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Title: Prediction and Control of Network Cascade: Example of Power Grid or Networking Adaptability from WMD Disruption and Cascading Failures

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Prediction and Control of Network Cascade: Example of Power Grid or Networking Adaptability from WMD Disruption and Cascading Failures

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Center for Nonlinear Studies & Theory Division,
Los Alamos National Laboratory

DTRA, Basic Research Review, July 23, 2012

The DTRA project

Goals and Tasks

Develop a mathematical framework that will provide the fundamental understanding of network survivability, algorithms for detecting/inferring pre-cursors of abnormal network behaviors, and methods for network adaptability and self-healing from cascading failures

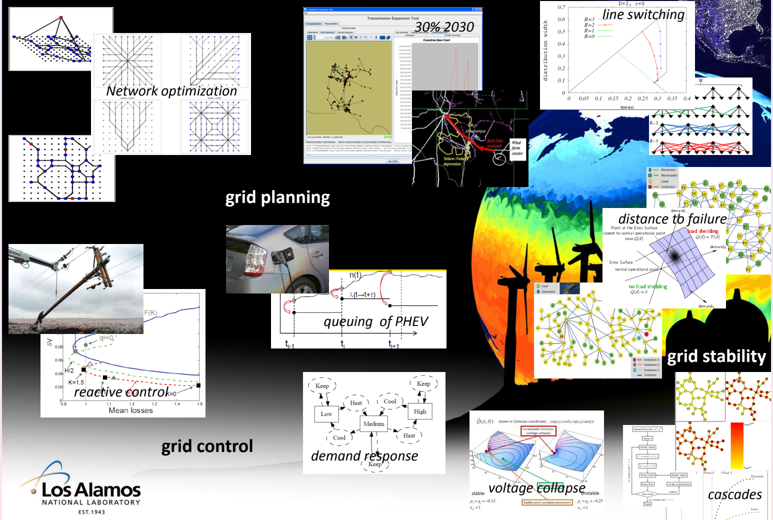
DTRA Nitches (wide area, cascades, hardening & mitigations)

- Physical Network (Power Grid)
- Adversarial Motivation & Intent (Distance to Failure)
- Computational Capability: Discovery and Mitigation

Started Apr 2010. Complements LANL LDRD/DR on "Smart Grids" ⇒.

- Misha Chertkov (PI, LANL - stat physics + algorithms)
- Feng Pan (co-PI, LANL - operation research)
- Misha Stepanov (subcontract, UA - applied math)
- + students

LANL LDRD DR (FY10-12): Optimization & Control Theory for Smart Grids



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

What is Smart Grid?

Traditional Power Engineering (power flows)

+

New Hardware (more options, more fluctuations)

New Politics & Problems (blackouts,nuclear, renewables, markets)

Smart Grid = New Solutions [Networks, New Algorithms] (optimization, control, economics, communications)

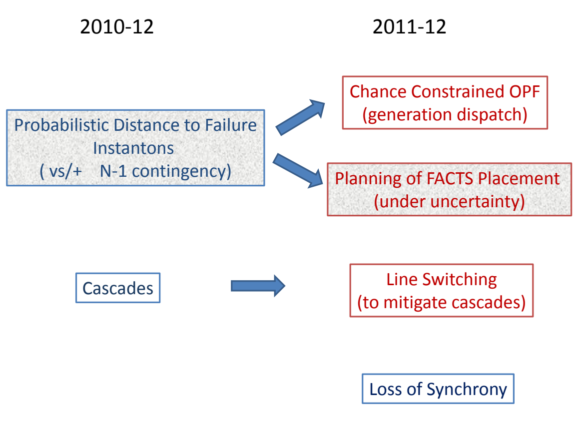
CS/IT/OR Complexity, Predictability

+

App. Math & Stat. Physics new/old phenomena

Big Picture of Our Efforts

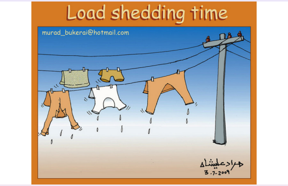
Exogenous Uncertainty (attack, wind, other fluctuations) | Network Consequences | Mitigation



Outline

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

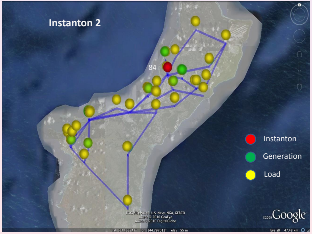
- Predicting Failures in Power Grids: The Case of Static Overloads, IEEE Transactions on Smart Grids **2**, 150 (2010).



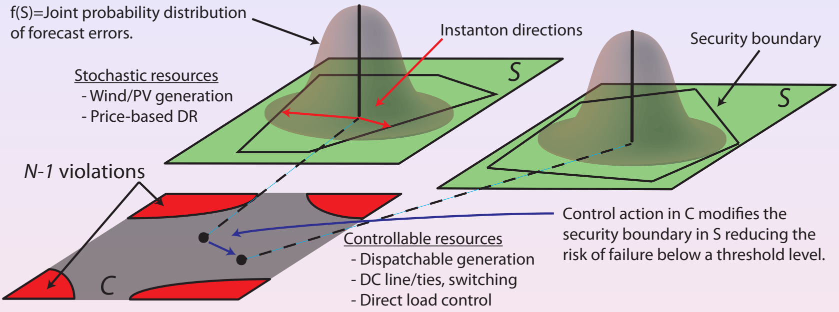
MC, FP, MS & R. Baldick (UT Austin)

- 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.

- How to estimate a probability of a failure?
- How to predict (anticipate) and then prevent the system from going towards a failure?
- Phase space of possibilities is huge (finding the needle in the haystack)



Why do we care?

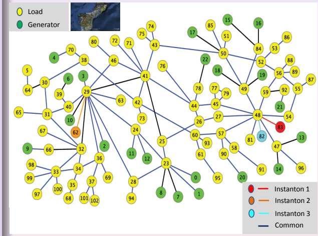


Towards a GOOD emergency control

- Gen. loads (e.g. renewables = "negative loads") fluctuate
- "N-1"-security gives no guarantees under uncertainty
- The first, modest, task: given statistics of "errors", to describe the instantons = most probable failures

Transmission System. DC approximation. Static Overload

- Probabilistic Forecast of (Gen.) Loads (given)
- DC Power Flows
- Constraints = Thermal and Generation
- Check if generation can be re-dispatched (like in OPF) to avoid "load shedding"
- SAT= Load shedding is avoidable; UNSAT=load shedding is unavoidable
- Find the most probable UNSAT configuration of loads



Extreme Statistics of Failures

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

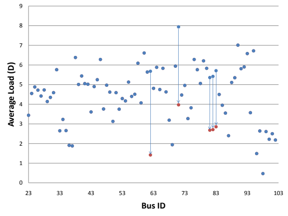
Most Dangerous Configuration of the demand = the Instanton

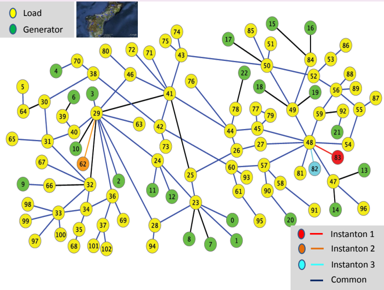
- $\arg\max_{\mathbf{d}} \mathcal{P}(\mathbf{d})\big|_{\mathbf{d}\notin SAT}$ - most probable instanton
- SAT is a polytope (finding min-shedding solution is an LP) which is not tractable (generally); $-\log(\mathcal{P}(\mathbf{d}))$ is (typically) convex

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)

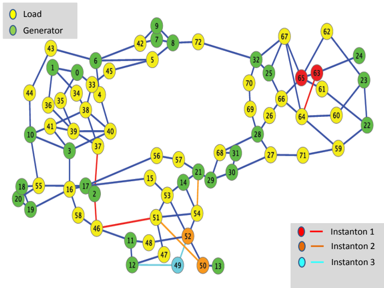
Example of Guam





- Gaussian Statistics of demands (input) leads to Intermittency (output) = instantons (rare, UNSAT) are distinctly different from normal (typical, SAT)
- The instantons are sparse (difference with "typical" is localized on troubled nodes)
- The troubled nodes are repetitive in multiple-instantons
- Violated constraints (edges) are next to the troubled nodes
- Instanton structure is not sensitive to small changes in statistics of demands

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

Lowering demand may be bad - a "paradox"

Instantons for Wind Generation

Setting

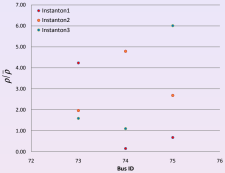
- Renewables is the source of fluctuations
- Loads are fixed (5 min scale)
- Standard generation is adjusted according to a droop control (low-parametric, linear)

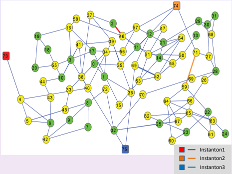
Results

- 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.

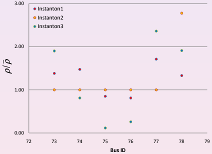
Simulations: IEEE RTS-96 + renewables

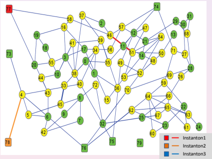
10% of penetration - localization, long correlations



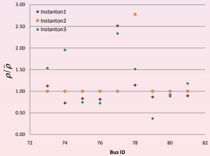


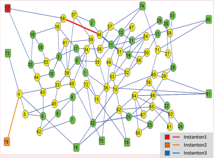
20% of penetration - worst damage, leading instanton is delocalized





30% of penetration - spreading and diversifying decreases the damage, instantons are localized



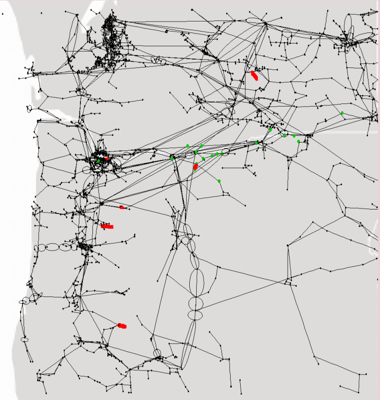


Outline

Chance Constrained Optimum Power Flow: Risk-Aware Network Control under Uncertainty

D. Bienstock (Columbia), M. Chertkov (LANL)
S. Harnett (Columbia/LANL)

- Instanton = find the rare problem
- CC-OPF = discover (instantons) and mitigate (simultaneously and efficiently) at low cost



OPF vs CC-OPF

Standard OPF

$\min_p \underbrace{c(p)}_{\text{cost of generation}}$ | Power Flow Eqs; Generation is within Bounds; Thermal Capacity Limits are obeyed

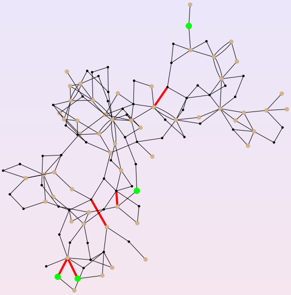
Chance Constrained OPF

- $\min_{\bar{p},\alpha} \mathbb{E}\left[c(\bar{p},\alpha)\right]$ | Power Flow for Average (Wind); Chance Constrains for Thermal Limits; Chance Constraints for Generators
- Averaging (evaluation of CC) is explicit for given $\bar{p},\alpha$
- The resulting outer problem is convex (conic) optimization
- CC-OPF is solved efficiently [sequence of cutting plane LP $\to$ 20 s for Polish Grid (2746 nodes) on laptop]

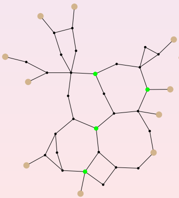
$$\text{CC for TL}: \quad \forall (i,j)\in\mathcal{E}: \quad \text{Prob}(|f_{ij}| > f_{ij}^{max}) < \varepsilon_{ij}$$

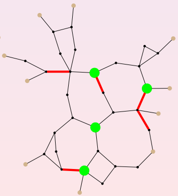
Experiments with CC-OPF (I)

- **CC-OPF succeeds where standard OPF fails**
- Example of 118bus case. Four wind farms (green). 5% penetration. Standard deviation is 30% of the mean. Red lines exceed their limits 8% or more



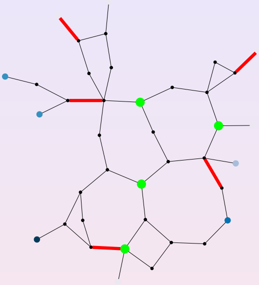
- **Cost of Reliability** [CC-OPF saving over standard OPF]
- 39-bus case under standard OPF. Cost of 5% (standard OPF is ok) is 5 times of the cost of 30% (CC-OPF is ok)



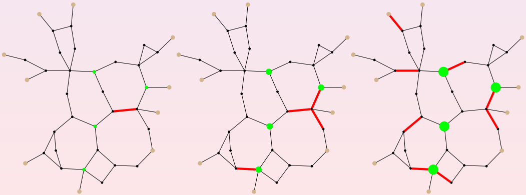


Experiments with CC-OPF (II)

- **CC-OPF is not a naive fix.** Changes are nonlocal.
- 39-bus case. Darker shades of blue (for generators) indicating greater change from CC-OPF to standard OPF.

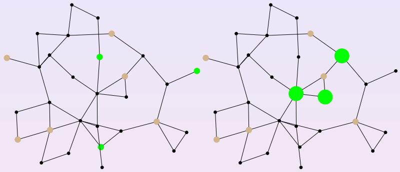


- **What is the penetration that can be tolerated** (without upgrading)?
- 39-bus case. Left to right .1%, 8%, and 30% average wind penetration. With 30% CC-OPF becomes infeasible.

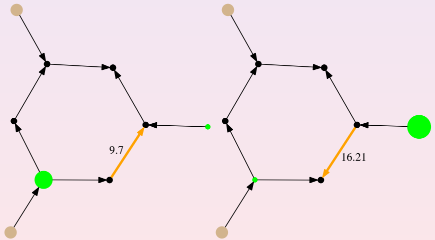


Experiments with CC-OPF (III)

- **Where to place wind-farms?** (Which sites to leave insecure if this is inevitable.)
- 30 bus case with three wind farms. Left vs Right - supports 10% vs 55% of penetration



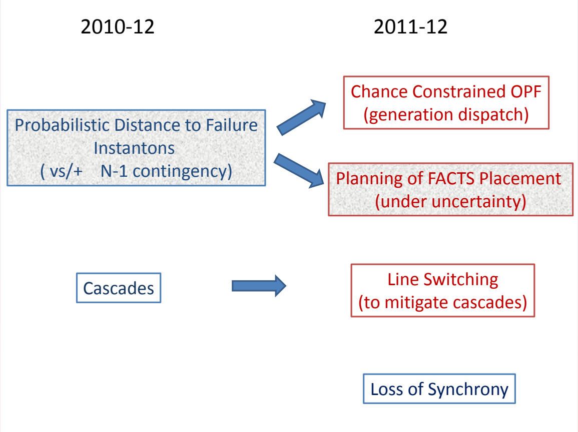
- CC-OPF valid configurations may **show significant (allowed!) variability**, e.g. flow reversal.
- 9-bus case, 25% average penetration - two significantly different flows.



We also did out-of-sample tests. [Work well!]

Big Picture of Our Efforts

Exogenous Uncertainty (attack, wind, other fluctuations) Network Consequences Mitigation



DTRA Publications:

- R. Pfitzner, K. Turitsyn, M. Chertkov , Controlled Tripping of Overheated Lines Mitigates Power Outages, arxiv:1104.4558.
- 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 at CDC/ECC 2011, arxiv:1104.0183.
- R. Pfitzner, K. Turitsyn, and M. Chertkov , Statistical Classification of Cascading Failures in Power Grids , arxiv:1012.0815, IEEE PES 2011.
- M. Chertkov, F. Pan and M. Stepanov, Predicting Failures in Power Grids: The Case of Static Overloads , IEEE Transactions on Smart Grids 2, 150 (2010), arXiv:1006.0671.
- F. Dorfler, M. Chertkov and F. Bullo, Synchronization Assessment in Power Networks and Coupled Oscillators, invited at CDC12.
- F. Dorfler, M. Chertkov and F. Bullo, Synchronization in Complex Oscillator Networks and Smart Grids, submitted.
- D. Bienstock, M. Chertkov, S. Harnett, Chance Constrained Optimal Power Flow: Risk-Aware Network Control under Uncertainty, in preparation.
- V. Frolov, M. Chertkov, S. Backhaus, Optimal Placement of FACTS devices to mitigate Risk, in preparation.

DTRA Invited Presentations:

Around 20 in two years

Path Forward

- Instanton/theory: extend to dynamics and voltage collapse
- Instanton/applications: work on applications (e.g. in cyber-physical attacks)
- CC-OPF: extend to unit commitment, planning and cyber-security, develop distributed implementation
- Cascades: integrate instanton approach, consider broader mitigation strategies, link to scaling/physics

- Classification and Mitigation of Cascades
- Loss of Synchrony
- Placement of FACTS devices

Rene Pfitzner (ETH), Konstantin Turitsyn (MIT) & 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

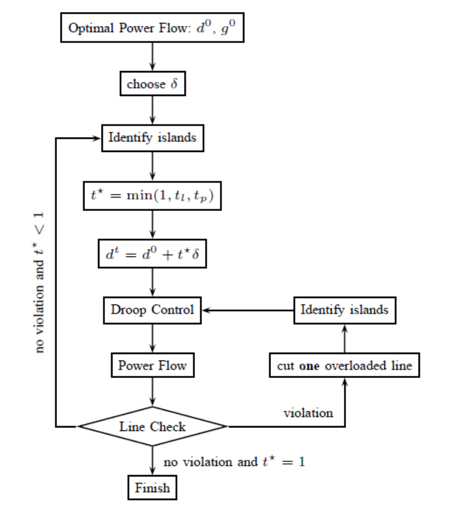
- Synergy with DTRA project of G. Zussman and D. Bienstock (Columbia)

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 at the sub-minute scale
- (first paper) fluctuations in demand and then (second paper) tripping of few most stressed lines
- Analyze the results, e.g. in terms of phases observed, on available power grid models [IEEE test beds]

- Building on ... I. Dobson, et al, *An initial model for complex dynamics in electric power system blackouts*, HICSS-34, 2001
- Similar recent work (2011) of D. Bienstock with collaborators , and P. Hines with collaborators

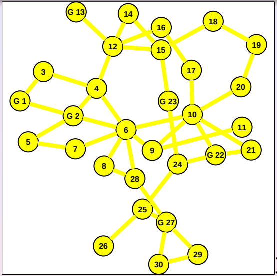
Algorithm of the Cascade



- *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 systems (30, 39, 118 buses)

- The base configuration of demand, $\mathbf{d}^0$ is a part of the system description. Contingency (in demand) is generated according to
- $\mathcal{P}(\delta_i) =$
$$\begin{cases} \frac{\exp(-(\delta_i)^2/(2d_i^0\Delta))}{\sqrt{\pi d_i^0 \Delta/2}}, & d_i^0 + \delta_i > d_i^0 \\ 1/2, & d_i^0 + \delta_i = d_i^0 \\ 0, & d_i^0 + \delta_i < d_i^0 \end{cases}$$
- Δ is the governing parameter, measuring level of fluctuations
- Collect statistics averaging over multiple (200) samples for each Δ



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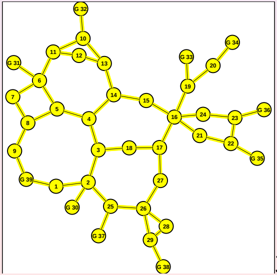

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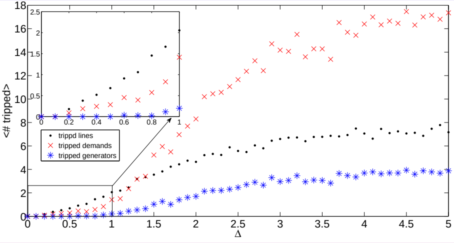
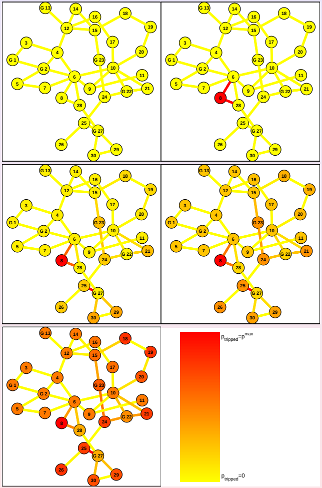
Tests on IEEE 30 system

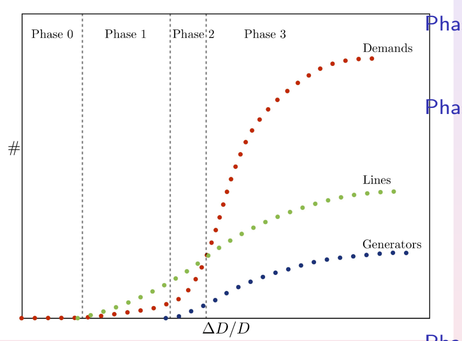




- Average # vs level of fluctuations.
- Stress Diagram. Average # of failures per edge/node. $\Delta = 0.1, 0.2, 0.9, 1.2, 2.0 \Rightarrow$

IEEE 39,118 tests

General Conclusions (3 phases)



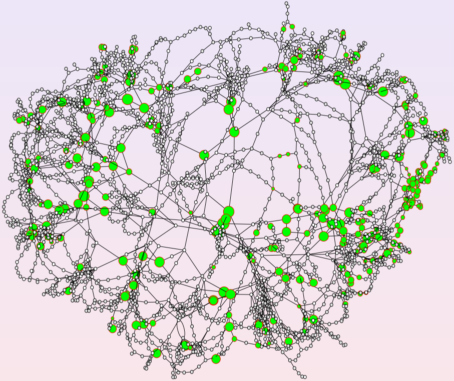
Phase #0 The grid is resilient against fluctuations in demand.

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.

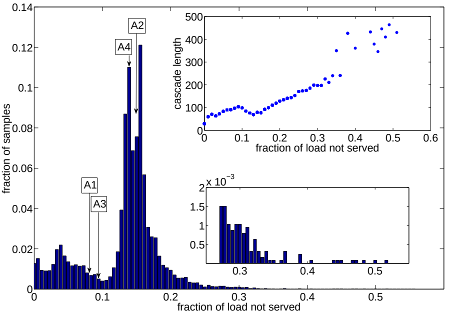
Study Cascade ... and Mitigate ...



Polish Grid (MATPOWER)

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

Experiments with Trippings



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]

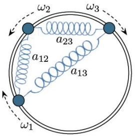
A4 Trip line, (i,j), with the maximal current relative overload, $p_{ij} = \max\{p_{\mathcal{O}}\}$ ... anti [A3] also "natural"

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

Synchronization Criteria

Phase Stability and Synchronization

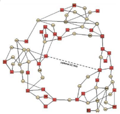
F. Dorfler, MC, F. Bullo (LANL & UCSB)



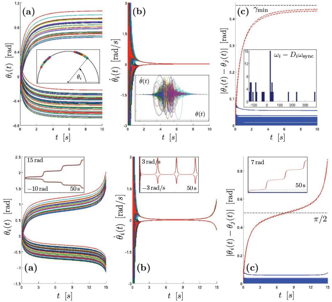
$$M_i\ddot{\theta}_i + D_i\dot{\theta}_i = \omega_i - \sum_{j \in \text{neighbors}(i)} a_{ij}\sin(\theta_i - \theta_j), \quad i \in \{1,\ldots,m\},$$

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

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

Path Forward

Optimization of Transmission with FACTS devices [V. Frolov, MC, S. Backhaus 201

- FACTS=Flexible AC Transmission Systems, in particular (integrated in a line) allow to change inductance of the line without changing its capacity
- Assume that top contingencies, $p_0, \cdots$ (vectors of N-k failures, or instantons) violating some of the thermal (line limits) are known

Can one improve transmission performance by modifying inductances?

- β_0 is the bare vector of inductance over the network edges; $\text{TC}(\beta_0; p_0)$ are violated
- $\min_\beta |\beta - \beta_0||_{\text{TC}(\beta;p_0)}$ are ok
- Difficult (non-convex) Optimization solved efficiently with Sequential LP
- Solutions are typically sparse (can use for placement) and non-local