Optimization & Control Theory for Smart Grids

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LANL IS&T Capability Review, Apr 14, 2011

Outline

So What? Impact! Savings!

- $30b\$$ annually is the cost of power losses
- 10% efficiency improvement - $3b\$$ savings
- cost of 2003 blackout is $7-10b\$$
- $80b\$$ is the total cost of blackouts annually in US
- further challenges (more vulnerable, cost of not doing planning, control, mitigation)

Grid is being redesigned [stimulus]

- The research is timely: $\sim 2T\$$ in 20 years (at least) in US
- Renewables - Desirable but difficult to handle
- Integration within itself, but also with Other Infrastructures, e.g. Transportation (Electric Vehicles)
- Tons of Interesting (Challenging) Research Problems !

Our (LANL) *Road Map* for Smart Grids

New Systems

Renewables | PHEV & Storage | Metering

Grid Stability

- distance to failure
- dynamic stability
- outages/rare events
- cascading
- signature detection

Grid Control

- load balancing
- queuing and scheduling
- optimal power flows
- feeder lines control
- distribution and switching with redundancy

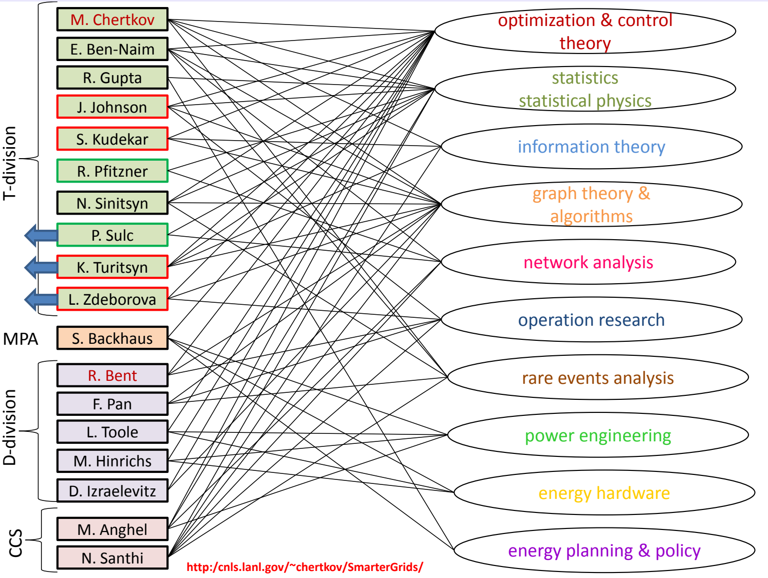
Grid Design

- placement of generations and storage
- intermittent wind as an integrated capacity
- accounting for outages and intermittency in planning

New Challenges

All of the above also requires scientific advances in

- Analysis & Control
- Stability/Reliability Metrics
- State Estimation
- Data Aggregation & Assimilation
- Middleware for the Grid
- Modeling Consumer Response


T-division
M. Chertkov
E. Ben-Naim
R. Gupta
J. Johnson
S. Kudekar
R. Pfitzner
N. Sinitsyn
P. Sulc
K. Turitsyn
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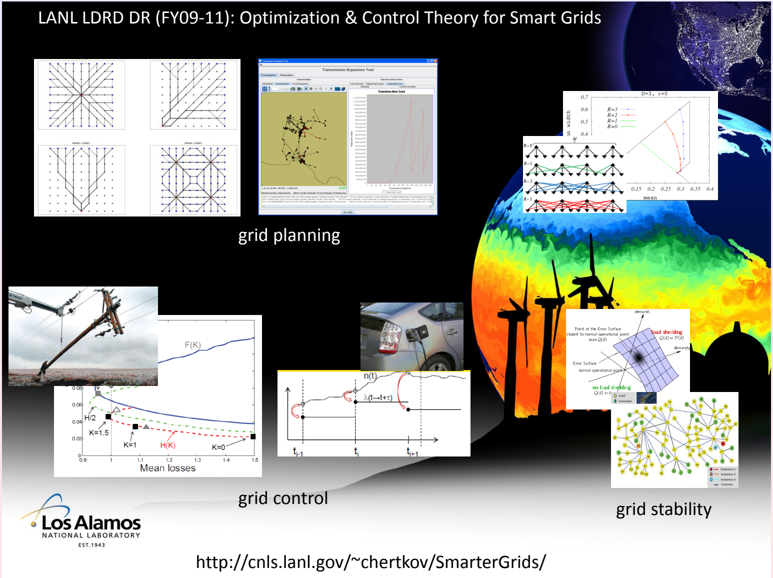
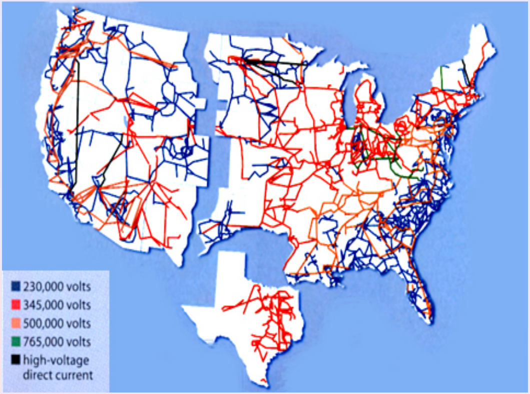
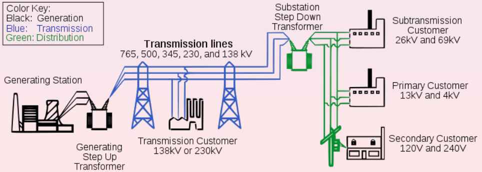
CCS
M. Anghel
N. Santhi
optimization & control theory
statistics statistical physics
information theory
graph theory & algorithms
network analysis
operation research
rare events analysis
power engineering
energy hardware
energy planning & policy
http:/cnls.lanl.gov/~chertkov/SmarterGrids/


LANL LDRD DR (FY09-11): Optimization & Control Theory for Smart Grids
Transmission Expansion Tool
grid planning
F(K)
H/2
K=1.5
K=1
H(K)
K=0
Mean losses
n(t)
λ(t→t+τ)
grid control
Point at the Error Surface closest to normal operational point
load shedding
no load shedding
Error Surface
normal operational point
demand
grid stability
Los Alamos
NATIONAL LABORATORY
EST.1943
http://cnls.lanl.gov/~chertkov/SmarterGrids/



US power grid

The greatest Engineering Achievement of the 20th century



will require **smart revolution** in the 21st century

Preliminary Remarks

The power grid operates according to the laws of electrodynamics

- Transmission Grid (high voltage) vs Distribution Grid (low voltage)
- Alternating Current (AC) flows ... but DC flow is often a valid approximation
- No waiting periods $\Rightarrow$ power constraints should be satisfied immediately. Many Scales.
- Loads and Generators are players of two types (distributed renewable will change the paradigm)
- At least some generators are adjustable - to guarantee that at each moment of time the total generation meets the total load
- The grid is a graph ... but constraints are (graph-) global

Many Scales Involved

Power & Voltage

- $1KW$ - typical household; $10^3KW = 1MW$ - consumption of a medium-to-large residential, commercial building; $10^6KW = 1GW$-large unit of a Nuclear Power plant ($30GW$ is the installed wind capacity of Germany =8% of total, US wind penetration is 5%- [30% by 2030?]); $10^9KW = 1TW$ - US capacity ($\sim$ 5% of the World)
- Transmission - $4 - 13$KV. Distribution - $100 - 1000$KV.

Spatial Scales

- $1mm - 10^3km$; US grid $= 3 * 10^6 km$ lines (operated by $\sim$ 500 companies)

Temporal Scales

- 17ms -AC (60Hz) period, target for Phasor Measurement Units sampling rate (10-30 measurements per second)
- 1s - electro-mechanical wave [motors induced] propagates $\sim 500km$
- 2-10s - SCADA delivers measurements to control units
- $\sim$ 1 min - loads change, wind ramps, etc (toughest scale to control)
- 5-15min - state estimations (for markets) are made
- up to hours - maturing of a cascading outage over a large grid.

Basic AC Power Flow Equations (Static)

The Kirchhoff Laws

$$\forall a \in \mathcal{G}_0: \quad \sum_{b\sim a} J_{ab} = J_a \text{ for currents}$$
$$\forall (a,b) \in \mathcal{G}_1: \quad J_{ab} z_{ab} = V_a - V_b \text{ for potentials}$$
$$\Rightarrow \forall (a,b) \in \mathcal{G}_1: \quad J_a = \sum_{b\in\mathcal{G}_0} Y_{ab} V_b$$
$$\hat{Y} = (Y_{ab} | a,b \in \mathcal{G}_0), \quad \forall \{a,b\}: \; Y_{ab} = \begin{cases} 0, & a \neq b, \; a \nsim b \\ -y_{ab}, & a \neq b, \; a \sim b \\ \sum_{c\neq a}^{c\sim a} y_{ac}, & a = b. \end{cases}$$
$$\forall \{a,b\}: \quad y_{ab} = g_{ab} + i\beta_{ab} = (z_{ab})^{-1}, \quad z_{ab} = r_{ab} + x_{ab}$$

Complex Power Flows [balance of power]

$$\forall a \in \mathcal{G}_0: \quad P_a = p_a + iq_a = V_a J_a^* = V_a \sum_{b\sim a} J_{ab}^* = V_a \sum_{b\sim a} \frac{V_a^* - V_b^*}{z_{ab}^*}$$
$$= \sum_{b\sim a} \frac{\exp(2\rho_a) - \exp(\rho_a + \rho_b + i\theta_a - i\theta_b)}{z_{ab}^*}$$

- Flows on graphs, but very different from transportation networks
- Nonlinear in term of Real and Reactive powers
- Reactive Power needs to be injected to maintain reasonably stable voltage
- Quasi-static (transients may be relevant on the scale of seconds)
- Different (injection/consumption/control) conditions on generators (p, V) and loads (p, q)
- (θ, ρ) are conjugated (Lagrangian multipliers) to (p, q)

DC approximation (for AC power flows)

(0) The amplitude of the complex potentials are all fixed to the same number (unity, after trivial re-scaling): $\forall a: \quad \rho_a = 0$.

(1) $\forall\{a,b\}: \quad |\theta_a - \theta_b| \ll 1$ - phase variation between any two neighbors on the graph is small

(2) $\forall\{a,b\}: \quad r_{ab} \ll x_{ab}$ - resistive (real) part of the impedance is much smaller than its reactive (imaginary) part. Typical values for the r/x is in the $1/27 \div 1/2$ range.

It leads to

- Linear relation between powers and phases (at the nodes):
$$\forall a \in \mathcal{G}_0: \quad p_a = \sum_{b\sim a} \frac{\theta_a - \theta_b}{x_{ab}}$$
- Losses of real power are zero in the network (in the leading order) $\sum_a p_a = 0$
- Reactive power needs to be injected (lines are inductances - only consume reactive power)

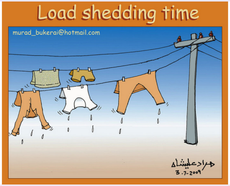
Our Publications on Grid Stability

- 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.
- 16. P. van Hentenryck, C. Coffrin, and R. Bent , Vehicle Routing for the Last Mile of Power System Restoration, submitted to PSCC.
- 15. R. Pfitzner, K. Turitsyn, and M. Chertkov , Statistical Classification of Cascading Failures in Power Grids , arxiv:1012.0815, accepted for 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.
- 8. M. Chertkov, F. Pan and M. Stepanov, Predicting Failures in Power Grids, arXiv:1006.0671, IEEE Transactions on Smart Grids 2, 150 (2010).

Outline

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

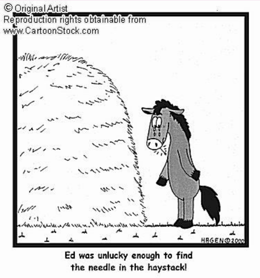
- Predicting Failures in Power Grids: The Case of Static Overloads, IEEE Transactions on Smart Grids **2**, 150 (2010).



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

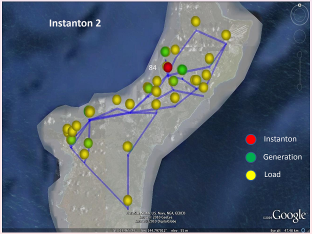
- Exact and Efficient Algorithm to Discover Extreme Stochastic Events in Wind Generation over Transmission Power Grids, invited session on Smart Grid Integration of Renewable Energy at CDC/ECC 2011.

- Normally the grid is ok (SAT) ... but sometimes failures (UNSAT) happens
- How to estimate a probability of a failure?
- How to predict (anticipate and hopefully) prevent the system from going towards a failure?
- Phase space of possibilities is huge (finding the needle in the haystack)



Ed was unlucky enough to find the needle in the haystack!

You were right: There's a needle in this haystack...



Model of Load Shedding [MC, F.Pan & M.Stepanov '10]

Minimize Load Shedding = Linear Programming for DC

$$LP_{DC}(\mathbf{d}|\mathcal{G};\mathbf{x};\mathbf{u};\mathbf{P}) = \min_{\mathbf{f},\boldsymbol{\varphi},\mathbf{p},\mathbf{s}} \left(\sum_{a\in\mathcal{G}_d} s_a\right)_{COND(\mathbf{f},\boldsymbol{\varphi},\mathbf{p},\mathbf{d},\mathbf{s}|\mathcal{G};\mathbf{x};\mathbf{u};\mathbf{P})}$$

$$COND = COND_{flow} \cup COND_{DC} \cup COND_{edge} \cup COND_{power} \cup COND_{over}$$

$$COND_{flow} = \left(\forall a: \quad \sum_{b\sim a} f_{ab} = \begin{cases} p_a, & a\in\mathcal{G}_p \\ -d_a+s_a, & a\in\mathcal{G}_d \\ 0, & a\in\mathcal{G}_0\setminus(\mathcal{G}_p\cup\mathcal{G}_d) \end{cases}\right)$$

$$COND_{DC} = \left(\forall\{a,b\}: \varphi_a-\varphi_b+x_{ab}f_{ab}=0\right), \quad COND_{edge} = \left(\forall\{a,b\}: -u_{ab}\le f_{ab}\le u_{ab}\right)$$

$$COND_{power} = \left(\forall a: \quad 0\le p_a\le P_a\right), \quad COND_{over} = \left(\forall a: \quad 0\le s_a\le d_a\right)$$

φ -phases; f -power flows through edges; x - inductances of edges

SAT/UNSAT & Error Surface

Statistics of Loads

$$\mathcal{P}(\mathbf{d}|\mathbf{D};c) \propto \exp\left(-\frac{1}{2c}\sum_i \frac{(d_i-D_i)^2}{D_i^2}\right)$$

$\mathbf{D}$ is the normal operational position in the space of demands

Instantons (special instances of demands from the error surface)

- Points on the error-surface maximizing $\mathcal{P}(\mathbf{d}|\mathbf{D};c)$ - locally!
- $\arg\max_{\mathbf{d}} \mathcal{P}(\mathbf{d})|_{LP_{DC}(\mathbf{d})>0}$ - most probable instanton
- The maximization is not concave (multiple instantons)

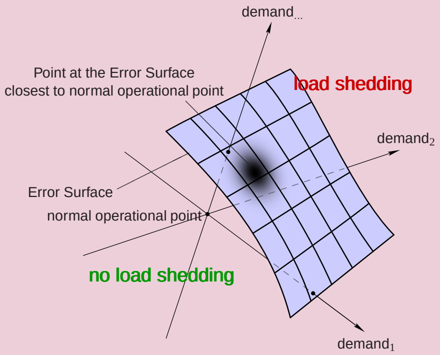
No Shedding (SAT) - Boundary - Shedding (UNSAT) = Error Surface

The task: to find the most probable failure modes [instantons]

Instanton Search Algorithm [Sampling]

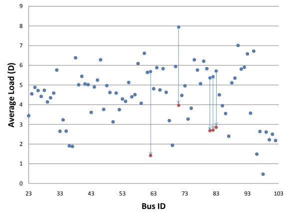
Borrowed (with modifications) from Error-Correction studies: analysis of error-floor [MC, M.Stepanov, et al '04-'10]

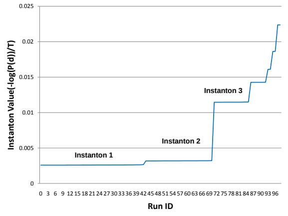
- Construct $\mathcal{Q}(\mathbf{d}) = \begin{cases} \mathcal{P}(\mathbf{d}), & LP_{DC}(\mathbf{d}) > 0 \\ 0 & , LP_{DC}(\mathbf{d}) = 0 \end{cases}$
- Generate a simplex (N+1 points) of UNSAT points
- Use Amoeba-Simplex [Numerical Recepies] to maximize $\mathcal{Q}(\mathbf{d})$
- Repeat multiple times (sampling the space of instantons)

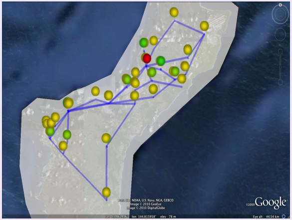


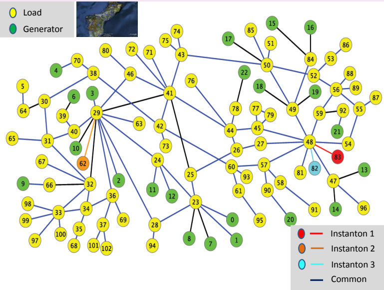
Example of Guam

[MC, F.Pan & M.Stepanov '10]



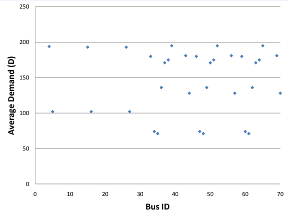


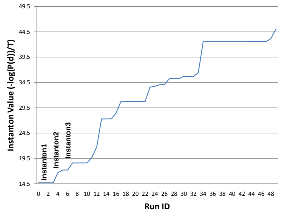


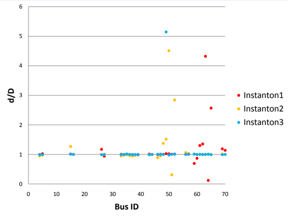


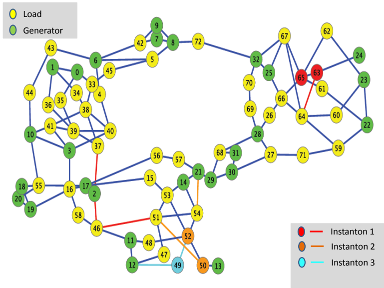
- The instantons are sparse (localized on troubled nodes)
- The troubled nodes are repetitive in multiple-instantons
- Instanton structure is not sensitive to small changes in **D** and statistics of demands

Example of IEEE RTS96 system [MC, F.Pan & M.Stepanov '10]



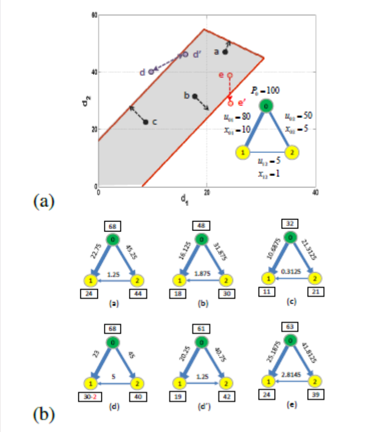






- The instantons are well localized (but still not sparse)
- The troubled nodes and structures are repetitive in multiple-instantons
- Instanton structure is not sensitive to small changes in **D** and statistics of demands

Triangular Example (illustrating a "paradox")



- lowering demand may be troublesome [SAT -¿ UNSAT]
- develops when a cycle contains a weak link
- similar observation was made in other contexts before, e.g. by S. Oren and co-authors
- the problem is typical in real examples
- consider "fixing it with extra storage [future project]

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

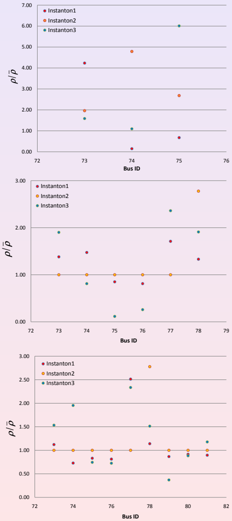
- The instanton algorithm discovers most probable extreme statistics events
- The algorithm is EXACT and EFFICIENT (polynomial)
- Illustrate utility and performance on IEEE RTS-96 example extended with additions of $10\%, 20\%$ and 30% of renewable generation.

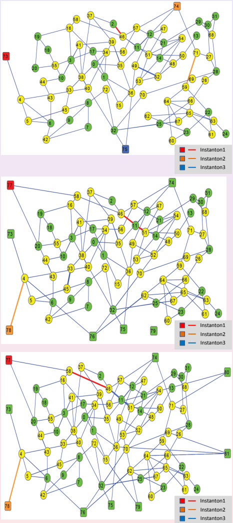
Simulations: IEEE RTS-96 + renewables

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





Path Forward (for predicting failures)

Path Forward

- Many large-scale practical tests, e.g. ERCOT wind integration
- The instanton-amoeba allows upgrade to other (than LP_{DC}) network stability testers, e.g. for AC flows and transients
- Instanton-search can be accelerated, utilizing LP-structure of the tester (exact & efficient for example of renewables)
- This is an important first step towards exploration of "next level" problems in power grid, e.g. on interdiction [Bienstock et. al '09], optimal switching [Oren et al '08], cascading outages [Dobson et al '06], and control of the extreme [outages] [Ilic et al '05]

Our Publications on Grid Control

- 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.
- 19. S. Kundu, N. Sinitsyn, S. Backhaus, and I. Hiskens, Modeling and control of thermostatically controlled loads, submitted to 17th Power Systems Computation Conference 2011, arXiv:1101.2157.
- 16. P. van Hentenryck, C. Coffrin, and R. Bent , Vehicle Routing for the Last Mile of Power System Restoration, submitted to PSCC.
- 12. P. Sulc, K. Turitsyn, S. Backhaus and M. Chertkov , Options for Control of Reactive Power by Distributed Photovoltaic Generators, arXiv:1008.0878, to appear in Proceedings of the IEEE, special issue on Smart Grid (2011).
- 11. F. Pan, R. Bent, A. Berscheid, and D. Izrealevitz , Locating PHEV Exchange Stations in V2G, arXiv:1006.0473, IEEE SmartGridComm 2010
- 10. K. S. Turitsyn, N. Sinitsyn, S. Backhaus, and M. Chertkov, Robust Broadcast-Communication Control of Electric Vehicle Charging, arXiv:1006.0165, IEEE SmartGridComm 2010
- 9. K. S. Turitsyn, P. Sulc, S. Backhaus, and M. Chertkov, Local Control of Reactive Power by Distributed Photovoltaic Generators, arXiv:1006.0160, IEEE SmartGridComm 2010
- 7. K. S. Turitsyn, Statistics of voltage drop in radial distribution circuits: a dynamic programming approach, arXiv:1006.0158, accepted to IEEE SIBIRCON 2010
- 5. K. Turitsyn, P. Sulc, S. Backhaus and M. Chertkov, Distributed control of reactive power flow in a radial distribution circuit with high photovoltaic penetration, arxiv:0912.3281 , selected for super-session at IEEE PES General Meeting 2010.
- 2. L. Zdeborova, S. Backhaus and M. Chertkov, Message Passing for Integrating and Assessing Renewable Generation in a Redundant Power Grid, presented at HICSS-43, Jan. 2010, arXiv:0909.2358
- 1. L. Zdeborova, A. Decelle and M. Chertkov, Message Passing for Optimization and Control of Power Grid: Toy Model of Distribution with Ancillary Lines, arXiv:0904.0477, Phys. Rev. E 80 , 046112 (2009)

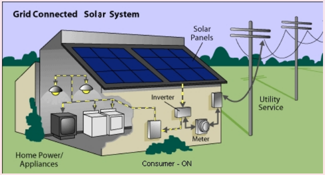
Outline

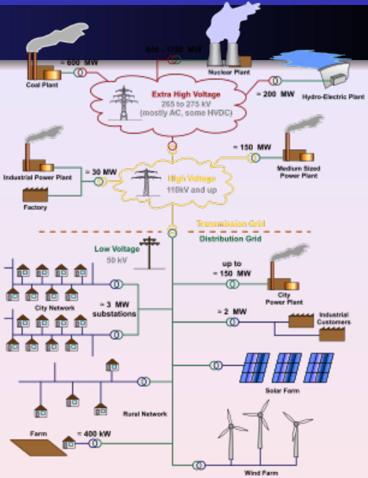
K. Turitsyn (MIT), P. Sulc (NMC), S. Backhaus and M.C.

- *Optimization of Reactive Power by Distributed Photovoltaic Generators*, to appear in Proceedings of the IEEE, special issue on Smart Grid (2011), `http://arxiv.org/abs/1008.0878`
- *Local Control of Reactive Power by Distributed Photovoltaic Generators*, proceedings of IEEE SmartGridComm 2010, `http://arxiv.org/abs/1006.0160`
- *Distributed control of reactive power flow in a radial distribution circuit with high photovoltaic penetration*, IEEE PES General Meeting 2010 (invited to a super-session), `http://arxiv.org/abs/0912.3281`

Setting & Question & Idea

- Distribution Grid (old rules, e.g. voltage is controlled only at the point of entrance)
- Significant Penetration of Photovoltaic (new reality)
- How to control swinging/fluctuating voltage (reactive power)?



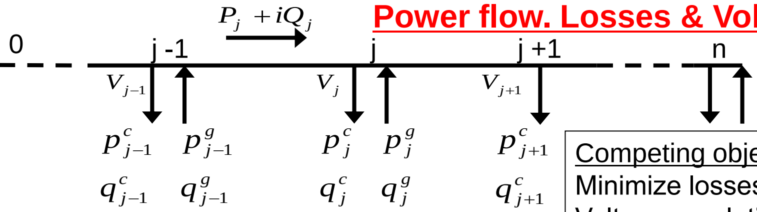


Idea(s)

- Use Inverters.
- Control Locally.

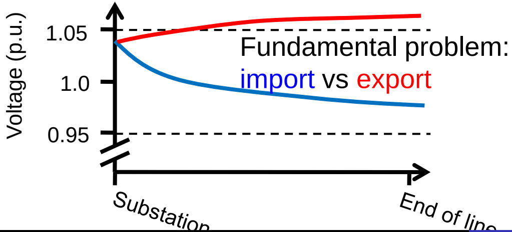
Optimization & Control Theory for Smart Grids: Control (of reactive power)

Power flow. Losses & Voltage



$$Loss_j = r_j \frac{P_j^2 + Q_j^2}{V_0^2}$$

$$\Delta V_j = -(r_j P_j + x_j Q_j)$$



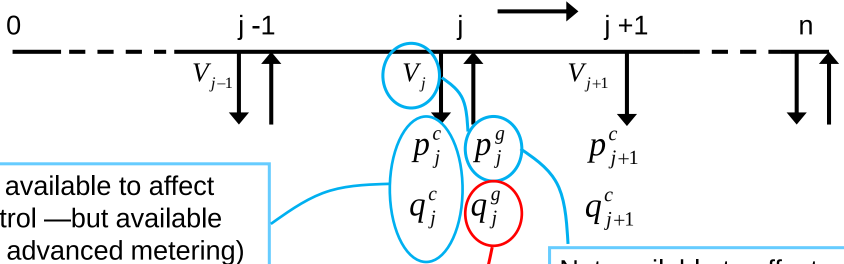
Competing objectives

Minimize losses → $Q_j=0$

Voltage regulation → $Q_j=-(r_j/x_j)P_j$

- **Rapid reversal of real power flow can cause undesirably large voltage changes**
- **Rapid PV variability cannot be handled by current electro-mechanical systems**
- **Use PV inverters to generate or absorb reactive power to restore voltage regulation**
- **In addition… optimize power flows for minimum dissipation**

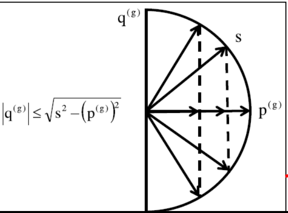
Parameters available & limits for control



Not available to affect control —but available (via advanced metering) for control input

Not available to affect control — but available (via inverter PCC) for control input

Available—minimal impact on customer, extra inverter duty



Schemes of Control

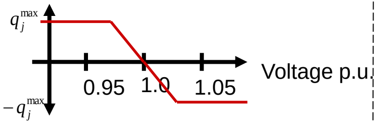
- Base line (do nothing)

$$q_j^g = 0$$

- Unity power factor

$$q_j^g = q_j^c \qquad F^{(L)}$$

- Proportional Control (EPRI white paper)



- voltage control heuristics

$$q_j^g = q_j^c + \frac{r_j}{x_j}(p_j^c - p_j^g)$$

- composite control

$$q_j^g = Kq_j^c + (1-K)[q_j^c + r_j / x_j (p_j^c - p_j^g)]$$

$$= KF_j^{(L)} + (1-K)F_j^{(V)}$$

- Hybrid (composite at V=1 built in proportional)

$$q_j^g = F_j(K) + (q_j^{\max} - F_j(K))\left(1 - \frac{2}{1+\exp(-4(V_j-1)/\delta}\right)$$

$$F_j(K) = Constr_j\left(KF_j^{(L)} + (1-K)F_j^{(V)}\right)$$

$$\mathrm{Constr}_j[q] = \begin{cases} q, & |q| \le q_j^{max} \\ (q/|q|)q_j^{max}, & \text{otherwise} \end{cases}$$

Prototypical distribution circuit: case study

Import—Heavy cloud cover

- p^c = uniformly distributed 0-2.5 kW
- q^c = uniformly distributed $0.2p^c$-$0.3p^c$
- p^g = 0 kW
- Average import per node = 1.25 kW

Export—Full sun

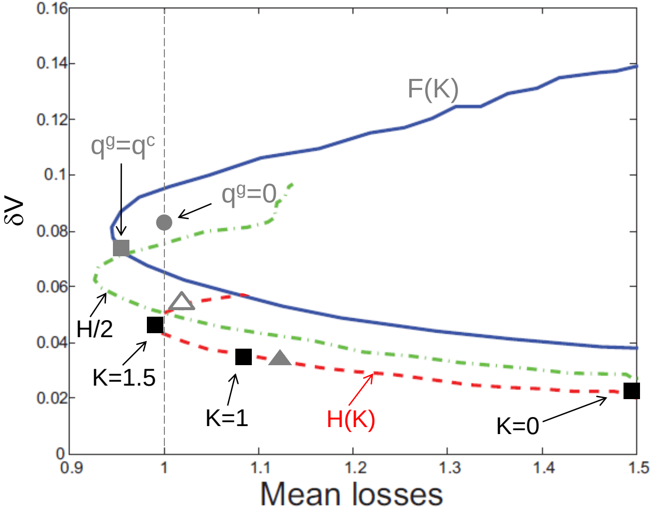
- p^c = uniformly distributed 0-1.0 kW
- q^c = uniformly distributed $0.2p^c$-$0.3p^c$
- p^g = 2.0 kW
- Average export per node = 0.5 kW

- V_0=7.2 kV line-to-neutral
- n=250 nodes
- Distance between nodes = 200 meters
- Line impedance = 0.33 + i 0.38 Ω/km
- 50% of nodes are PV-enabled with 2 kW maximum generation
- Inverter capacity s=2.2 kVA – 10% excess capacity

Measures of control performance

- δV—maximum voltage deviation in transition from export to import
- Average of import and export circuit dissipation relative to "Do Nothing-Base Case"

Performance of different control schemes



Hybrid scheme

- **Leverage nodes that already have V_j~1.0 p.u. for loss minimization**
- **Provides voltage regulation and loss reduction**
- **K allows for trade between loss and voltage regulation**
- **Scaling factor provides related trades**

Conclusions:

- **In high PV penetration distribution circuits where difficult transient conditions will occur, adequate voltage regulation and reduction in circuit dissipation can be achieved by:**
  - Local control of PV-inverter reactive generation (as opposed to centralized control)
  - Moderately oversized PV-inverter capacity ($s\sim 1.1\ p^{g,max}$)

- **Using voltage as the only input variable to the control may lead to increased average circuit dissipation**
  - Other inputs should be considered such as p^c, q^c, and p^g.
  - Blending of schemes that focus on voltage regulation or loss reduction into a hybrid control shows improved performance and allows for simple tuning of the control to different conditions.

- **Equitable division of reactive generation duty and adequate voltage regulation will be difficult to ensure simultaneously.**
  - Cap reactive generation capability by enforcing artificial limit given by $s\sim 1.1\ p^{g,max}$

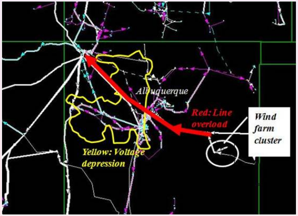
Our Publications on Grid Planning

- 18. R. Bent, A. Berscheid, and L. Toole , Generation and Transmission Expansion Planning for Renewable Energy Integration, submitted to Power Systems Computation Conference (PSCC).
- 17. R. Bent and W.B. Daniel , Randomized Discrepancy Bounded Local Search for Transmission Expansion Planning, accepted for IEEE PES 2011.
- 11. F. Pan, R. Bent, A. Berscheid, and D. Izrealevitz , Locating PHEV Exchange Stations in V2G, arXiv:1006.0473, IEEE SmartGridComm 2010
- 6. J. Johnson and M. Chertkov, A Majorization-Minimization Approach to Design of Power Transmission Networks, arXiv:1004.2285, 49th IEEE Conference on Decision and Control (2010).
- 4. R. Bent, A. Berscheid, and G. Loren Toole, Transmission Network Expansion Planning with Simulation Optimization, Proceedings of the Twenty-Fourth AAAI Conference on Artificial Intelligence (AAAI 2010), July 2010, Atlanta, Georgia.
- 3. L. Toole, M. Fair, A. Berscheid, and R. Bent, Electric Power Transmission Network Design for Wind Generation in the Western United States: Algorithms, Methodology, and Analysis , Proceedings of the 2010 IEEE Power Engineering Society Transmission and Distribution Conference and Exposition (IEEE TD 2010), April 2010, New Orleans, Louisiana.

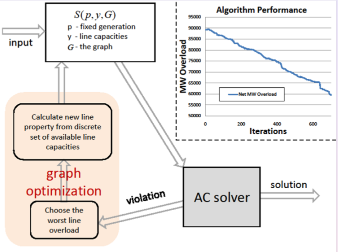
Outline

Grid Design: Motivational Example

- Cost dispatch only (transportation,economics)
- Power flows highly approximate
- Unstable solutions
- Intermittency in Renewables not accounted



An unstable grid example



Hybrid Optimization - is current "engineering" solution developed at LANL: Toole,Fair,Berscheid,Bent 09 extending and built on NREL "20% by 2030 report for DOE

Network Optimization ⇒

- Design of the Grid as a tractable global optimization

Network Optimization (for fixed production/consumption $\mathbf{p}$)

$$\underbrace{\min_{\hat{g}} \mathbf{p}^{+}\left(\hat{G}(\hat{g})\right)^{-1}\mathbf{p},}_{\substack{\text{minimize losses}\\ \text{convex over} \hat{g}}} \qquad \underbrace{G_{ab} = \begin{cases} 0, & a \neq b,\quad a \nsim b \\ -g_{ab}, & a \neq b,\quad a \sim b \\ \sum_{c\neq a}^{c\sim a} g_{ac}, & a = b. \end{cases}}_{\text{Discrete Graph Laplacian of conductance}}$$

Network Optimization (averaged over $\mathbf{p}$)

$$\min_{\hat{g}}\langle \mathbf{p}^{+}\left(\hat{G}(\hat{g})\right)^{-1}\mathbf{p}\rangle = \min_{\hat{g}} \operatorname{tr}\left(\left(\hat{G}(\hat{g})\right)^{-1}\langle \mathbf{p}\mathbf{p}^{+}\rangle\right) =$$

$$\underbrace{\min_{\hat{g}} \operatorname{tr}\left(\left(\hat{G}(\hat{g})\right)^{-1}\hat{P}\right)}_{\text{still convex}}, \quad \hat{P} - \text{covariance matrix of load/generation}$$

Boyd,Ghosh,Saberi '06 in the context of resistive networks

also Boyd, Vandenberghe, El Gamal and S. Yun '01 for Integrated Circuits

Network Optimization: Losses+Costs [J. Johnson, MC '10]

Costs need to account for

- "sizing lines" - grows with g_{ab}, linearly or faster (convex in $\hat{g}$)
- "breaking ground" - l_0-norm (non convex in $\hat{g}$) but also imposes desired sparsity

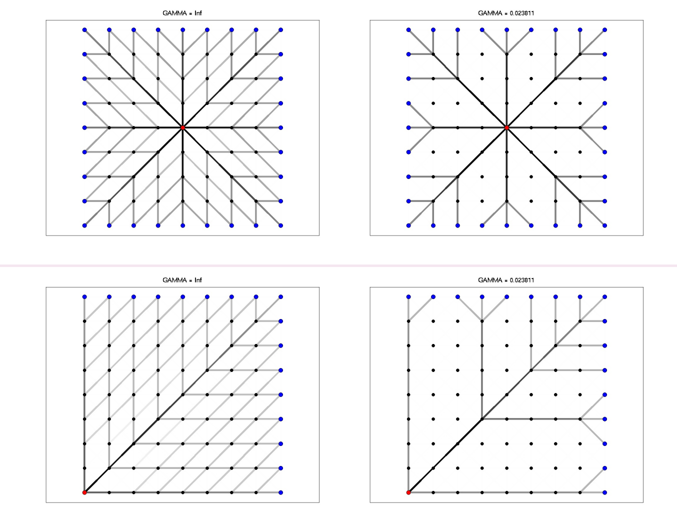
Resulting Optimization is non-convex

$$\min_{\hat{g}>0}\left(\mathrm{tr}\left(\left(\hat{G}(\hat{g})\right)^{-1}\hat{P}\right)+\sum_{\{a,b\}}\left(\alpha_{ab}g_{ab}+\beta_{ab}\phi_\gamma(g_{ab})\right)\right),\quad \phi_\gamma(x)=\frac{x}{x+\gamma}$$

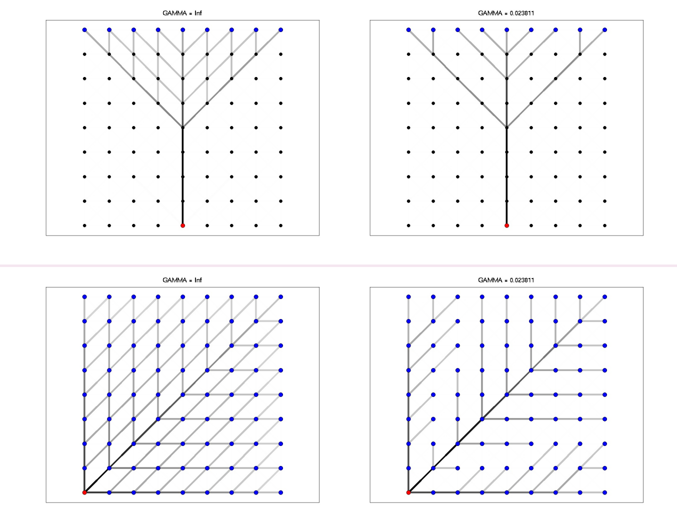
Tricks (for efficient solution of the non-convex problem)

- "annealing": start from large (convex) γ and track to $\gamma\to 0$ (combinatorial)
- Majorization-minimization (from Candes, Boyd '05) for current γ: $\hat{g}^{t+1}=\mathrm{argmin}_{\hat{g}>0}\left(\mathrm{tr}(\mathcal{L})+\hat{\alpha}.*\hat{g}+\hat{\beta}.*\phi'_\gamma(g^t_{ab}).*g_{ab}\right)$

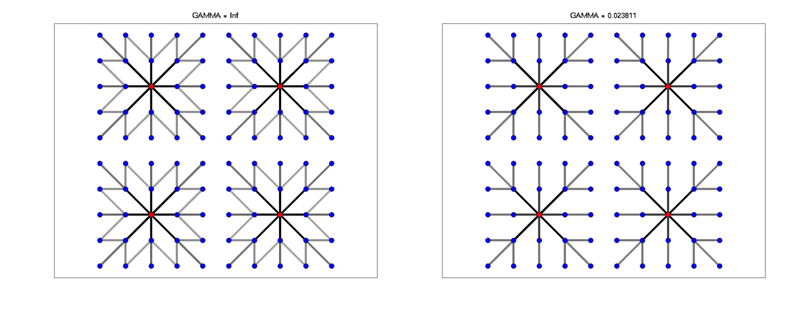
Single-Generator Examples (I)



Single-Generator Examples (II)



Multi-Generator Example



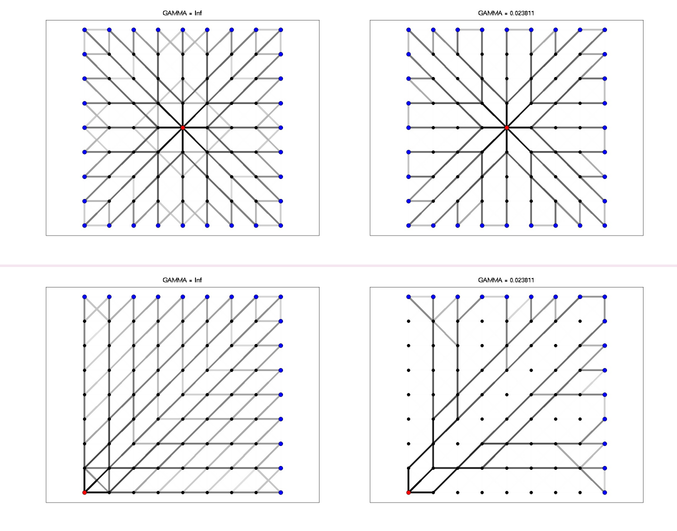
Adding Robustness

To impose the requirement that the network design should be robust to failures of lines or generators, we use the worst-case power dissipation:

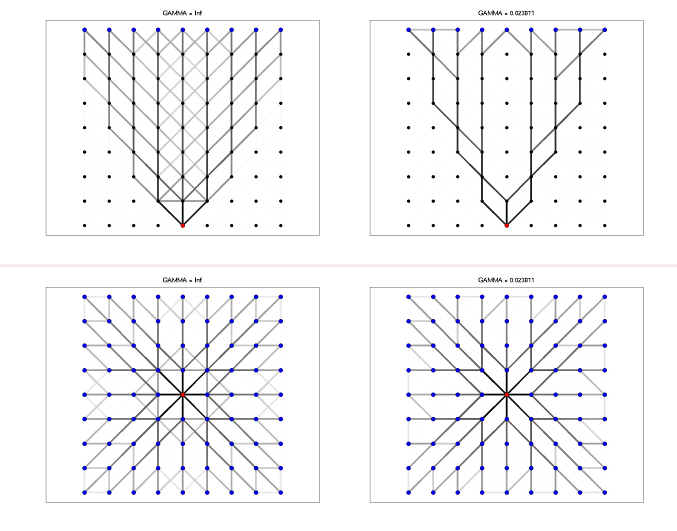
$$\mathcal{L}^{\setminus k}(\hat{g}) = \max_{\forall\{a,b\}: z_{ab}\in\{0,1\} \mid \sum_{\{a,b\}} z_{ab}=N-k} \mathcal{L}(\hat{z}.*\hat{g}))$$

- It is tractable to compute only for small values of k.
- Note, the point-wise maximum over a collection of convex function is convex.
- So the linearized problem is again a convex optimization problem at every step continuation/MM procedure.

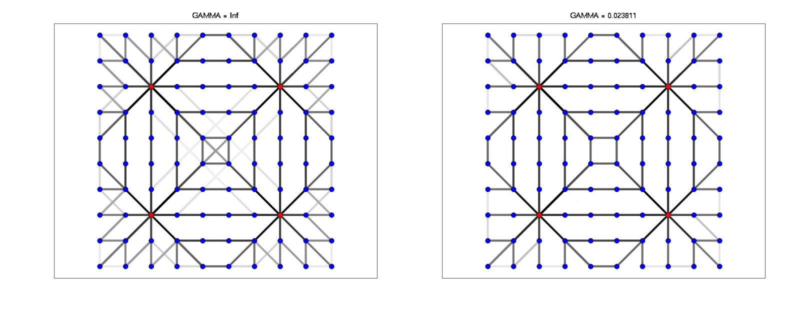
Single-Generator Examples [+Robustness] (I)



Single-Generator Examples [+Robustness] (II)



Multi-Generator Example [+Robustness]



Conclusion (for the Network Optimization part)

A promising heuristic approach to design of power transmission networks. However, cannot guarantee global optimum.

- CDC10: `http://arxiv.org/abs/1004.2285`

Future Work:

- Applications to real grids, e.g. for 30/2030
- Bounding optimality gap?
- Use non-convex continuation approach to place generators
- possibly useful for graph partitioning problems
- adding further constraints (e.g. don't overload lines)
- extension to (exact) AC power flow?

Bottom Line

- A lot of interesting collective phenomena in the power grid settings for Applied Math, Physics, CS/IT analysis
- The research is timely (blackouts, renewables, stimulus)

Other Problems the team plans working on

- Efficient PHEV charging via queuing/scheduling with and without communications and delays
- Power Grid Spectroscopy (power grid as a medium, electro-mechanical waves and their control, voltage collapse, dynamical state estimations)
- Effects of Renewables (intermittency of winds, clouds) on the grid & control
- Load Control, scheduling with time horizon (dynamic programming +)
- Price Dynamics & Control for the Distribution Power Grid
- Post-emergency Control (restoration and de-islanding)

For more info - check:

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

Collaborations & Programm Development

- LANL has unique combination of theory (T-,CCS-) and application (D-) expertise to tackle the challenging network/collective problems
- The ultimate goal is to lead efforts within the DOE complex

- Multiple collaborations (students, joint grants, exploration) with MIT, Berkeley, U of Michigan, U of Texas, UCSB, PNNL and others
- Actively involved in (NEW) community Building (new confs, journals,etc)

- New DTRA funding (1.2M over 3 years) Cascading Failures
- New OE funding (350K for FY10 with possible growth in future FYs) -Control of PV with NEDO & LA county
- Wait for NSF [via NMC] on Grid Spectroscopy (electro-mech. waves)
- Plan responding to multiple DOE/EERE calls related to the off-shore wind
- Multiple other submissions/calls, mainly from DOE & DHS

Smart Grid Program at LANL

Challenges

- Pool of interested researchers and students currently small (but growing fast!)
- We need to encourage students in CS/IT/Control/Optimization/Physics to work on these problems through development of joint graduate programs with top schools such as MIT, Berkeley, Stanford, USC, and others.
- Transition to Programmatic (DOE+) funding - path to practical software/middleware (via D- ?)
- Need to hire in this new area - especially our best CS/IT/Control/Optimization/Physics postdocs working on the Smart Grid Project

Thank You!