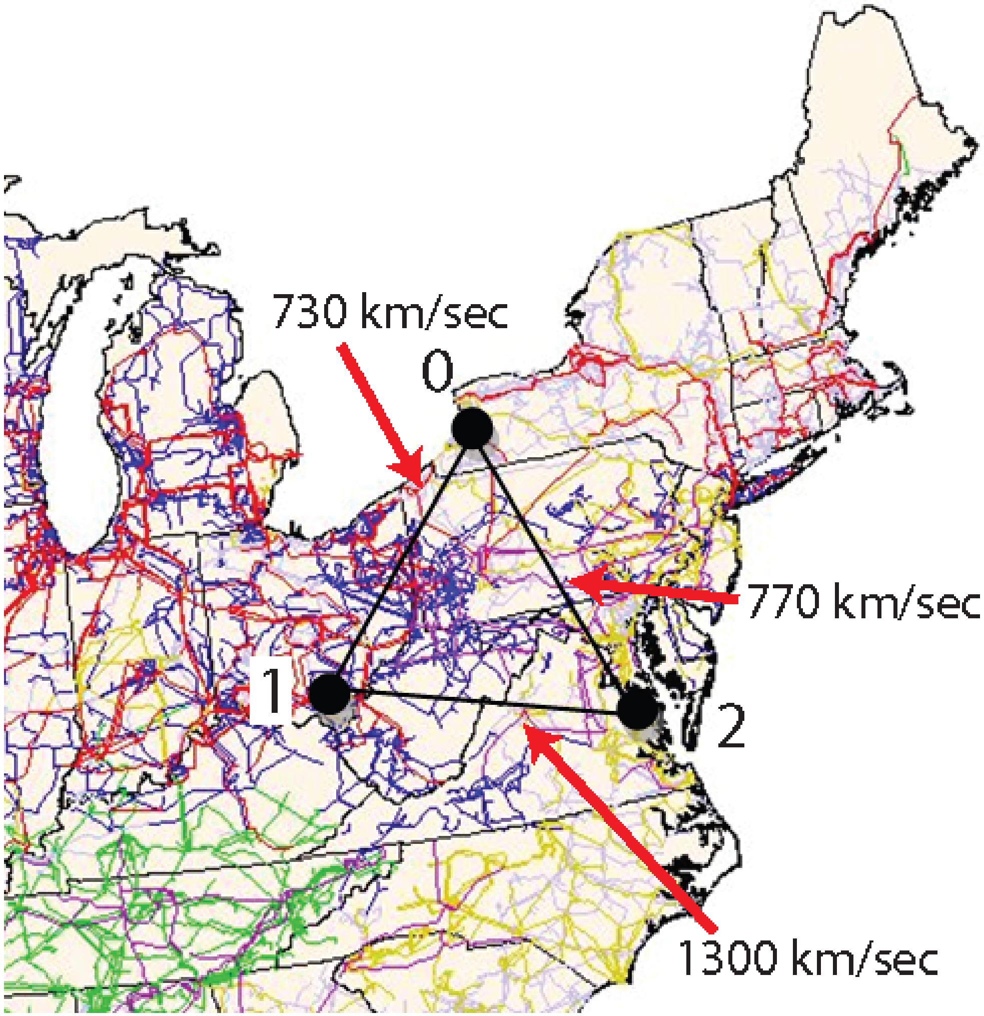


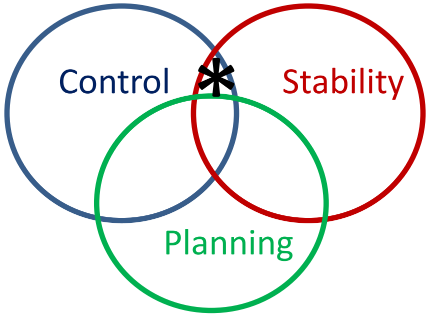




EM waves, detection, PMUs and Green functions

- Greens functions can be used to extract speed and damping of EM waves
- Create a map of EM-wave propagation properties
- Map → predict the response of the grid to a disturbance
- Map → predict the frequency and damping of the grid's resonant modes
- Can be done in real-time and on-line



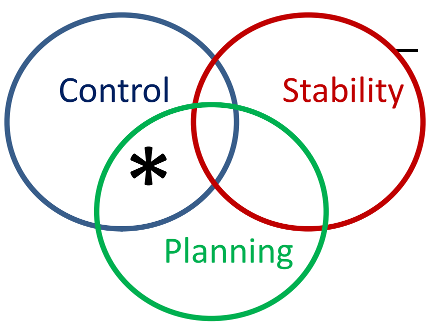


LANL + University of Tennessee

S. Backhaus and Y. Liu, [Electromechanical Wave Green's Function Estimation from Ambient Electrical Grid Frequency Noise](), HICCS 2012 ,arxiv:1108.1804.

Grid Expansion Planning with Non-Linear Power Flow Models

- Development of a randomized constructive heuristic algorithm that improves the efficiency of the algorithm developed in the first year by a factor of 10.
- Integrated resource planning for combined generation and transmission expansion.
  - Capability to determine the best places to build renewable generation, weighing the expected renewable output of generation sites vs. the cost to build transmission to the generation sites.
- Ability to combine grid operations with grid planning
  - Expansion planning based solely on costs may not have the desired operating outcomes
  - Example: Adding renewable generation may not have the expected carbon reduction as it can curtail existing carbon-neutral generation instead of heavy carbon emitters.



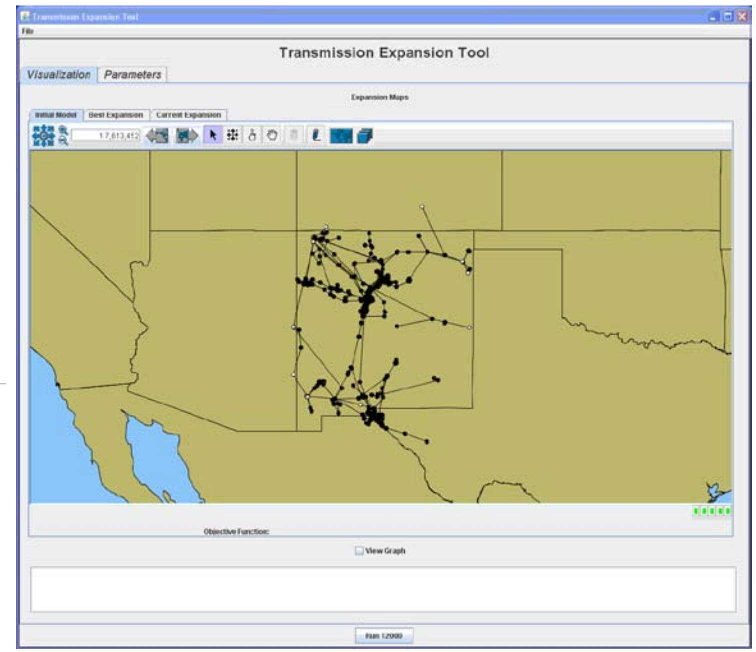
Grid Expansion Planning Studies

Problems taken from IEEE literature

	DC	AC
G1	390K	1316K
G2	392K	1977K
G3	272K	1003K
G3	381K	1978K

- Expansion based on AC modeling considerable more expensive than DC modeling when problems are tightly constrained (renewable energy integration)

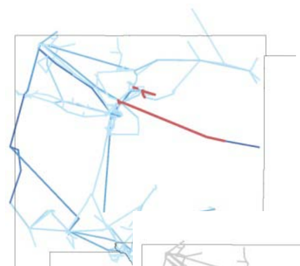
- Empirical evidence of the importance of using complex power flow models

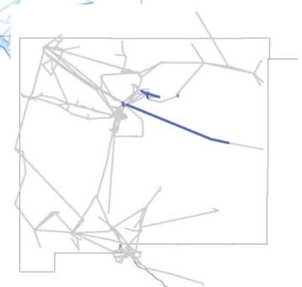


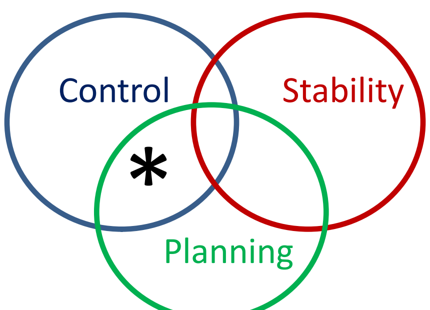
- Scales to state (and national) size models

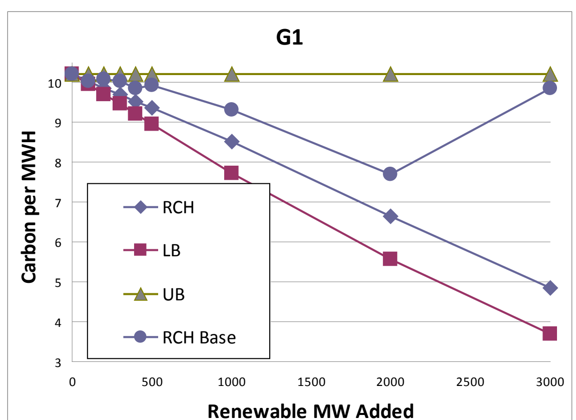
- 2020 load and generation projections for New Mexico

- 1700 MVA of overloads in 31 corridors









- Planning without operation leads to undesirable outcomes.

- Integration of renewables based on economic costs may displace existing green generation (RCH Base)

- Must take into account grid operations (generator dispatching) when expanding to reduce carbon emissions

Student Projects (this summer)

- PHEV charging station expansion planning
  - Stefan Solntsev – Northwestern (with Russell Bent and Feng Pan)
- Game Theoretic Modeling of cyber attacks on power systems
  - Devin Pohly – Penn State (with Scott Backhaus, Russell Bent, and David Wolpert)
- Numerical Evaluation of power flow modeling approximations for smart grid applications
  - Carleton Coffrin – Brown University (with Russell Bent)
- PHEV charging station operations and scheduling
  - Sara Nurre – Rensselaer Polytechnic (with Feng Pan and Russell Bent)
  - Yunjian Xu —MIT (with Feng Pan)
- Transmission Switching
  - Kunaal Verma – Michigan State (with Loren Toole and Russell Bent)
  - Clayton Barrows – Penn State (with Russell Bent)
- Distributed Control Algorithm Discovery
  - Soumya Kundu—University of Michigan (with Scott Backhaus)
- Operations-Based Planning
  - Krishnamurthy Dvijotham—University of Washington (with Scott Backhaus and Misha Chertkov)
- Robust Optimum Power Flow
  - Sean Harnett —Columbia University (with Misha Chertkov)
- Phase Stability, Synchronization Criteria
  - Florian Dorfler —UCSB (with Misha Chertkov)
- Stochastic Stability and Topology of Power Flows
  - Grisha Syzov—Landau Institute, Moscow (with Misha Chertkov)

Our Publications

29. **R. Bent, A. Berscheid, and L. Toole,** Transmission Network Expansion Planning with Complex Power Flow Models, submitted to IEEE Transactions on Power Systems.
28. **F. Pan and R. Bent,** Online Dynamic Scheduling for Charging PHEVs in V2G, under review.
27. **R. Bent and G. Loren Toole,** Grid Expansion Planning for Carbon Emissions Reduction, under review.
26. **S. Backhaus and Y. Liu**, Wave Green's Function Estimation from Ambient Electrical Grid Frequency Noise, HICCS 2012 ,arxiv:1108.1804.
25. **F. Milano and M. Anghel,** Impact of Time Delays on Power System Stability, submitted to IEEE Transactions on Circuits and Systems.
24. **K. Dvijotham, S. Backhaus, and M. Chertkov**, Operations-Based Planning for Placement and Sizing of Energy Storage in a Grid With a High Penetration of Renewables, arxiv:1107.1382.
23. **M. Chertkov, S. Backhaus, K. Turtisyn, V. Chernyak and V. Lebedev**, Voltage Collapse and ODE Approach to Power Flows: Analysis of a Feeder Line with Static Disorder in Consumption/Production, arxiv:1106.5003.
22. **R. Pfitzner, K. Turitsyn, M. Chertkov** , Controlled Tripping of Overheated Lines Mitigates Power Outages, submitted to IEEESmartGridComm 2011, arxiv:1104.4558.
21. **M. Chertkov, M. Stepanov, F. Pan, and R. Baldick** , Exact and Efficient Algorithm to Discover Stochastic Contingencies in Wind Generation over Transmission Power Grids , invited session on Smart Grid Integration of Renewable Energy: Failure analysis, Microgrids, and Estimation at CDC/ECC 2011, arxiv:1104.0183.
20. **K. Turitsyn, S. Backhaus, M. Ananyev and M. Chertkov** , Smart Finite State Devices: A Modeling Framework for Demand Response Technologies , invited session on Demand Response at CDC/ECC 2011, arxiv:1103.2750.
19. **S. Kundu, N. Sinitsyn, S. Backhaus, and I. Hiskens** Modeling and control of thermostatically controlled loads , 17th Power Systems Computation Conference 2011, arXiv:1101.2157.
18. **R. Bent, A. Berscheid, and L. Toole** , Generation and Transmission Expansion Planning for Renewable Energy Integration , Power Systems Computation Conference (PSCC) 2011.
17. **R. Bent and W.B. Daniel** , Randomized Discrepancy Bounded Local Search for Transmission Expansion Planning , IEEE PES 2011.
16. **P. van Hentenryck, C. Coffrin, and R. Bent** , Vehicle Routing for the Last Mile of Power System Restoration , Power Systems Computation Conference (PSCC) 2011.
15. **R. Pfitzner, K. Turitsyn, and M. Chertkov** , Statistical Classification of Cascading Failures in Power Grids , arxiv:1012.0815, IEEE PES 2011.
14. **S. Kadloor and N. Santhi** , Understanding Cascading Failures in Power Grids , arxiv:1011.4098 submitted to IEEE Transactions on Smart Grids.
13. **N. Santhi and F. Pan** , Detecting and mitigating abnormal events in large scale networks: budget constrained placement on smart grids , proceedings of HICSS44, Jan 2011.
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3rd Year Plans

- Expansion Planning
  - Storage expansions
  - FACTS devices (DC lines, phase shifters, etc)
  - Incorporating improved network optimization scheme
  - Reliability criteria
    - Moving beyond the traditional “n-1” criteria to incorporate resilience to renewable energy fluctuations (instanton)
  - More planning based on grid operations
    - Switching, demand response, energy storage, etc.
- Disturbance Detection and On-line Monitoring (PMU)
  - EM waves and Greens functions
    - Implementation at PNNL Operations Center
  - Extraction of dynamic load models
- Control Algorithms (Centralized and Distributed)
  - Extend to electric vehicles, stationary batteries, demand response, etc…
  - Optimum Power Flows accounting for renewables (robust, stochastic)
  - Stochastic, Robust and Hysteresis Control of Transmission Grid Operations
- Cyber-Physical Security
  - Time-extended games
  - Models of bounded rationality
- Stability and Analysis of Power Flows
  - Static proxies for voltage and phase stability (feed these into control and planning)
  - Stochastic Modeling of topological changes in power grids (loop flows and related)
  - Robust Optimization, Chance Constraints +++ = extending the instanton (distance to failure) approach
  - Analysis and Mitigation of Cascades (general description, signatures, etc)
- Optimization and Control of Distribution Energy Markets
  - Stochastic Modeling of Loads
  - Design of Elastic Markets
- Communication, data accusation, control and security for Smart Grids
  - Compressive Sensing of PMU data
  - Information Theoretic limits and Communication Algorithms
- Operation, Optimization and Control of Wind Farms
  - Detection of Wind Gusts
  - Inhomogeneous Control (pitch, inertia) over the farm
  - Elasticity of the wind farm under uncertainty for grid operations

We need a programmatic help on …

Global Security

IS &T

Energy

• Distribution/distributed Controls

EERE (Wind Control)

contacts, meetings

SNL, NREL, ANL

contacts, collaborations

more research

DTRA

•Stability, monitoring, control (transmission)

OE/ASCR

help to set a mtg. in DC

D-div.

DHS

•Expansion Planning

ISO/PNNL

advice (on how to package) + contacts