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Title: Optimal Transmission Line Switching under Geomagnetic Disturbances

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Optimal Transmission Line Switching under Geomagnetic Disturbances

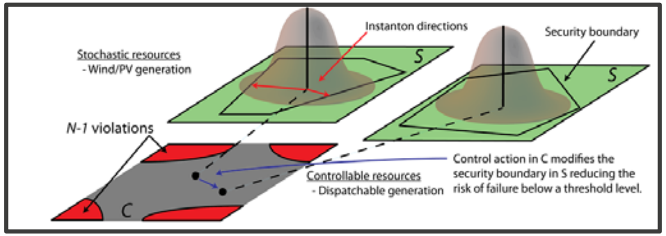
Russell Bent

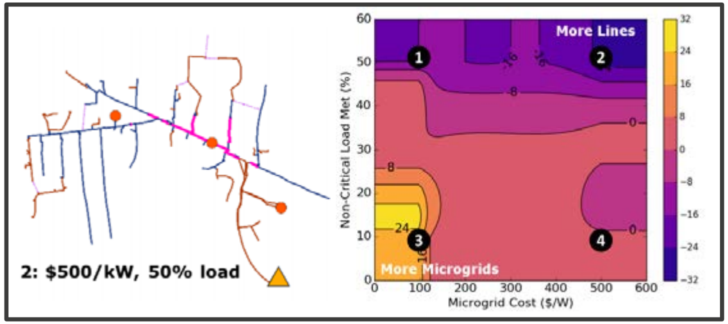
September 14, 2016

Joint work: Mowen Lu, Scott Backhaus, Harsha Nagarajan, and Emre Yamangil

Outline

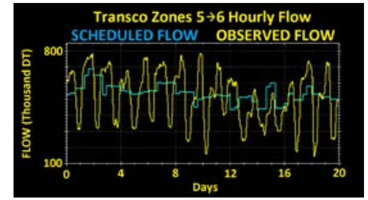
- **Overview of Energy Infrastructure R&D at Los Alamos**
- **Power Systems and Geomagnetic Disturbances 101**
- **Mitigation Model**
- **Algorithm**
- **Empirical Results**
- **Conclusion**

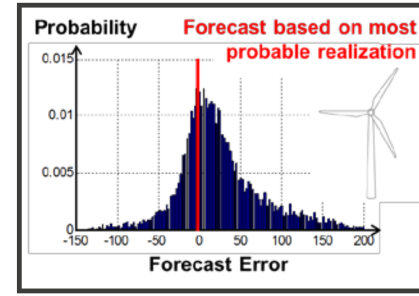




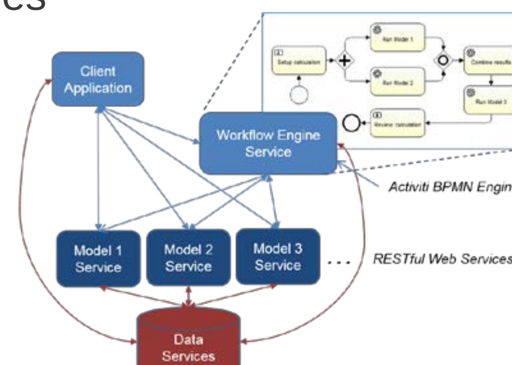
Energy and Infrastructure R&D at Los Alamos

- **Department of Energy**
  - Operations and control under uncertainty
  - Co-optimization of interacting infrastructures
  - Optimal resilient design for extreme events
  - Machine learning for power systems
  - …





- **Department of Homeland Security**
  - Modeling and analysis of system resilience to extreme events
  - Analysis and simulation of complex interacting infrastructures
  - Restoration and recovery optimization
  - Web-service tool deployment
  - …



Los Alamos Researchers and Project Teams

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Operations Research, Discrete and Continuous Optimization, Heuristics Design, Stochastic/Robust Network Design, Infrastructure Expansion, Resilient Design

Scott Backhaus
DOE and DHS Program Management
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Michael Chertkov (T Division)

Mathematical Physics, Statistical Physics, Applied Probability, Graphical Model Learning, Network Design, Stochastic Networks and Dynamics, Optimization

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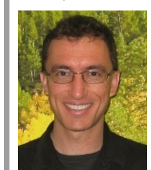

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Se-Young Yun

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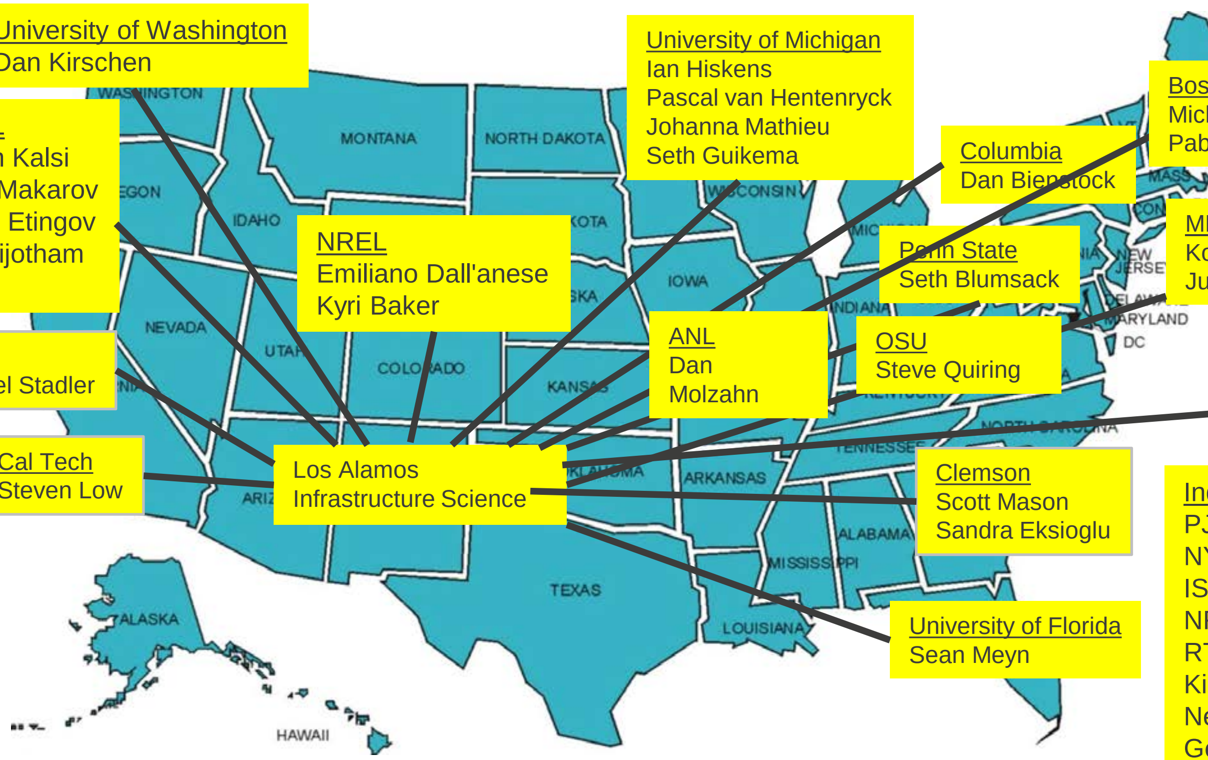

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General Electric
Burns Engineering
Alaska Center for Energy and Power

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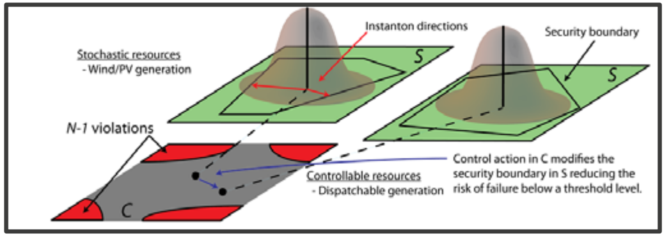
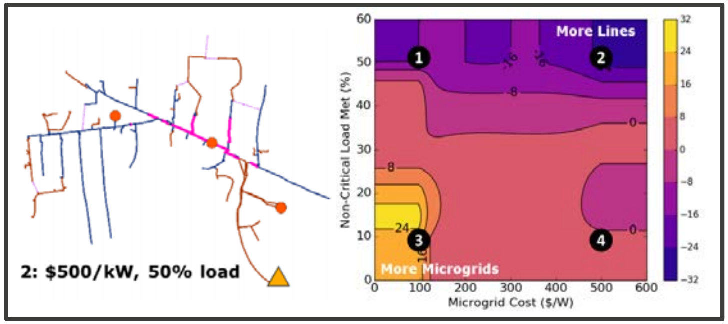
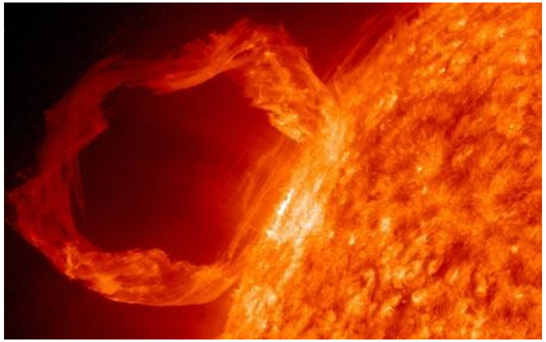
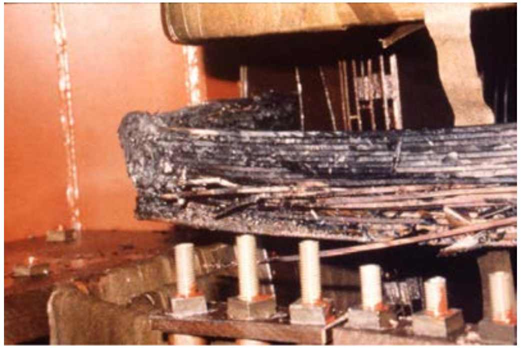




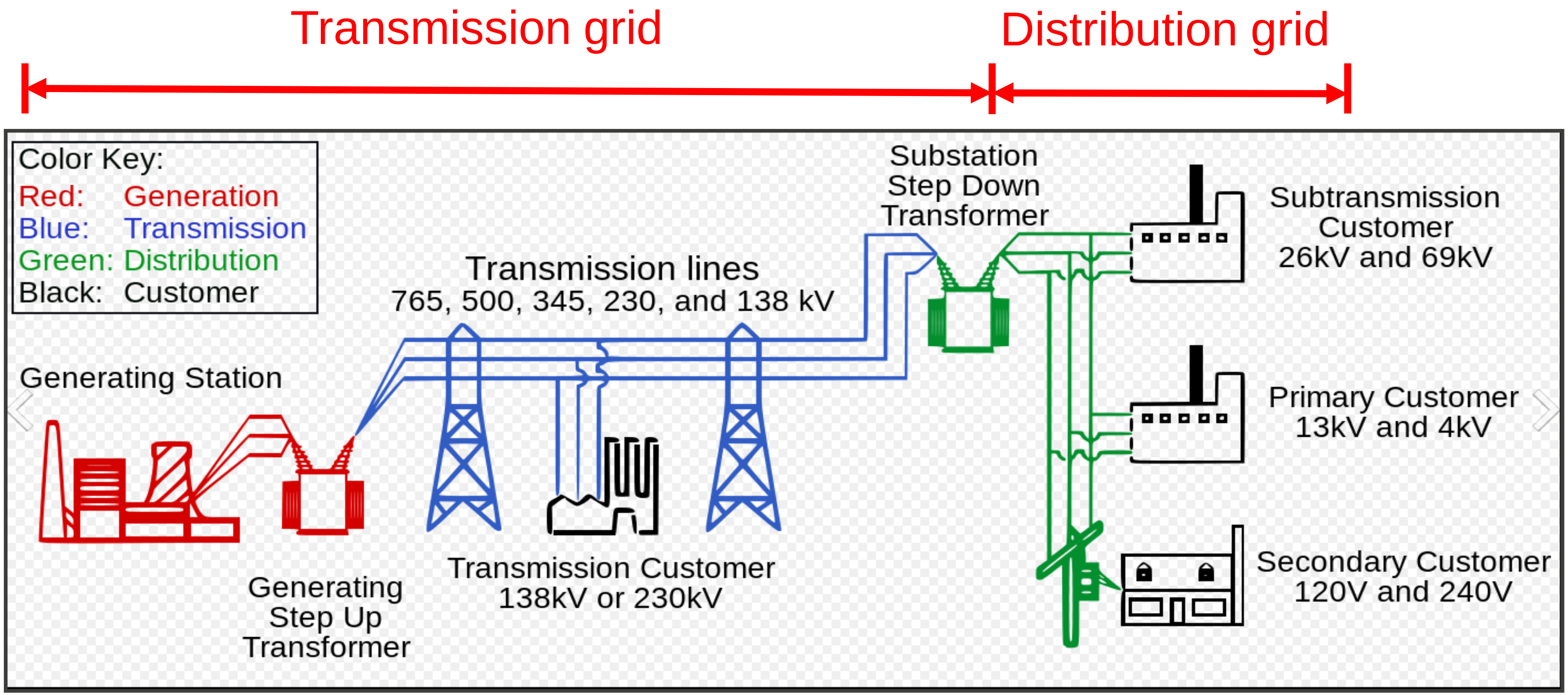
Introduction and Motivation

- **Global Magnetic Disturbances (GMD) have the potential to disrupt power delivery**
  - May 1806 – June, 1807: Alexander von Humboldt, Berlin
  - August 28 - September 2, 1859: United States and Europe
  - March 13, 1989: Hydro-Québec blackout
- **Motivates R&D of power system fragility**
  - Transformers
  - Generators
  - Control components
- **Motivates R&D on mitigation and prevention**
  - Blocking devices (Overbye 2013, 2015)
  - Generator dispatch, line switching, load shedding (this talk)
- **Presentation Focus**
  - Modeling GMD effects in a power system
  - Deriving constraints that ensure system protection
  - Optimized decisions to meet these constraints
  - Key application for advances in space weather modeling
    - University of Michigan Center for Space Environment Modeling

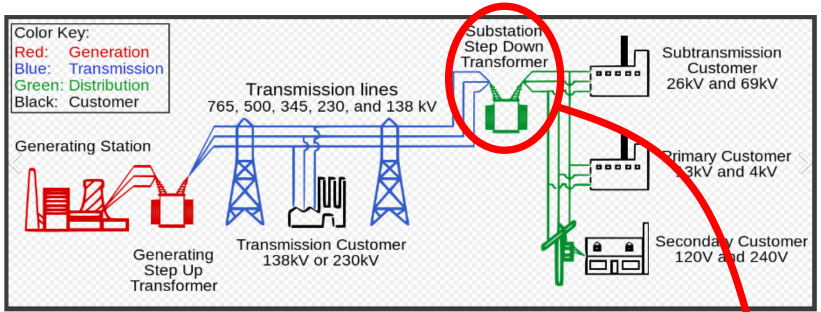


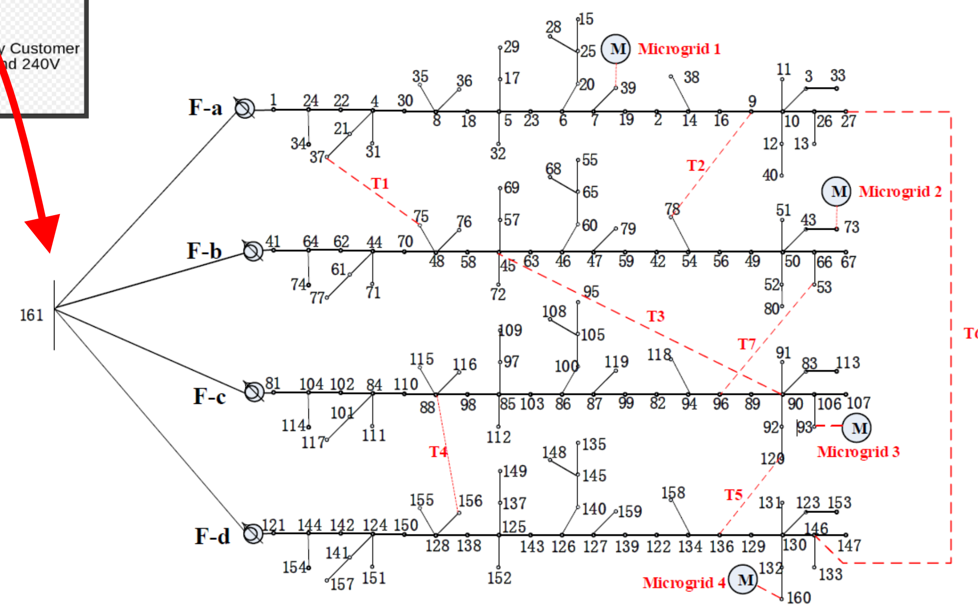


Power Systems Basics: Components and Subsystems



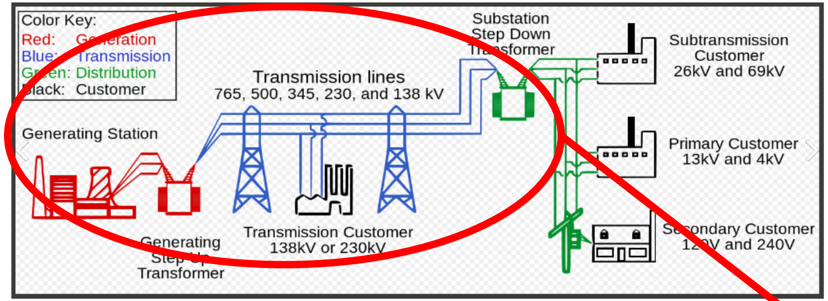
Power Systems Basics: Distribution Grids

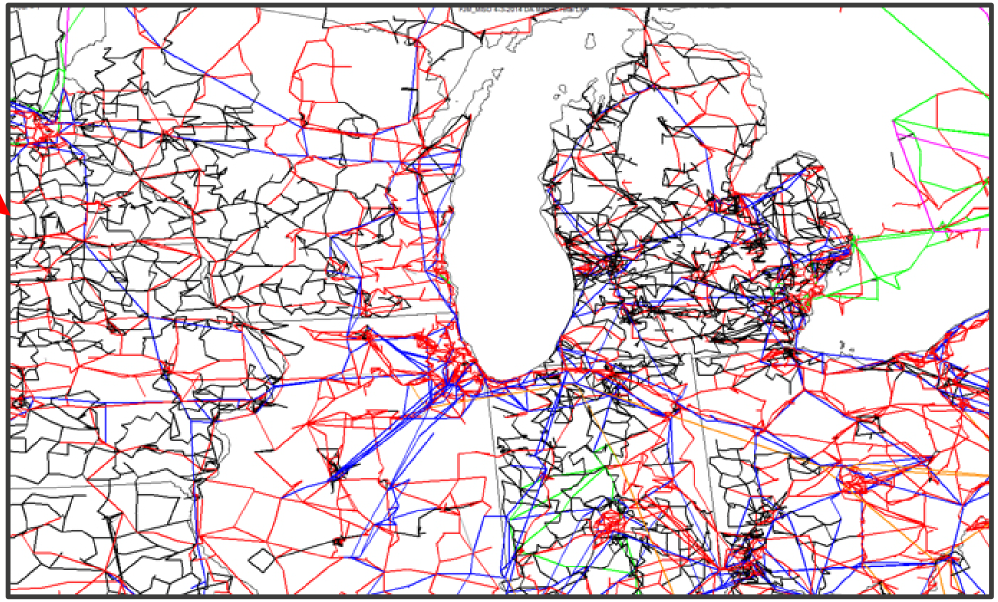




- **Tree-like topology**
- **Load served ~ 10's of MW per network**
  - Impact is relatively small if entire network is lost
  - Minor interaction between networks
- **Less interaction with GMD and geo-electric fields**
  - Spatial extent ~ 10 miles
  - Relatively high network resistance
- **…. Less attention paid to GMD effects on distribution**

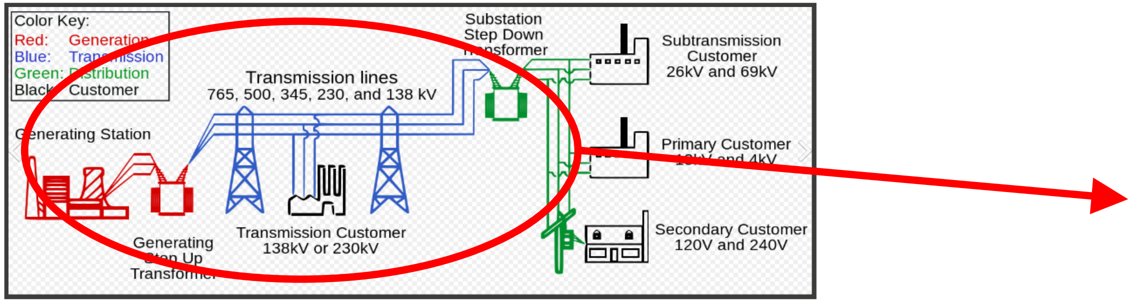
Power System Basics: Transmission Grids

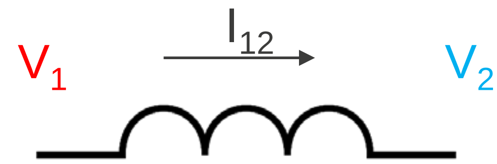




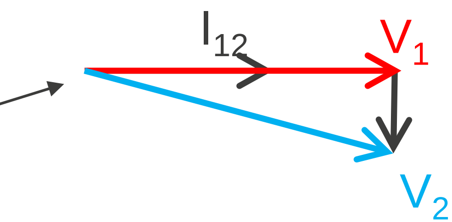
- **Meshed topology**
- **Load served ~ 100,000 MW**
  - Large impact is relatively small if entire network is lost
- **Significant interaction with GMD and geo-electric fields**
  - Spatial extent ~ 100's of miles
  - Relatively low network resistance
- **…. GMD effects on transmission have been a ongoing focus of regulators, utilities, national labs, academia**

Normal AC Physics @ 60 Hz: Real and Reactive Power

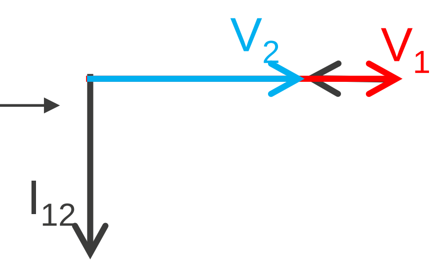




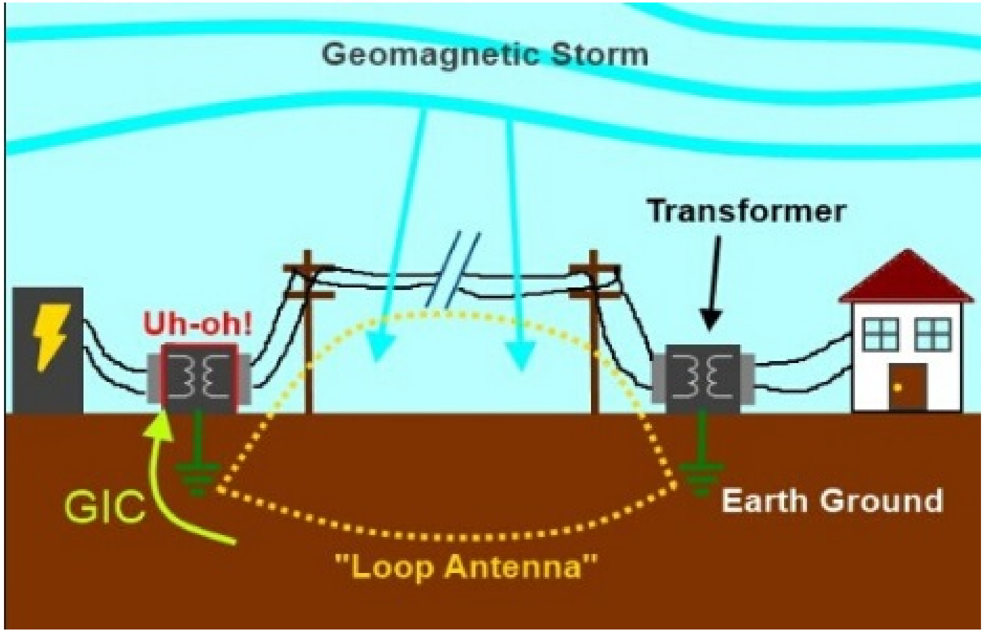
- **Transmission lines impedance typically dominated by reactance**
- **"Real" Power (P)—Current in-phase with voltage**
  - Transmission impedance mostly creates a phase shift of voltage
  - Voltage magnitude nearly fixed

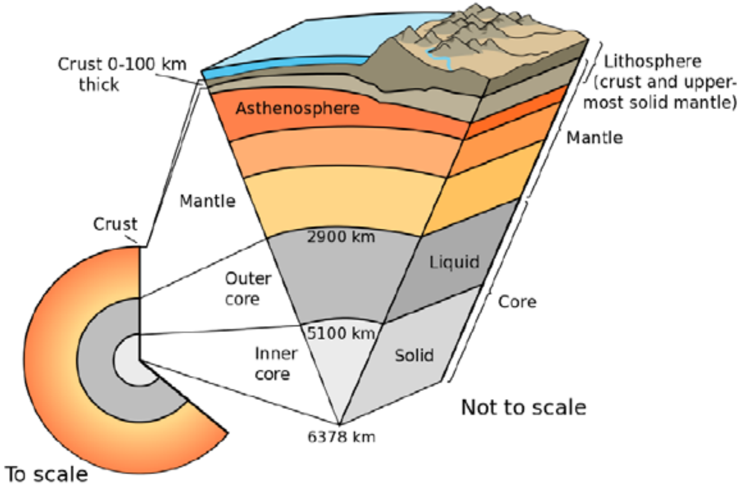


- **"Reactive" Power (Q)—Current out-of-phase with voltage**
  - Transmission impedance mostly creates a change in voltage magnitude
- **"Reactive" Power (Q) is used to control voltage**



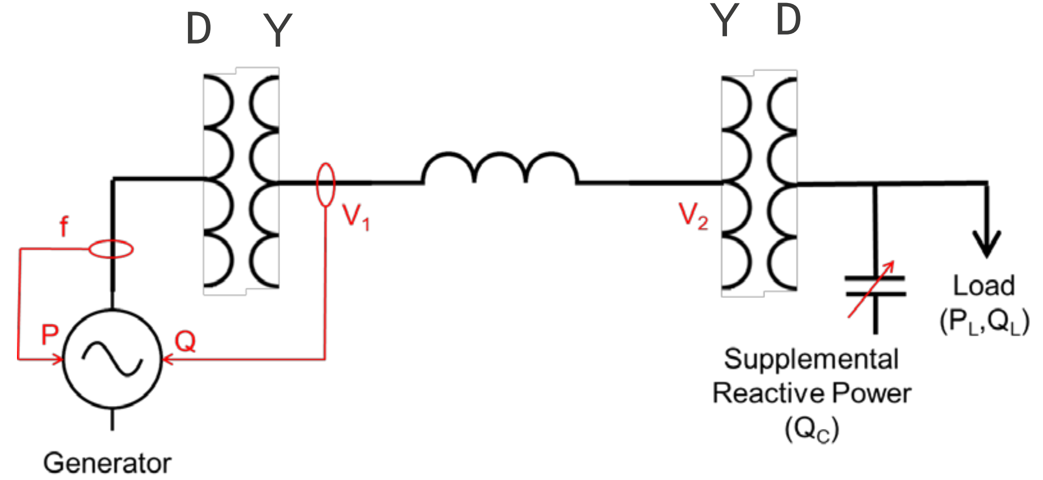
GMD and Physics: DC-Source Terms





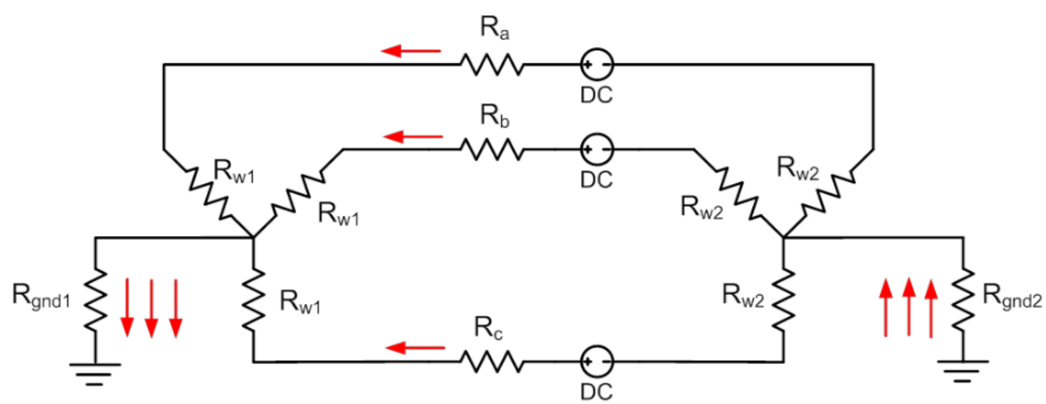
GMD Physics: DC vs AC Network

Simple AC Network—AC power flow is from left to right

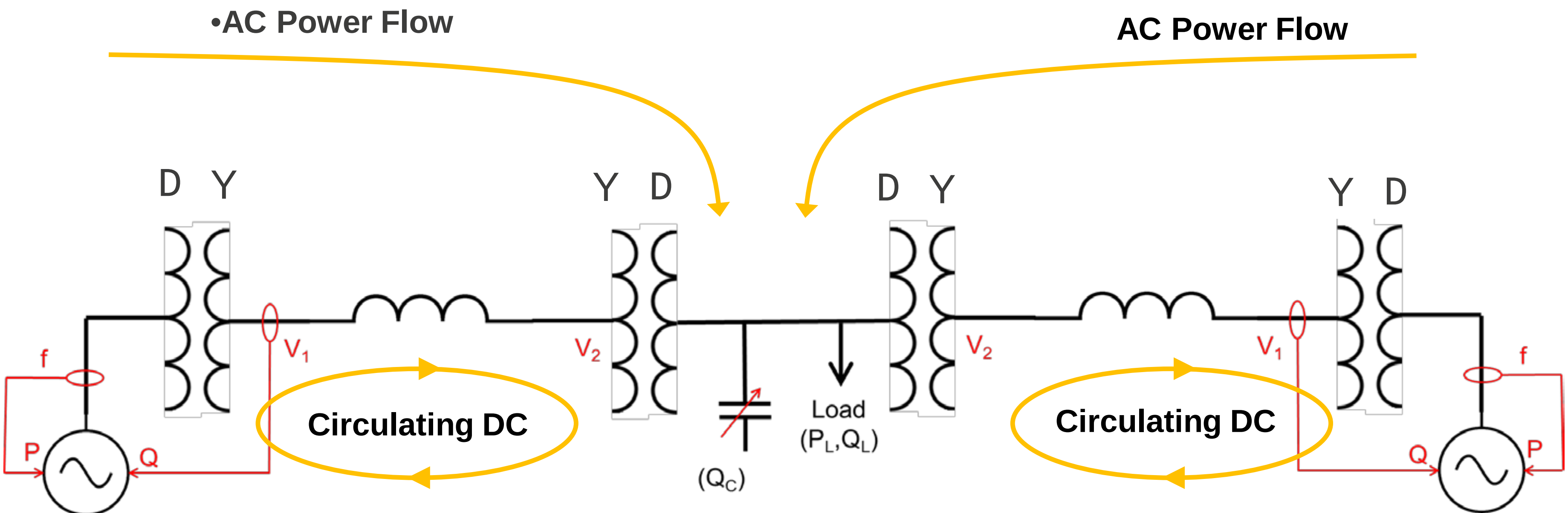


Associated DC Network

- GMD induced DC currents circulate between the two grounded-wye transformers
- No DC current on the ungrounded delta side of the transformers



GMD Physics: AC and DC Networks are Independent



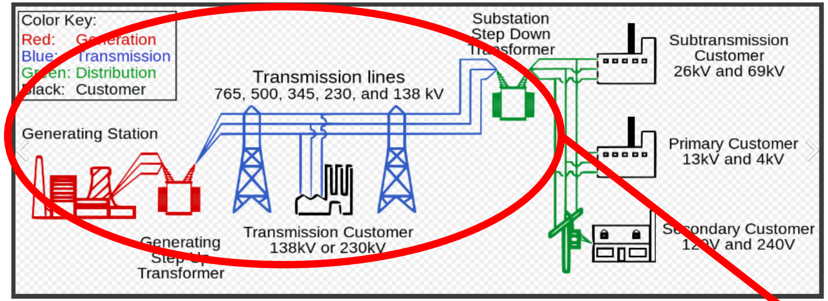
Locations with high AC power flow are controlled by

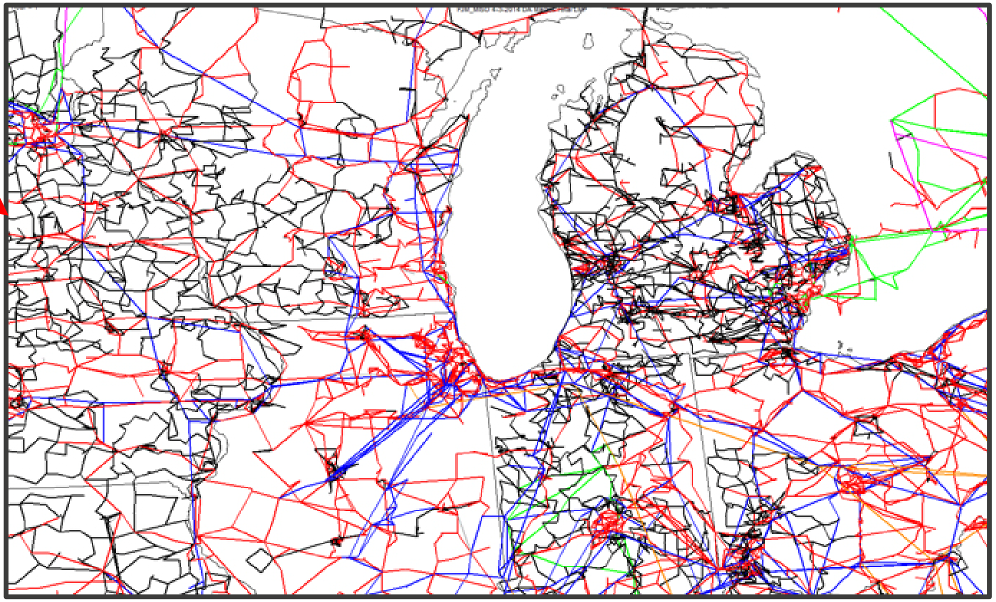
- The AC network
- Generator outputs

Locations with high DC currents

- The DC network
- Strength and orientation of the GMD

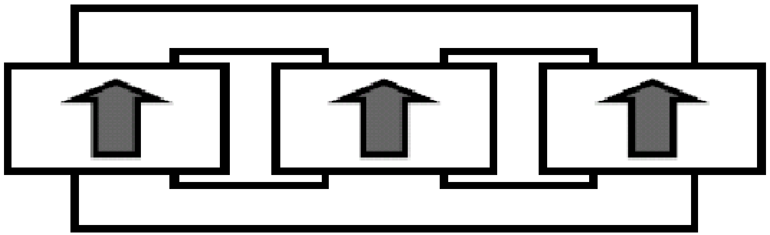
GMD Physics: Real World Interpenetrating AC and DC Networks



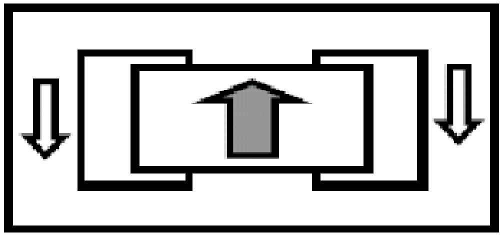


- **AC and DC networks are not completely independent**
- **Interactions occur at the transformers via nonlinearities**
- **Size and interconnectivity of real-world networks make calculation and control of simultaneous of AC and DC flows complex**
  - Simulation tools are becoming mature, but require validation
  - Simultaneous control of AC and DC is emerging R&D

AC and DC Interaction via Transformers

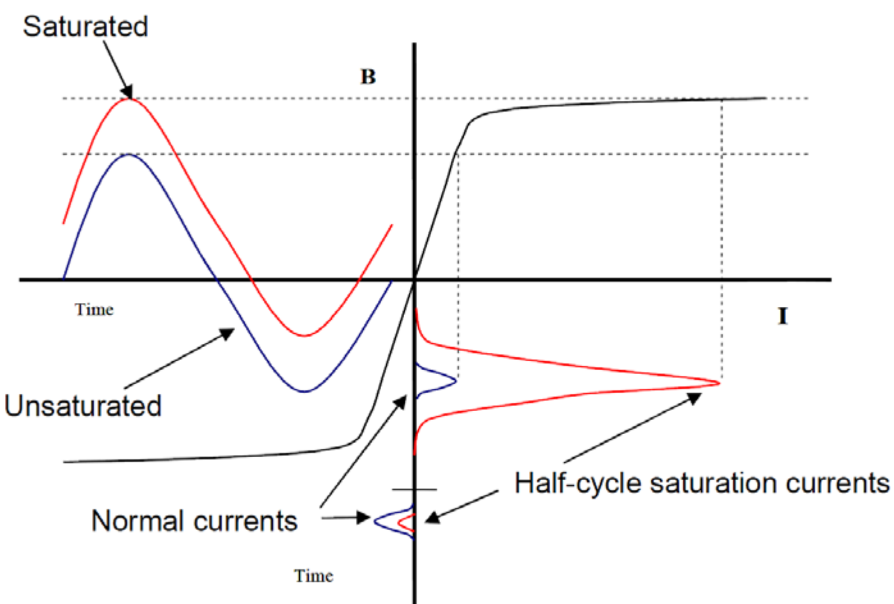


Core Form, 3 phase, 3 limb



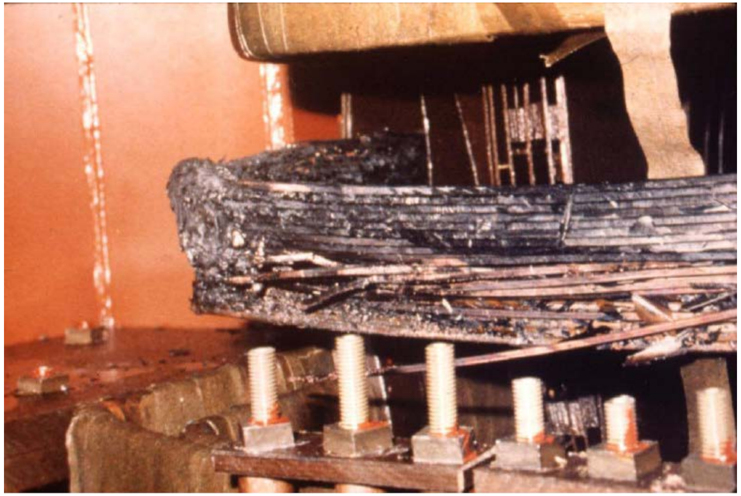
Core / Shell Form, 1 phase

- **DC (GMD) current creates a DC bias to the flux, leading to periodic transformer core saturation**
  - Degree of saturation depends on core configuration
  - Single phase construction is favored for weight and sparing considerations
- **Core saturation leads to:**
  - Stray flux that induces eddy currents in other parts of the transformer structure and housing
  - “Spiky” saturation currents have 60 Hz component—increased reactive (Q) power consumption
  - Significant increase in harmonic generation



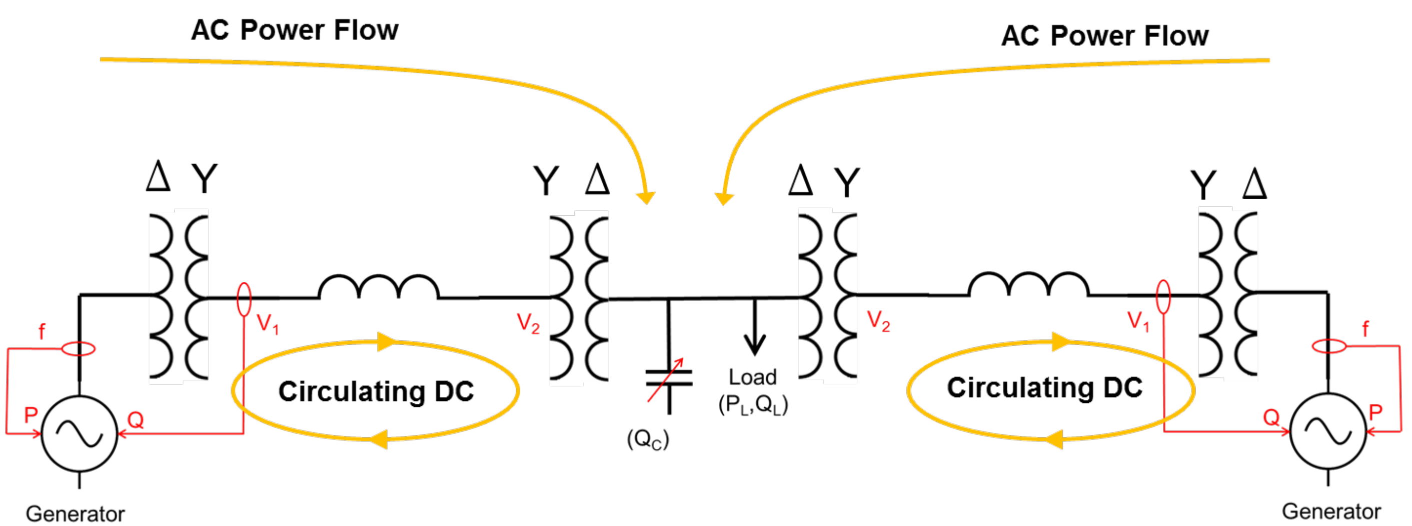
Impacts of Stray Flux

- **Stray flux—If severe enough and left unchecked, eddy current heating can cause permanent damage and subsequent transformer failure**
  - Damage accumulates over time
  - Thermal time constants ~ 5-15 minutes



Impacts of Harmonics and Reactive Power Consumption

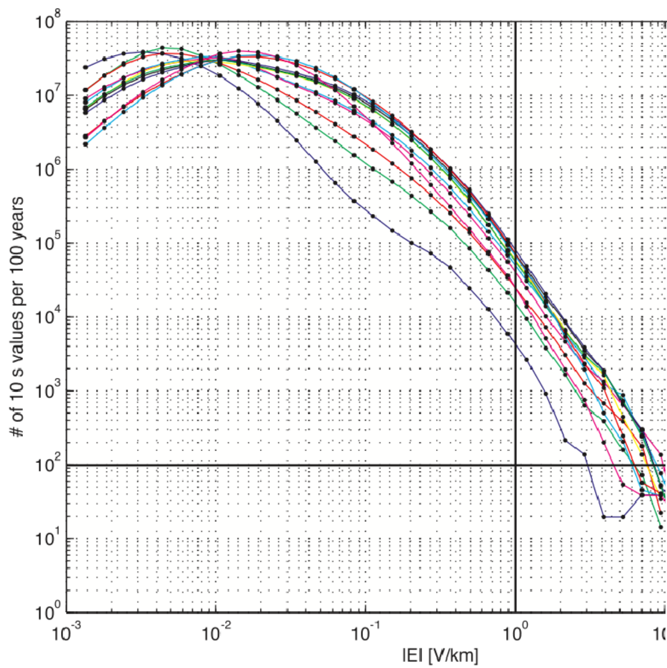
- **Increased reactive power consumption and harmonic generation can generate compounding effects**
  - Harmonics may be misinterpreted by protective relays as a fault or other dangerous condition
  - Subsequent relay misoperation can lead to disconnection of supplemental reactive power support and voltage suppression
  - Continued transformer saturation keeps reactive power loading high
  - System is very susceptible to voltage collapse and cascading failure

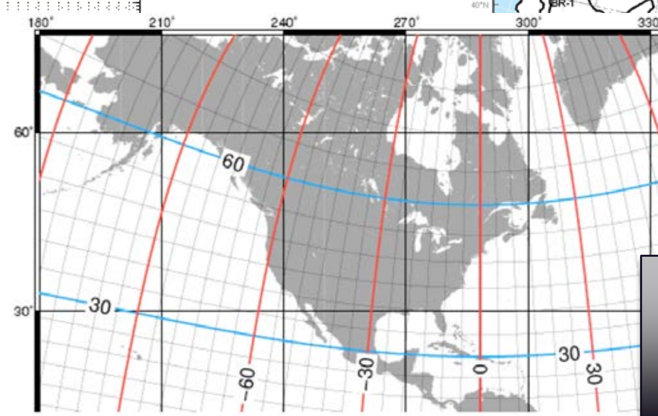


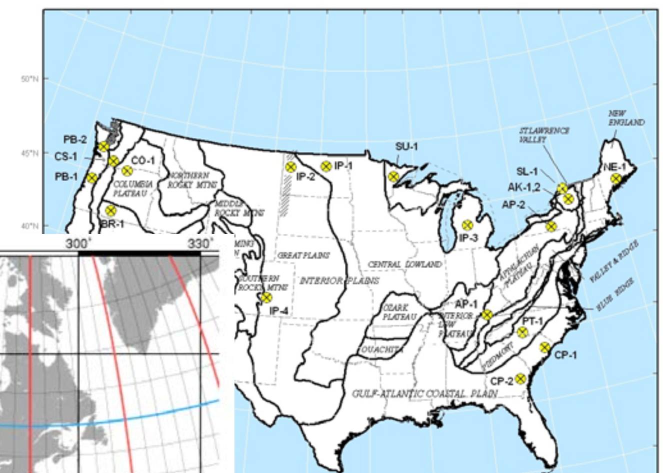
Current State of Practice

FERC (soon to be?) Standard TPL-007-1—A "Phase 1" approach

- **Phase 1—Assess the risk by including GMD simulation studies in required transmission planning studies that evaluate system reliability**
  - Defines a risk screening process for a locally-adapted 1/100 year GMD event







Next Step: Mitigation

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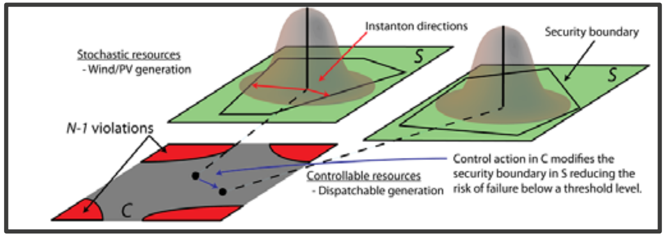
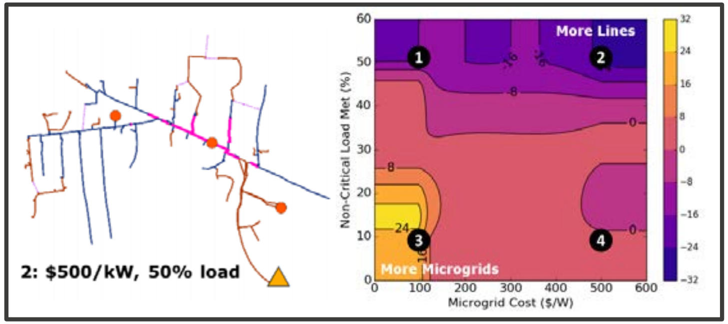




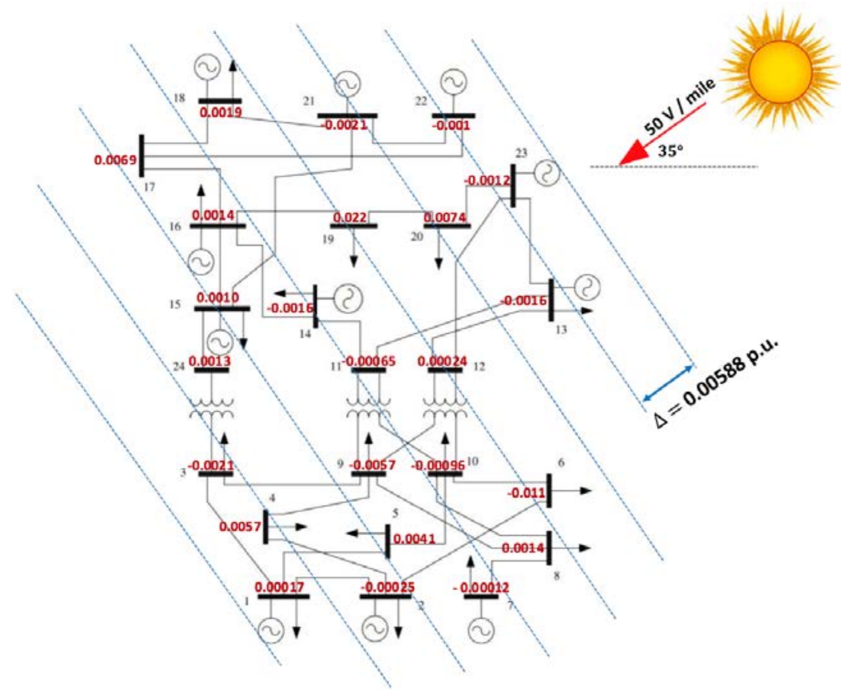
Mitigation Models: Prior Work

- **Challenging mixed-integer, non-convex optimization problem**
- **Prior work (Overbye 2013, 2015)**
  - Siting of protective devices
    - Blocks DC current
    - Expensive
  - Develop a proxy for safe operations
    - Minimize induced reactive losses
    - Ignores AC (normal) physics
    - Advantages
      - Mixed-Integer Linear Program
    - Disadvantages
      - Conservative
      - Neglects thermal heating
  - Our solution
    - Incorporate AC (normal physics)
    - Focus on utilizing existing control points
      - Line switching, generator set points, load shedding
      - Less expensive

Mitigation Model: Components

PhD Student Intern Project: Mowen Lu

- **Modeled as a network**
  - Nodes
  - Generators (producers of power)
  - Loads (consumers of power)
  - Inject or consume power
- **Edges**
  - Power lines
  - Transformers
  - Transport power from one location to another
- **GMD Events (E3)**
  - Introduce a DC current on the system
  - Combination of existing AC current and extra DC current can cause problems



Mitigation Model: High Level

Minimize generation cost and load shedding cost

Subject to:

a) Power flow balance constraints
b) Power flow equations
c) Power loss equations
d) Magnitude of AC current flow equations
e) Operational limits constrains

AC-OTS with reactive power losses induced by GIC

f) GICs calculation equations
g) Magnitude of GICs injection equations
h) Transformer thermal limits constraints
i) Reactive power losses equations
j) Topology decisions

DC-induced network by GMD

Mitigation Model: Nomenclature

Sets

N	set of nodes (buses) in transmission grid
$G \subseteq N$	set of generators
$\mathcal{E}$	set of edges (lines and transformers) in transmission grid
$\mathcal{E}^\tau \subseteq \mathcal{E}$	set of transformer lines
$\mathcal{E}^g \subseteq \mathcal{E}$	set of edges (ij) such that either i or $j \in G$

Binary Variables

y_{ij}	1 if line (ij) is switched on; 0 otherwise

Continuous Variables

θ_i	phase angle at bus $i \in N$
θ_{ij}	phase angle difference of line $(ij) \in \mathcal{E}$
V_i	voltage magnitude at bus $i \in N$
V_i^d	DC voltage magnitude at bus $i \in N$
l_{ij}	current flow magnitude squared on line $(ij) \in \mathcal{E}$
I_{ij}^d	DC current flow on line $(ij) \in N$
I_j^d	DC current injection at bus $i \in N$
$\tilde{I}_{ij}^a$	AC current flow magnitude on transformer lines $(ij) \in \mathcal{E}^\tau$
$\tilde{I}_i^d$	DC current injection magnitude at bus $i \in N$
Q_i^{loss}	Additional reactive power load due to transformer saturation at bus $i \in N$
p_{ij}, q_{ij}	real and reactive power flow on line $(ij) \in \mathcal{E}$
f_i^p, f_i^q	real and reactive power generated at bus $i \in N$
l_i^p, l_i^q	real and reactive power shed at bus $i \in N$

Parameters

c_i	cost of generation at bus $i \in N$
λ	cost of shedding load at bus $i \in N$
a_{ii}	admittance of grounding lines
a_{ij}	admittance of the edges $(ij) \in \mathcal{E}$
j_{ij}	induced current source by GMD on line $(ij) \in \mathcal{E}$
r_{ij}, x_{ij}	resistance and reactance of line $(ij) \in \mathcal{E}$
g_i, b_i	shunt conductance and susceptance at bus $i \in N$
	conductance and susceptance of line $(ij) \in \mathcal{E}$
	branch charging susceptance of line $(ij) \in \mathcal{E}$
	eal and reactive power demand at bus $i \in N$
	arent power thermal limit on line $(ij) \in \mathcal{E}$
	angle difference limit
	er and upper bound on AC voltage injection at bus $i \in N$
	DC voltage difference limit
I_{ij}	AC current flow limit on line $(ij) \in \mathcal{E}$
I_{ij}	current magnitude causing magnetic saturation of transformers on line $(ij) \in \mathcal{E}^\tau$
T_{ij}	thermal limit on transformer line $(ij) \in \mathcal{E}^\tau$
K_i	transformer specific scalar at bus $i \in N$, 0 if there is no transformer at but $i \in N$
$V_{pu,i}$	per unit AC terminal voltage at bus $i \in N$
$\underline{gp}_i$, $\overline{gp}_i$	lower and upper bound on real power generation capacity at bus $i \in G$
$\underline{gq}_i$, $\overline{gq}_i$	lower and upper bound on reactive power generation capacity at bus $i \in G$

Lots here… don't worry about the details

Mitigation Model: AC Physics

$$\min_{p,q,V,\theta,f,l} \sum_{i \in N} c_i f_i^p + \lambda l_i^p \qquad \text{(1a)}$$

Minimize generation and load shedding costs

AC power flow equations

$$\sum_{j:(ij)\in\mathcal{E}} p_{ij} = f_i^p + l_i^p - d_i^p - V_i^2 g_i \qquad \forall i \in N \qquad \text{(1b)}$$

Power flow balance constraints

$$\sum_{j:(ij)\in\mathcal{E}} q_{ij} = f_i^q + l_i^q - d_i^q + V_i^2 b_i - Q_i^{loss} \qquad \forall i \in N \qquad \text{(1c)}$$

$$p_{ij} = y_{ij}(g_{ij}V_i^2 - V_iV_jg_{ij}\cos(\theta_i - \theta_j) - V_iV_jb_{ij}\sin(\theta_i - \theta_j)) \qquad \forall ij \in \mathcal{E} \qquad \text{(1d)}$$

$$q_{ij} = y_{ij}(-(b_{ij} + \frac{b_{ij}^c}{2})V_i^2 + V_iV_jb_{ij}\cos(\theta_i - \theta_j) - V_iV_jg_{ij}\sin(\theta_i - \theta_j))$$

Real and Reactive Power Flow Equations with switching

$$p_{ji} = y_{ij}(g_{ij}V_j^2 - V_iV_jg_{ij}\cos(\theta_j - \theta_i) - V_iV_jb_{ij}\sin(\theta_j - \theta_i)) \qquad \forall ij \in \mathcal{E} \qquad \text{(1f)}$$

$$q_{ji} = y_{ij}(-(b_{ij} + \frac{b_{ij}^c}{2})V_j^2 + V_iV_jb_{ij}\cos(\theta_j - \theta_i) - V_iV_jg_{ij}\sin(\theta_j - \theta_i)) \qquad \forall ij \in \mathcal{E} \qquad \text{(1g)}$$

$$p_{ij} + p_{ji} = y_{ij}r_{ij}(l_{ij} + b_{ij}^c q_{ij} + (\frac{b_{ij}^c}{2})^2 V_i^2) \qquad \forall ij \in \mathcal{E} \qquad \text{(1h)}$$

Power loss equations

$$q_{ij} + q_{ji} = y_{ij}(x_{ij}(l_{ij} + b_{ij}^c q_{ij} + (\frac{b_{ij}^c}{2})^2 V_i^2) - \frac{b_{ij}^c}{2}(V_i^2 + V_j^2)) \qquad \forall ij \in \mathcal{E} \qquad \text{(1i)}$$

$$p_{ij}^2 + q_{ij}^2 = l_{ij}V_i^2 \qquad \forall ij \in \mathcal{E} \qquad \text{(1j)}$$

$$l_{ij} = (\widetilde{I}_{ij}^a)^2 \qquad \forall ij \in \mathcal{E}^\tau \qquad \text{(1k)}$$

Apparent and Current Power Flow Equations

Mitigation Model: Physical Constraints

Operational limits constraints

$$p_{ij}^2 + q_{ij}^2 \leq y_{ij} t_{ij} \qquad \forall ij \in \mathcal{E} \qquad (1l)$$

Thermal line limits

$$p_{ji}^2 + q_{ji}^2 \leq y_{ij} t_{ij} \qquad \forall ij \in \mathcal{E} \qquad (1m)$$

Current limits

$$0 \leq \widetilde{I}_{ij}^a \leq y_{ij} \overline{I}_{ij}^a \qquad \forall ij \in \mathcal{E} \qquad (1n)$$

Voltage limits

$$\underline{V}_i \leq V_i \leq \overline{V}_i \qquad \forall i \in \mathcal{E} \qquad (1o)$$

$$-\overline{\theta} \leq y_{ij}(\theta_i - \theta_j) \leq \overline{\theta} \qquad \forall ij \in \mathcal{E} \qquad (1p)$$

Phase angle limits

$$y_{ij} \underline{gp}_i \leq f_i^p \leq y_{ij} \overline{gp}_i \qquad \forall i \in G,\ ij \in \mathcal{E}^g \qquad (1q)$$

$$y_{ij} \underline{gq}_i \leq f_i^q \leq y_{ij} \overline{gq}_i \qquad \forall i \in G,\ ij \in \mathcal{E}^g \qquad (1r)$$

Generation limits

$$f_i^p = f_i^q = 0 \qquad \forall i \in N/G \qquad (1s)$$

Mitigation Model: GIC Model

Computing Geomagnetically-Induced Current in the Bulk Power System, NERC, 2013

GIC power flow equations

GIC injections

$$\sum_{j:(ij)\in\mathcal{E}} y_{ij} j_{ij} = I_i^d - \sum_{j:(ij)\in\mathcal{E}} y_{ij} a_{ij}(V_i^d - V_j^d) \qquad \forall i \in N \qquad (1t)$$

$$I_i^d = a_{ii} V_i^d \qquad \forall i \in N \qquad (1u)$$

GIC magnitudes and constraints

$$\tilde{I}_i^d \geq I_i^d, \quad \tilde{I}_i^d \geq -I_i^d \qquad \forall i \in N \qquad (1v)$$

GIC effects on transformers

Transformer heating safety limits

$$\tilde{I}_{ij}^a \leq \eta_{ij}^0 + \eta_{ij}^1 \tilde{I}_i^d + \eta_{ij}^2 (\tilde{I}_i^d)^2 \quad \forall ij \in \mathcal{E}^\tau \qquad \forall ij \in \mathcal{E}^\tau \qquad (1w)$$

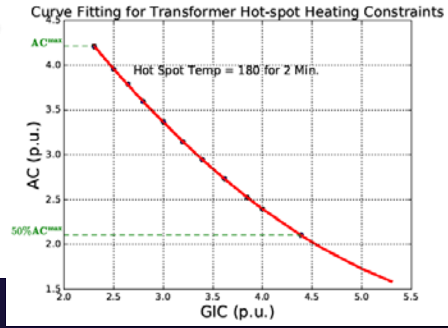
$$Q_i^{loss} = K_i V_{pu,i} I_i^d \qquad \forall i \in N \qquad (1x)$$

Induced reactive losses

$$y_{ij} \in \{0,1\} \qquad \forall ij \in \mathcal{E} \qquad (1y)$$

Zhu, Hao, and Thomas J. Overbye. *Blocking device placement for mitigating the effects of geomagnetically induced currents*. *IEEE Transactions on Power Systems* 30.4 (2015): 2081-2089

IEEE Guide for Establishing Power Transformer Capability while under Geomagnetic Disturbances, IEEE Power and Energy Society, 2015



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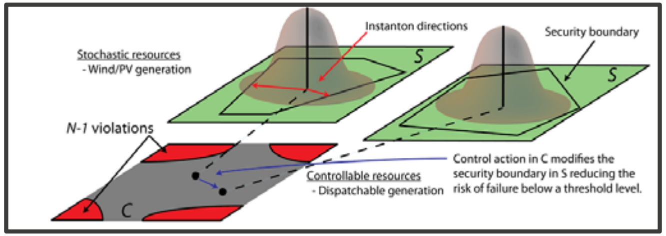
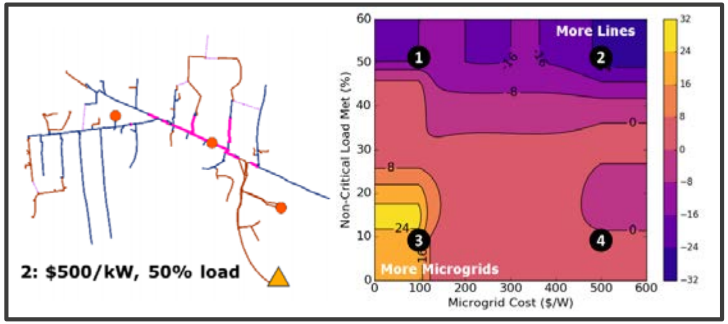
- Conclusion

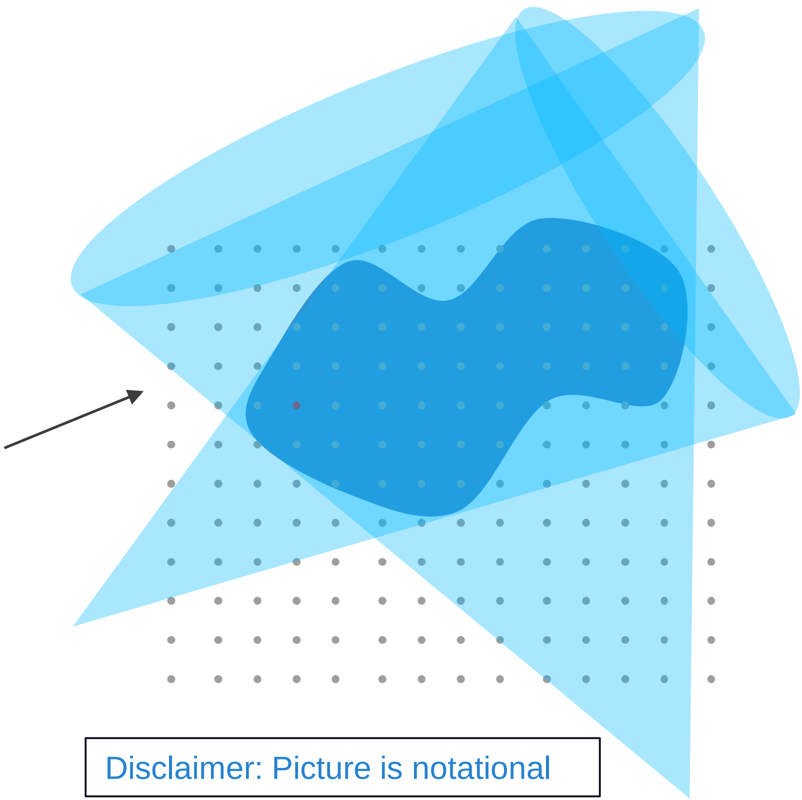




Convex Relaxtions

<u>**Challenges**</u>

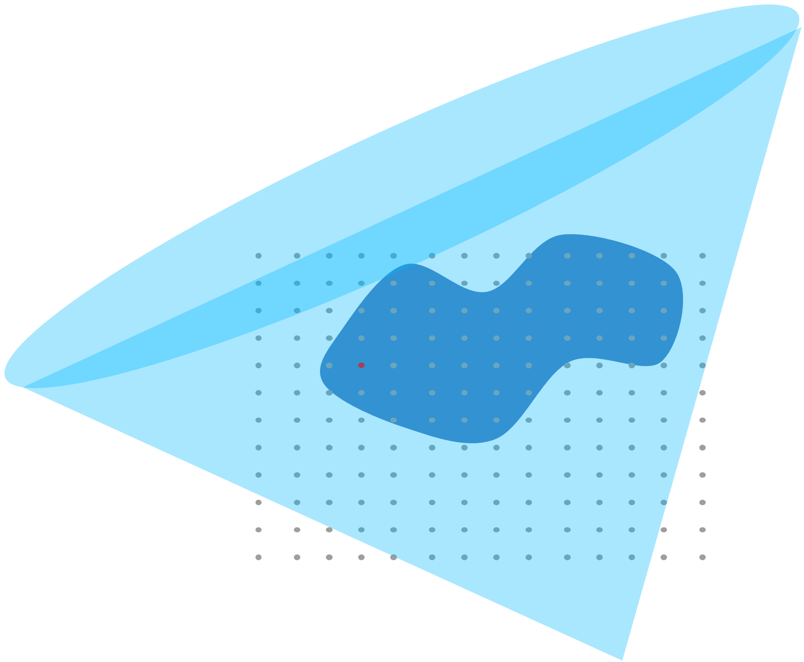
- **Discrete variables**
  - Opening or closing a line
- **Non-convex constraints**
  - Bi-linear terms, cosines, sines
  - Solution: replace non-convex terms with convex envelopes (McCormick)
    - See Coffrin, van Hentenryck, and Hijazi 2014, 2016
  - Solution with convex envelope is a lower bound on the solution to the original problem
    - Often tight in practice on power system problems



Disclaimer: Picture is notational

Convex Relaxation Weaknesses

- **The convex envelopes yield good results when the upper and lower bounds on variables are tight**
- **GIC voltages and currents do not have tight bounds**
  - We still have a (weak) lower bound
  - Sometimes “0”
- **Global spatial branching solvers are also challenged**

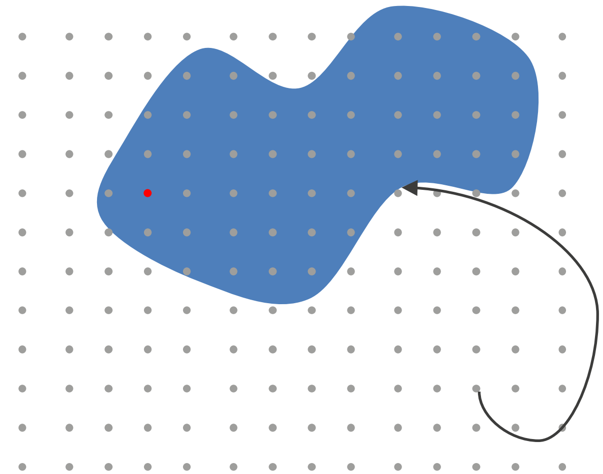


Disclaimer: Picture is notational

Bound Tightening

<u>**Infer new bounds**</u>

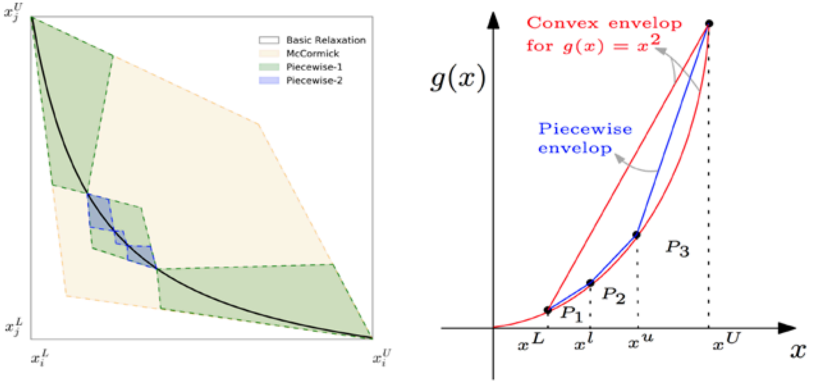
1. **Find a "local" solution to the original non-convex formulation**
   1. Gradient descent
   2. This solution is an upper bound
2. **Introduce a constraint that restricts solutions to have a value <= this upper bound**
3. **For each variable (i.e. GIC DC current) solve 2 problems with the convex formulation**
   1. Maximize the upper bound
   2. Minimize the lower bound
   3. Possible to iterate
4. **This procedure deduces tighter variable bounds that tighten the convex envelopes and improve solution quality**
   – There exist other (better) ways to do this, but this simple approach worked rather well



Dynamic Spatial Branching

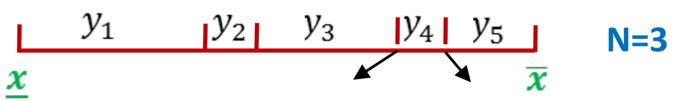
<u>**Discretize the bounds**</u>

1. **Solve the convex relaxation problem**
2. **Split the bounds of the variables into valid ranges around the current solution**
    1. Applies different convex envelopes depending on the variable choice
    2. Further tighten the relaxation
        1. Drawback: introduces binary variables
3. **Solve again**
4. **Further split the bounds for any variable whose value changes (xlocal)**
5. **Repeat until solution does not change more than a small value**



(a) Bilinear term

(b) Quadratic term



Note: This can be done with log discrete variables (Vielma et al 2010, and others) or SOS constraints

Results

- **Academic literature contains numerous problems with similar structure**
  - MINLPLIB
- **Our algorithm (DTMC) out-performed existing state-of-the-art**
  - Commercial solver—Baron
  - 6 hour time limit

Instances	Baron		DTMC	
	Gap (%)	Time (sec)	Gap (%)	Time (sec)
eniplac	< 0.0001	331	< 0.0001	2
blend531	< 0.0001	2349	< 0.0001	64
blend718	27.5	3600	< 0.0001	179
blend480	< 0.0001	2044	< 0.0001	1029
blend146	4.0	3600	0.035	3600

Nagarajan, Lu, Yamangil, and Bent, *Tightening McCormick Relaxations for Nonlinear Programs via Dynamic Multivariate Partitioning*, *The 22nd International Conference on the Principles and Practice of Constraint Programming*, 2016

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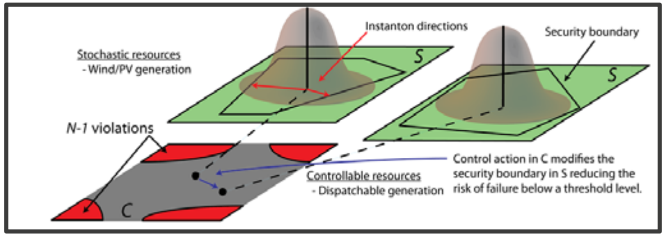
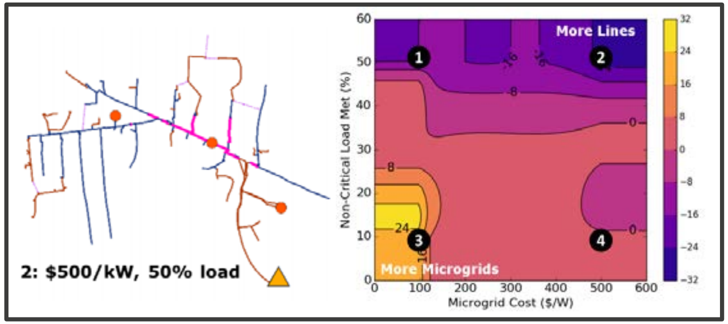
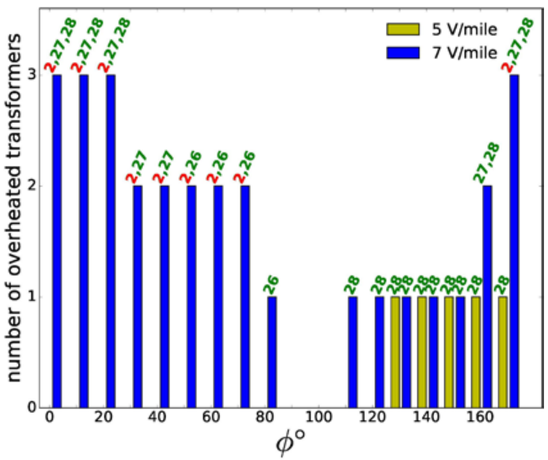


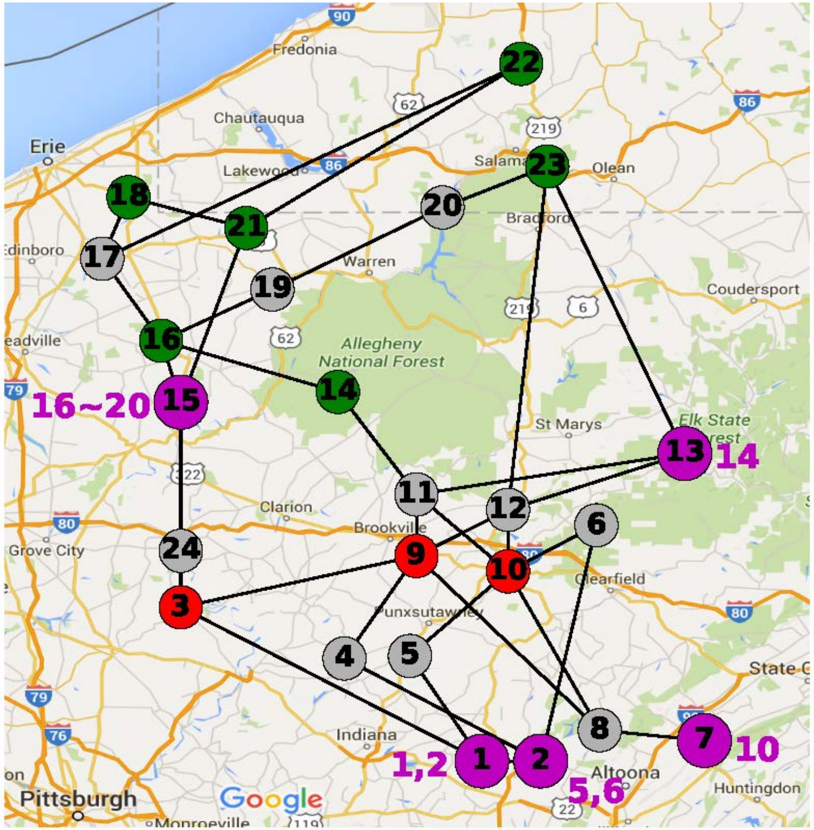


Case Study

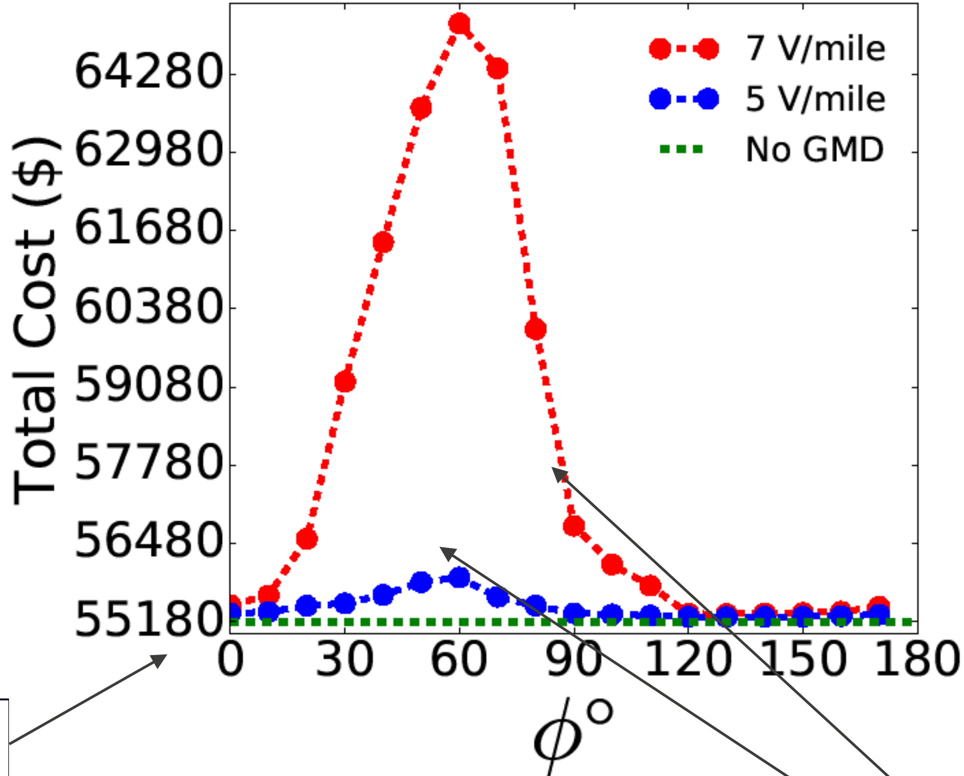
- Notional power system model
  - 3 transformers (red)
  - 5 nodes with generators (purple) - transformers
  - 5 nodes with load
- Uniform field strength applied at angle ϕ

<u>Overloads without mitigation</u>





Cost of Safe Operations



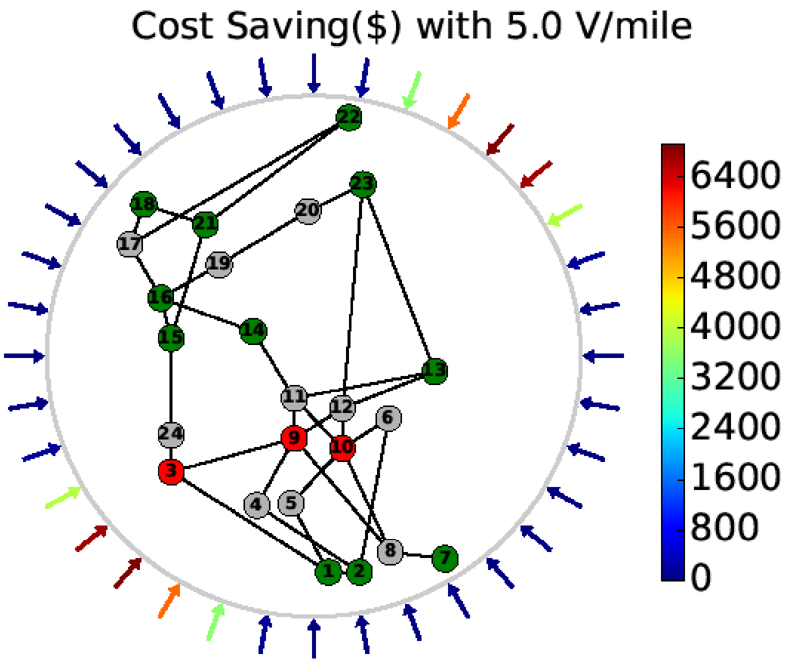
Under modest GMD, minor adjustments can preserve equipment

No GMD Cost

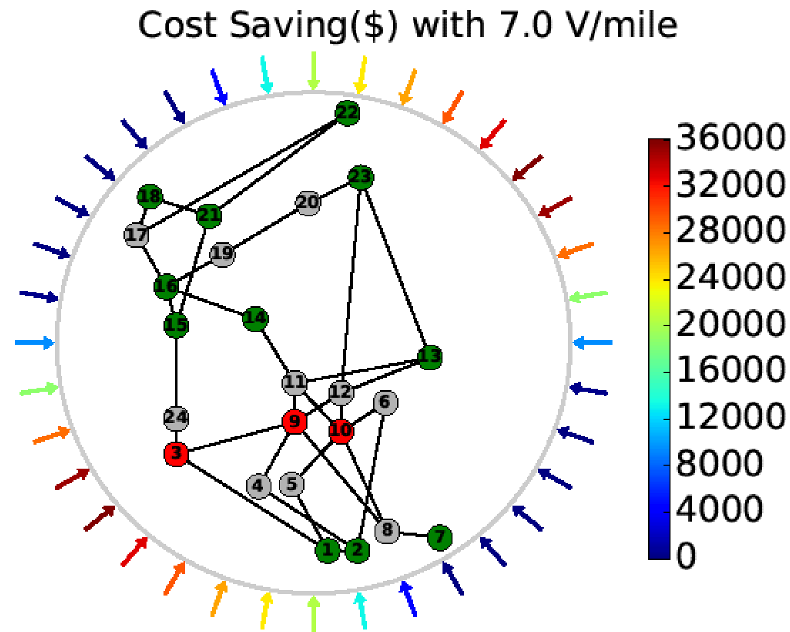
With GMD Cost

Benefits of Switching

5 V/mile

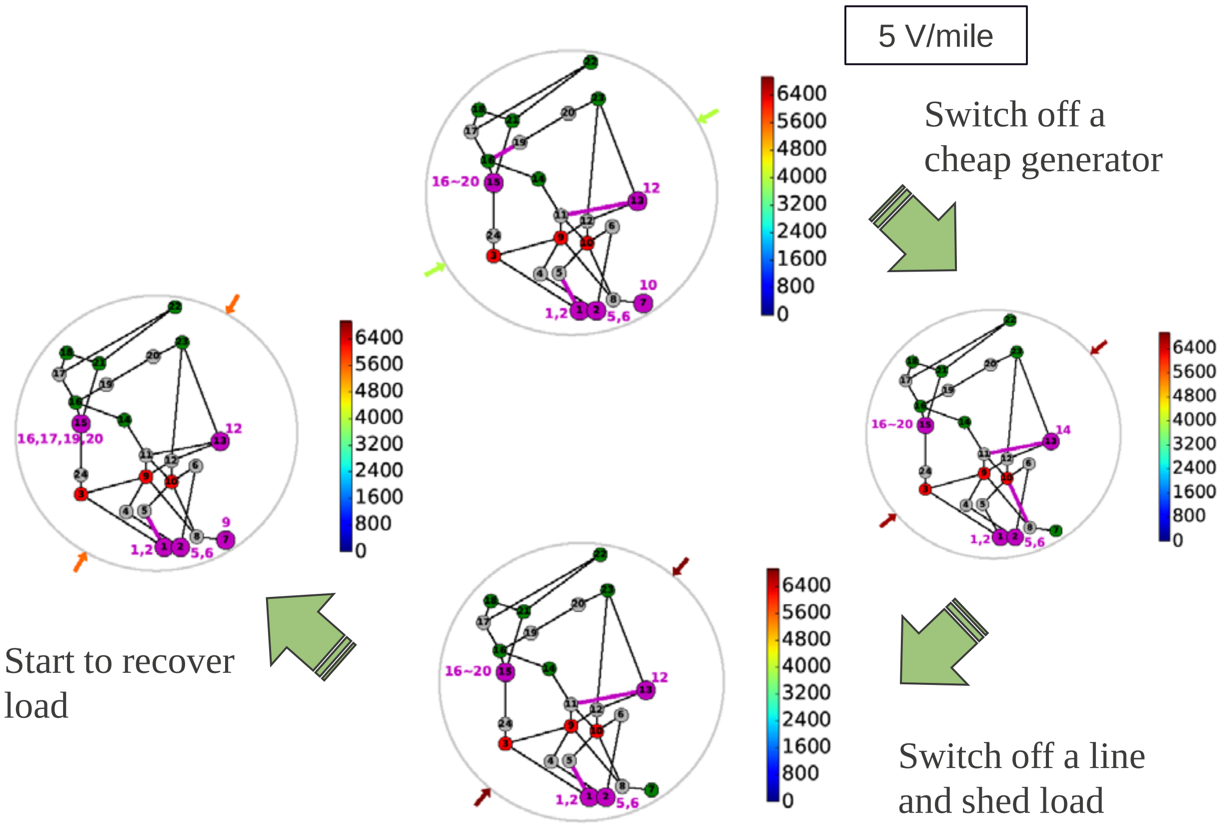


7 V/mile



The benefits of allowing line switching increases dramatically as event magnitude increases

Solution Structure



Solution Times (Global Optimality)

Wall Time (seconds)

Strength	Avg	Min	Max	Std
5	2133	45.58	16351	4091
7	34489	132.48	147256	49576

Getting a relaxed solution or local solution is considerably faster

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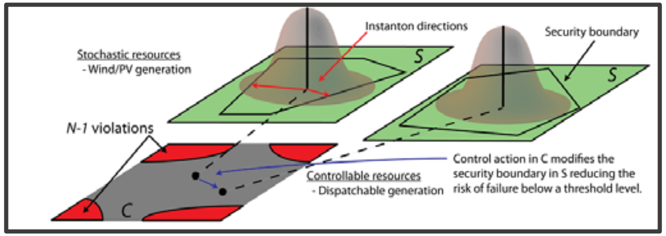

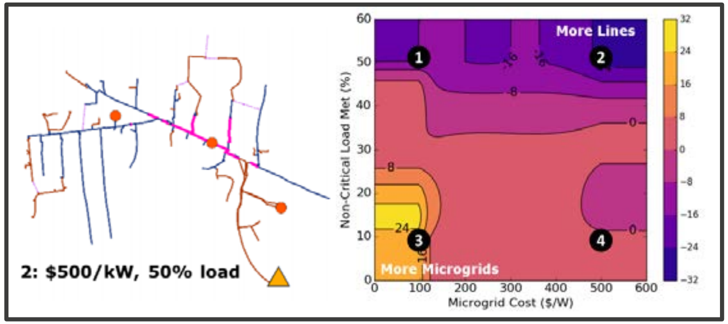

Conclusions

- **Contributions**
  - A model of GIC physics combined with AC power flow physics
    - A model of power system component safety margins
    - Optimization of operations that respect safety margins.
  - Builds on previous work
    - Focused on placing (expensive) blocking devices
    - Minimized a safety metric (reactive power loading at transformers)
      - Overbye et al., 2013, 2015
    - To the best of our knowledge, we have the first model that builds in the safety margins directly
  - A dynamic spatial branching algorithm
- **Publications**
  - H. Nagarajan, M. Lu, E. Yamangil, and R. Bent. *Tightening McCormick Relaxations for Nonlinear Programs via Dynamic Multivariable Partitioning*, 22nd International Conference on Principles and Practice of Constraint Programing, 2016.
  - M. Lu, H. Hagarajan, E. Yamangil, R. Bent, and S. Backhaus. *Optimal Transmission Line Switching under Geomagnetic Disturbances*, in progress.

Future Work

- **Stochastic events**
  - We assume the characteristics of the event are known
  - Connection to space weather, earth modeling and prediction
  - Robust operations
- **Modeling**
  - Improved algorithms
  - Other GMD impacts (E1, controls, etc.)
  - Real system studies
- **Algorithm**
  - Extensions to other convex relaxations

Winter School and Conference

New <u>interdisciplinary</u> R&D community for modernized infrastructure

Held in January 2015, next event January 11-15, 2017 cnls.lanl.gov/2017gridscience

2015 Grid Science Winter School and Conference

Physics, Control, Optimization, Computer Science, Statistics, Operations Research, Power Engineering

Students From: Columbia, Rutgers, MIT, CalTech, ETH Zurich, UC Berkeley, UCSD, UCSB, UTexas, UVermont, UMinnesota, UMichigan, UWashington, UConn, NICTA Australia, Skolkovo Tech, LANL

Lecturers:

		I. Hiskens,	UMichigan;
A. Conejo,	OSU;	F. Dorfler,	ETH Zurich
M. Chertkov,	LANL;	D. Bienstock,	Columbia
S. Low,	Cal Tech;	P. van Hentenryck,	NICTA Australia
K. Turitsyn,	MIT;	D. Callaway,	UC Berkeley

"The uniqueness of this workshop is inarguable"

"I've never learnt that much in such a short time!"

"Great opportunity for interdisciplinary contact and collaboration"

"I learnt a lot of things from the school and will apply those right away in the coming weeks"