Optimal Power Flow under Geomagnetic Disturbances

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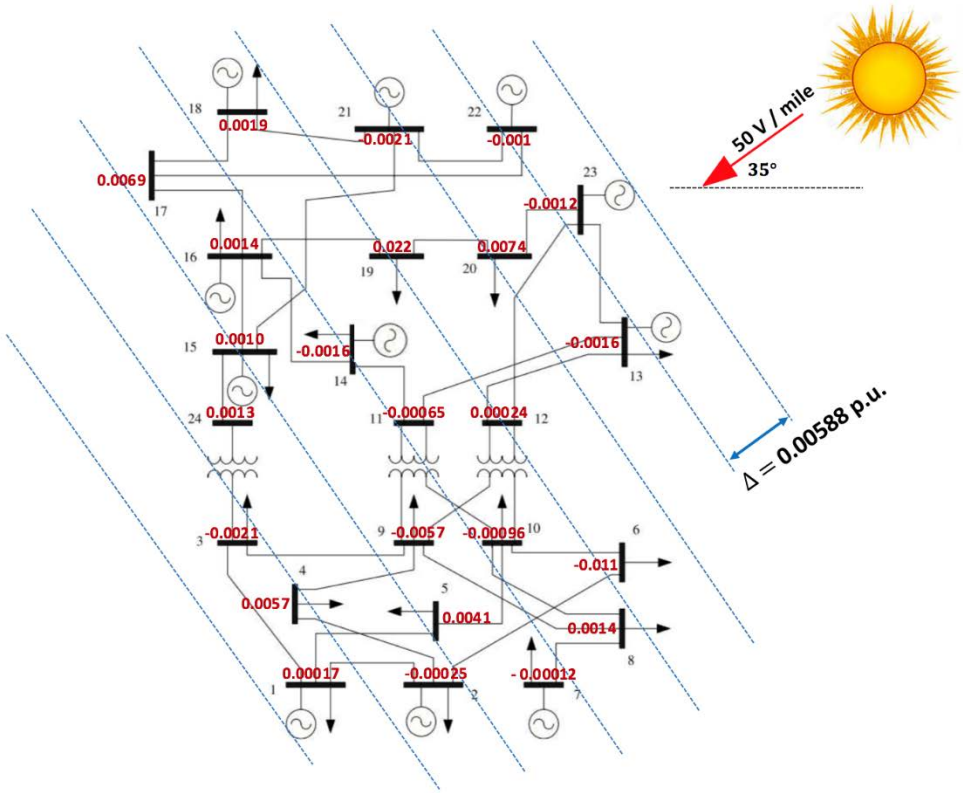
Introduction and Motivation

- **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 studies of power system fragility**
  - Transformers
  - Generators
  - Control components
- **Motivates studies 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

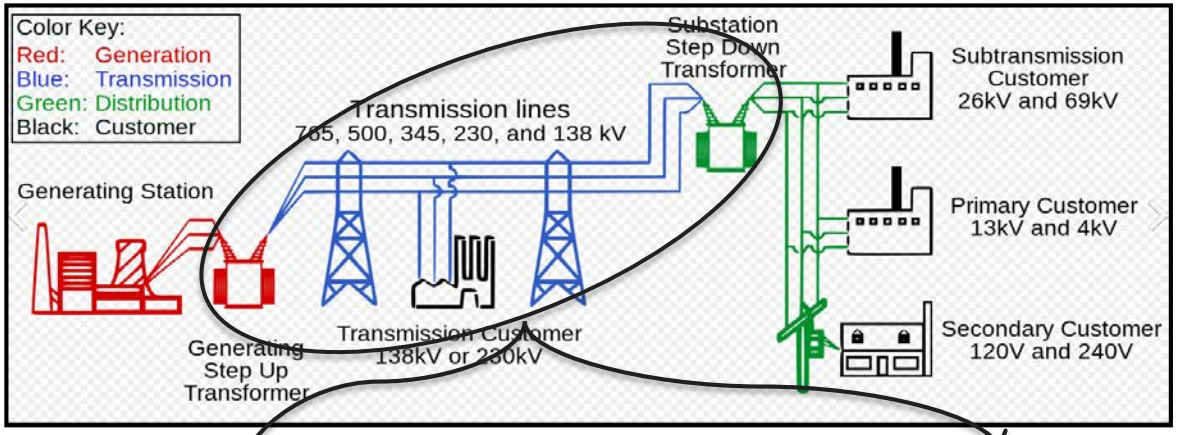
Power Grids

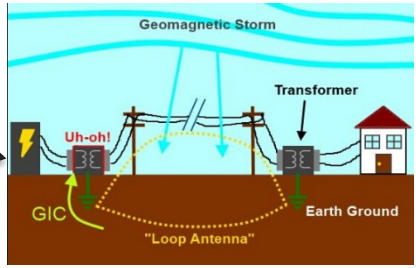
- **Modeled as a network**
  - Nodes
    - Generators (producers of power)
    - Loads (consumers of power)
    - Inject or consume power
  - Edges
    - Power lines
    - Transformers
    - Transport power from one location to another
- **GMD Events**
  - Introduce a DC current on the system
  - Combination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

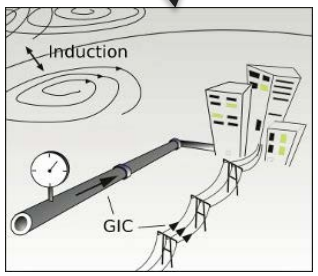


Power Grids during GMD (E3)

Transmission grid | Distribution grid







The quasi-DC GIC flow in transformer windings can cause half-cycle saturations of transformer cores, resulting in increased transformer hotspot heating, accelerated aging of the cellulosic insulation and gas generation.

Source: https://en.wikipedia.org/wiki/Geomagnetic_storm

Steady-State Power Flow Modeling - Overview

Minimize generation cost and load shedding cost

Subject to:

a) Power flow balance constraints
b) Power flow equations
c) Power losses 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

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 othe

Continuous Variables

θ_i	phase angle at bus $i \in N$
θ_{ij}	phase angle difference of line $(ij) \in$
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_i^d	DC current injection at bus $i \in N$
$\widetilde{I}_{ij}^a$	AC current flow magnitude on transformer lines $(ij) \in \mathcal{E}^{\tau}$
$\widetilde{I}_i^d$	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	admittance of the edges $(ij) \in \mathcal{E}$
	induced current source by GMD on line $(ij) \in \mathcal{E}$
	resistance and reactance of line $(ij) \in \mathcal{E}$
	shunt conductance and susceptance at bus $i \in N$
	conductance and susceptance of line $(ij) \in \mathcal{E}$
	branch charging susceptance of line $(ij) \in \mathcal{E}$
$_i$, d_i^q	real and reactive power demand at bus $i \in N$
t_{ij}	apparent power thermal limit on line $(ij) \in \mathcal{E}$
$\overline{\theta}$	phase angle difference limit
$\underline{V}_i$, $\overline{V}_i$	lower and upper bound on AC voltage injection at bus $i \in N$
$\overline{V}^d$	DC voltage difference limit
$\overline{I}_{ij}^a$	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

Steady-State Power Flow Modeling - Details

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

Minimize generation and load shedding costs

AC power flow equations

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

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

Power flow balance constraints

$$p_{ij} = y_{ij}(g_{ij}V_i^2 - V_iV_jg_{ij}\cos(\theta_i - \theta_j) - V_iV_jb_{ij}\sin(\theta_i - \theta_j))$$

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

$$p_{ji} = y_{ij}(g_{ij}V_j^2 - V_iV_jg_{ij}\cos(\theta_j - \theta_i) - V_iV_jb_{ij}\sin(\theta_j - \theta_i))$$

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

Real and Reactive Power Flow Equations

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

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

Power loss equations

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

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

Apparent and Current Power Flow Equations

Normal Operating 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

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

GIC Modeling

GIC power flow equations

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

GIC injections

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

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

GIC magnitudes and constraints

GIC effects on transformers

$$\widetilde{I}_{ij}^a (\widetilde{I}_{ij}^a + \widetilde{I}_i^d - I_{ij}) \leq T_{ij} \qquad \forall ij \in \mathcal{E}^\tau \qquad (1w)$$

Transformer heating safety limits

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

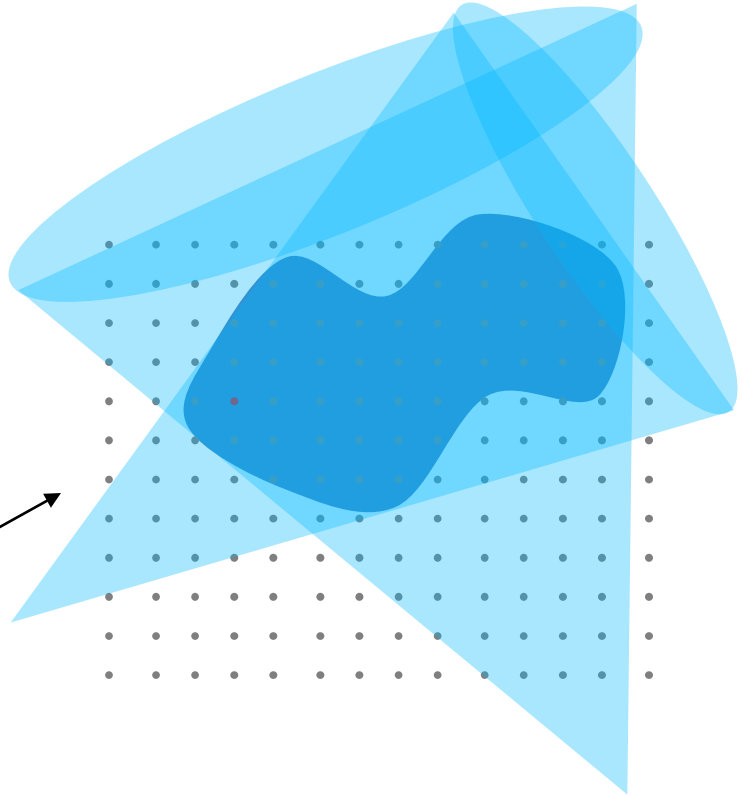
Induced reactive losses

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

Information Science Challenges

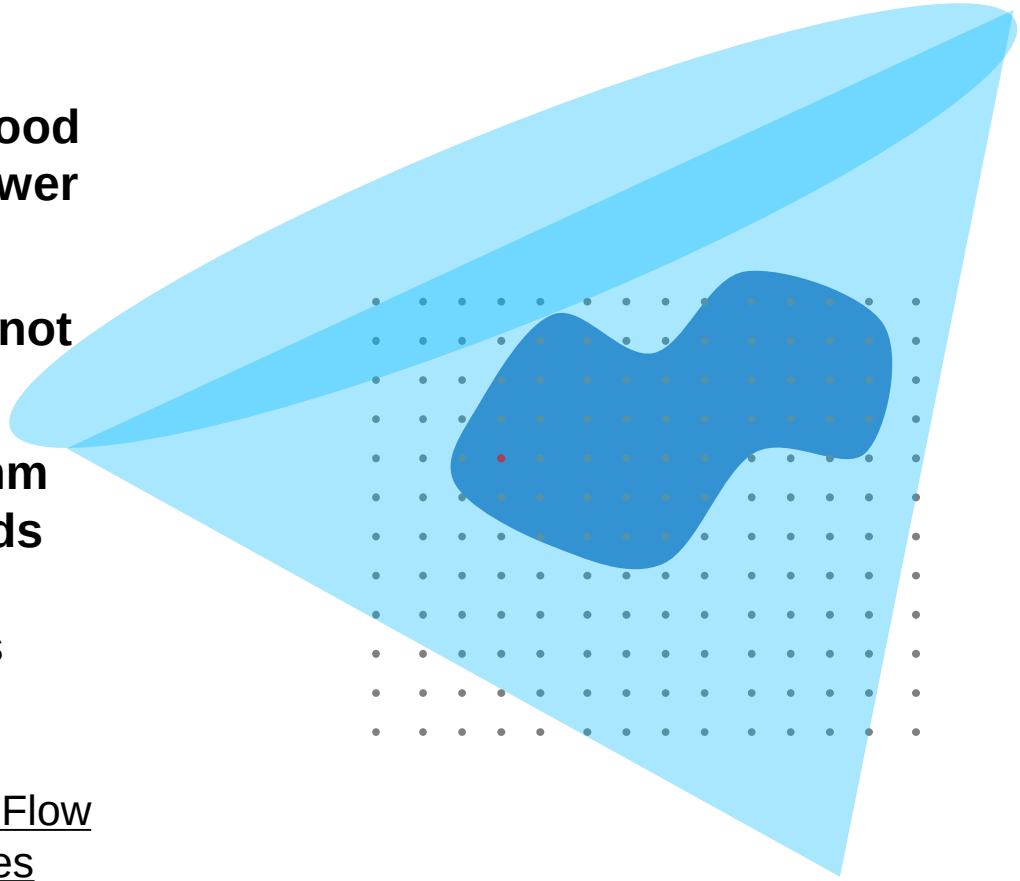
<u>What makes this problem computationally difficult?</u>

- **Discrete variables**
  - Opening or closing a line
  - Not a bottleneck… so far
- **Non-convex constraints**
  - Bi-linear terms, cosines, sines
  - Solution: replace non-convex terms with convex envelopes
    - See Coffrin, van Hentenryck, and Hijazi 14
  - Solution with convex envelope is a lower bound on the solution to the original problem
    - Often tight in practice



Novel Algorithm

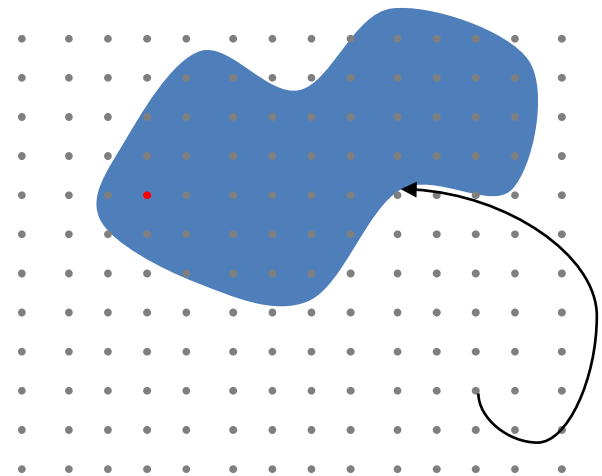
- **The convex envelopes yield good results when the upper and lower bounds on variables are tight**
- **GIC voltages and currents do not have tight bounds**
- **We developed a novel algorithm for problems with loose bounds**
  - Delivers strong performance on standard academic benchmarks (outside the scope of this talk)
  - Improved the computational performance on <u>Optimal Power Flow under Geomagnetic Disturbances</u>



Novel Algorithm: Key Idea 1

<u>Infer new bounds</u>

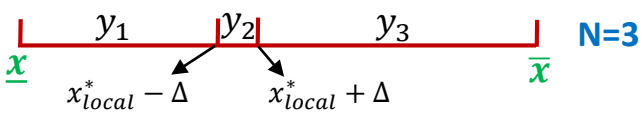
1. **Find a "local" solution to the original non-convex formulation**
   1. Gradient descent
   2. This solution is an upper bound
2. **Introduce a constraint that restricts solutions to have a value <= this upper bound**
3. **For each variable (i.e. GIC DC current) solve 2 problems with the convex formulation**
   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**

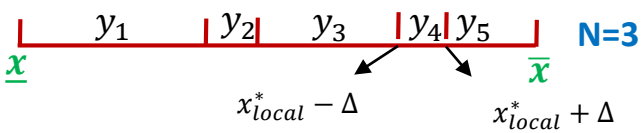


Novel Algorithm: Key Idea 2

<u>Discretize the bounds</u>

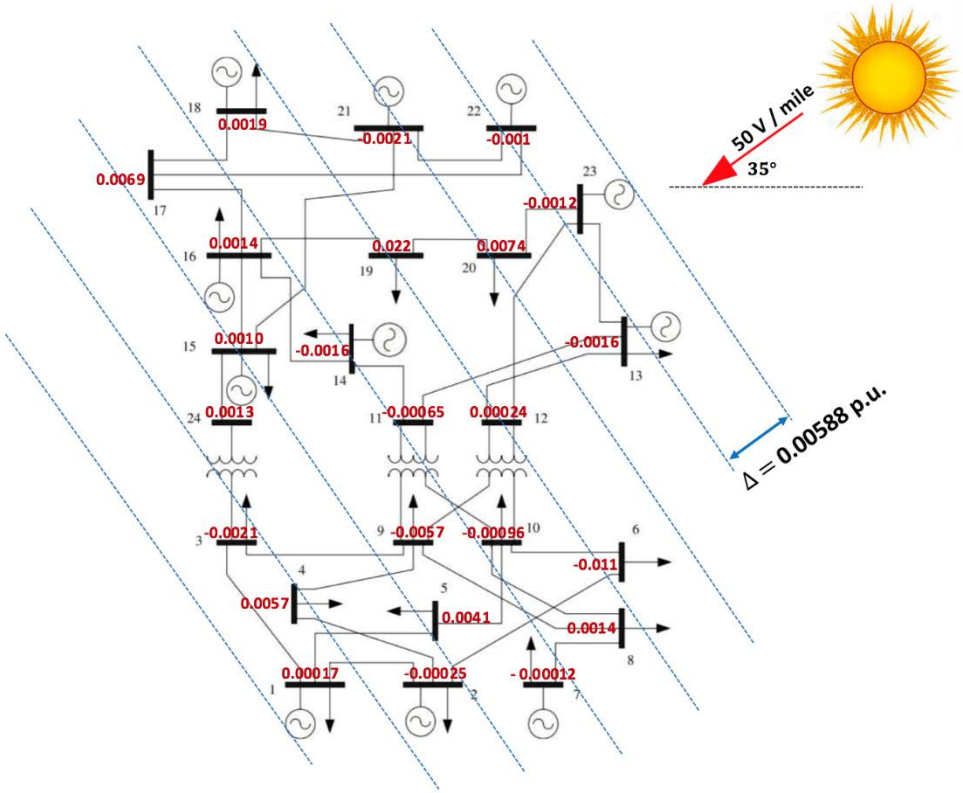
1. **Solve the convex relaxation problem**
2. **Split the bounds the variables into valid ranges, focused where the values these variables have in the solution**
   1. Applies different convex envelopes depending on the variable choice
   2. Further tightens the relaxation
      1. Drawback: introduces 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**



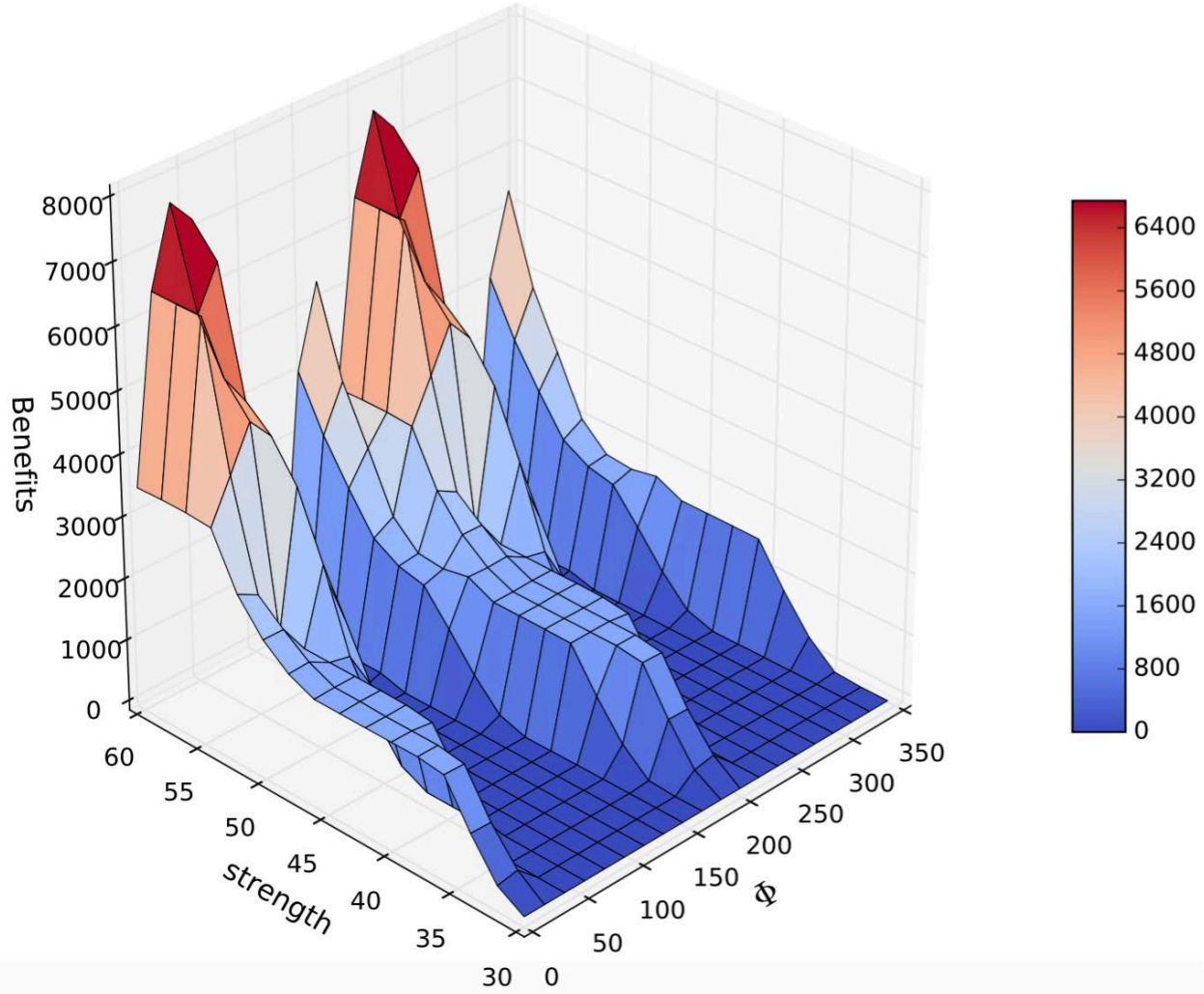


Results

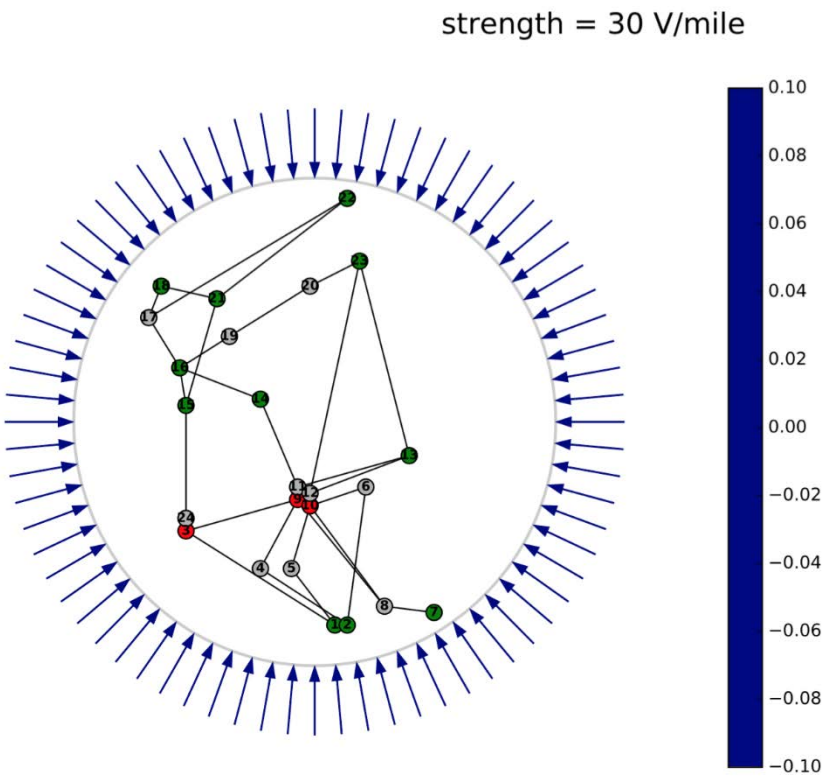
- **IEEE RTS-96 Test System**
- **GMD event with symmetric field strength gradients**
- **Analyzed how the solution changed depend on event direction and magnitude**

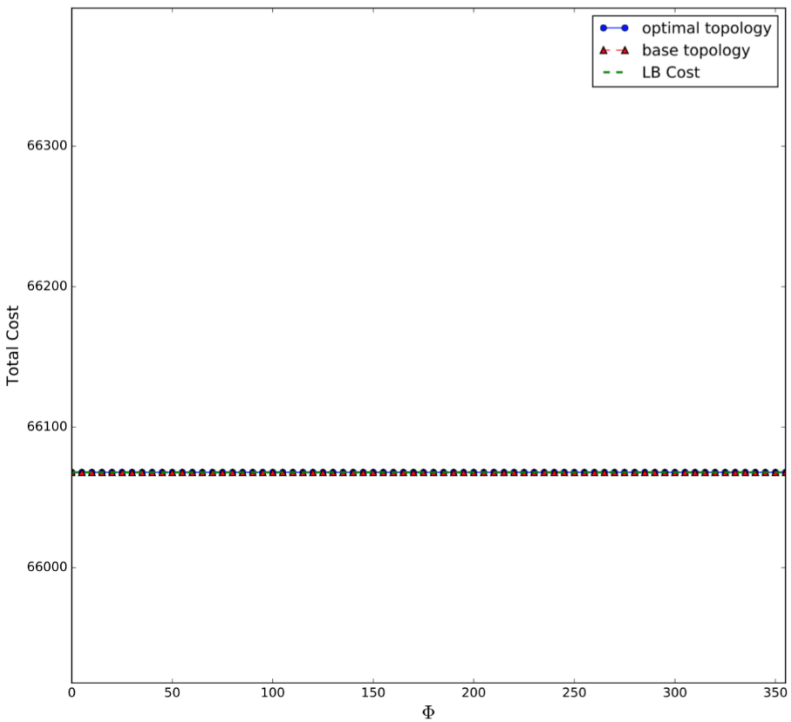


Overview Results



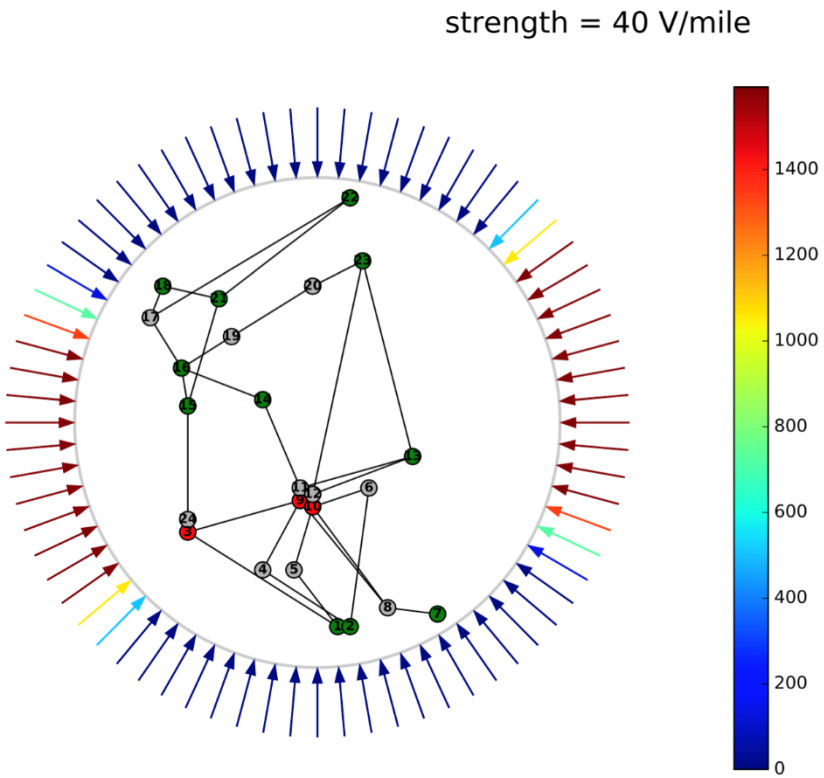
Drill down on 30 V per mile

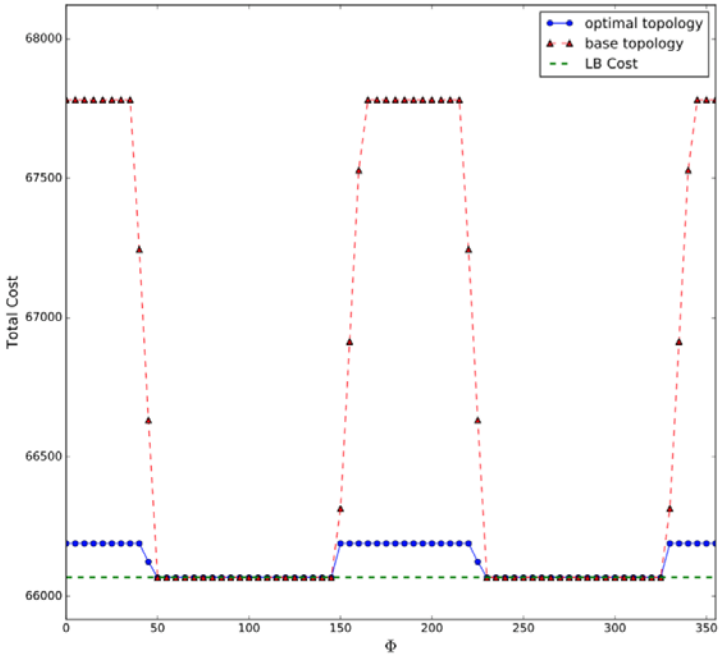




Thermal heating generally not an issue

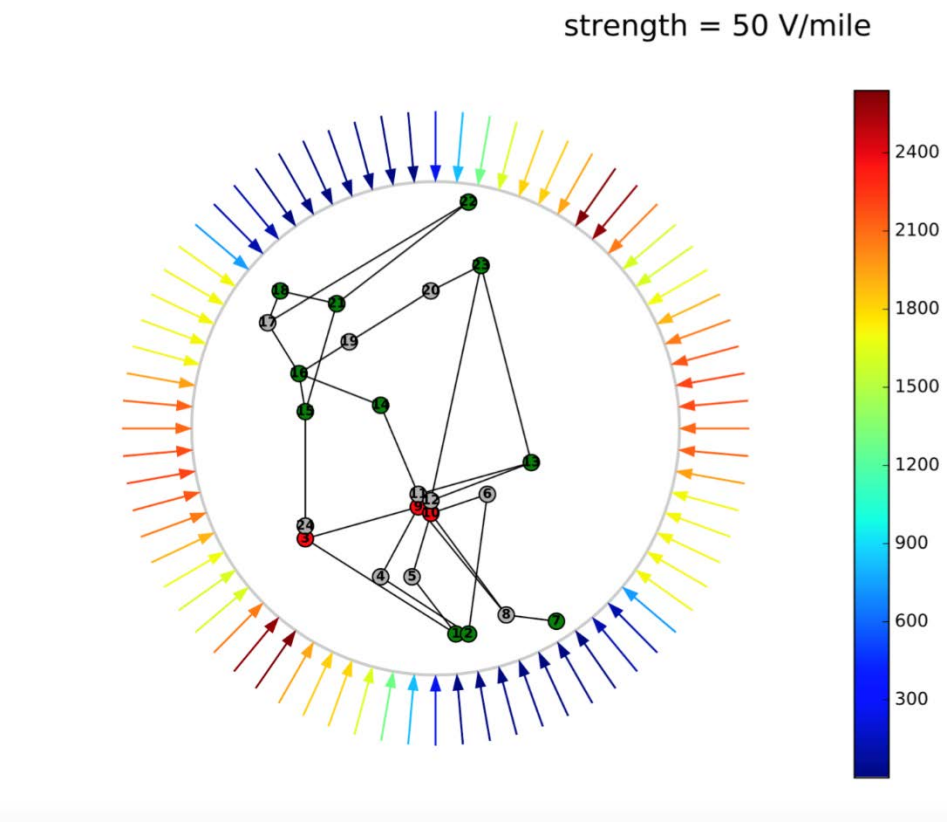
Drill Down on 40 V per mile

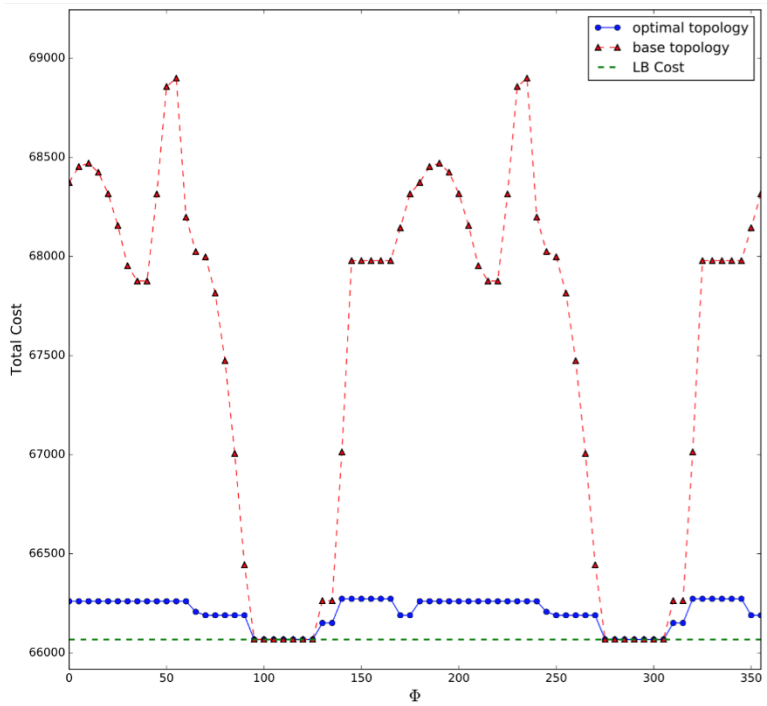




Some directions now require mitigation options

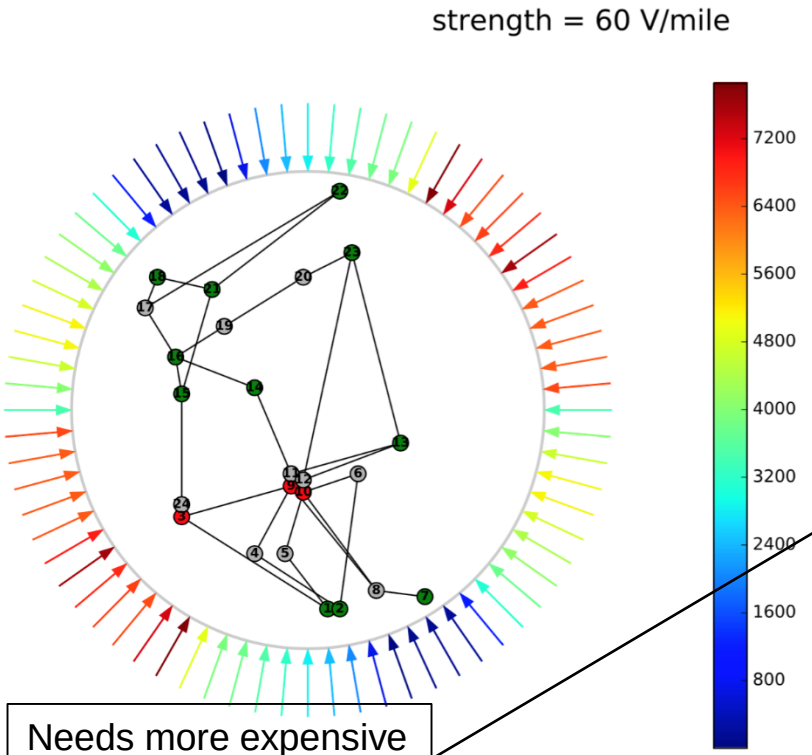
Drill Down on 50 V per mile

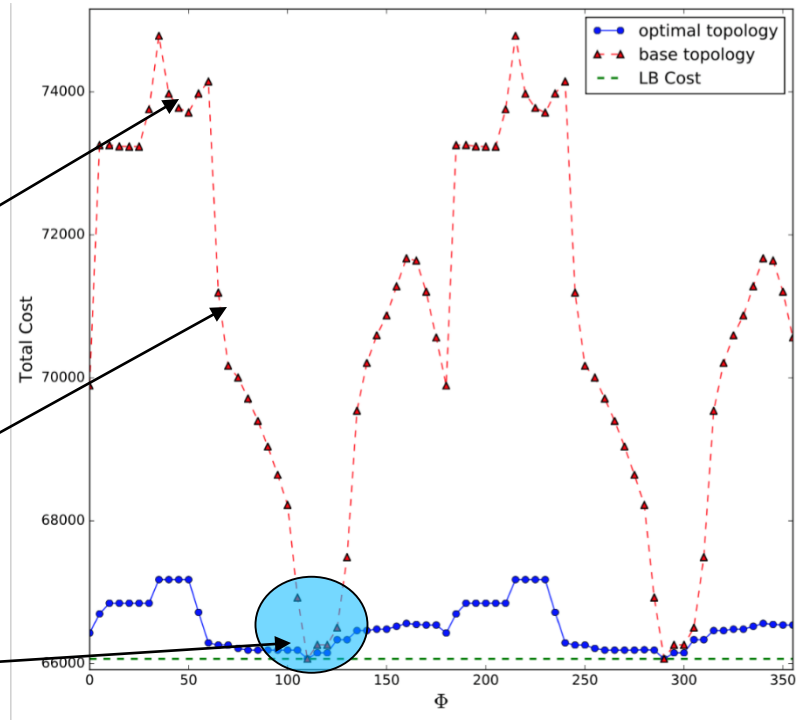




Impacts have increased

Drill Down on 60 V per mile



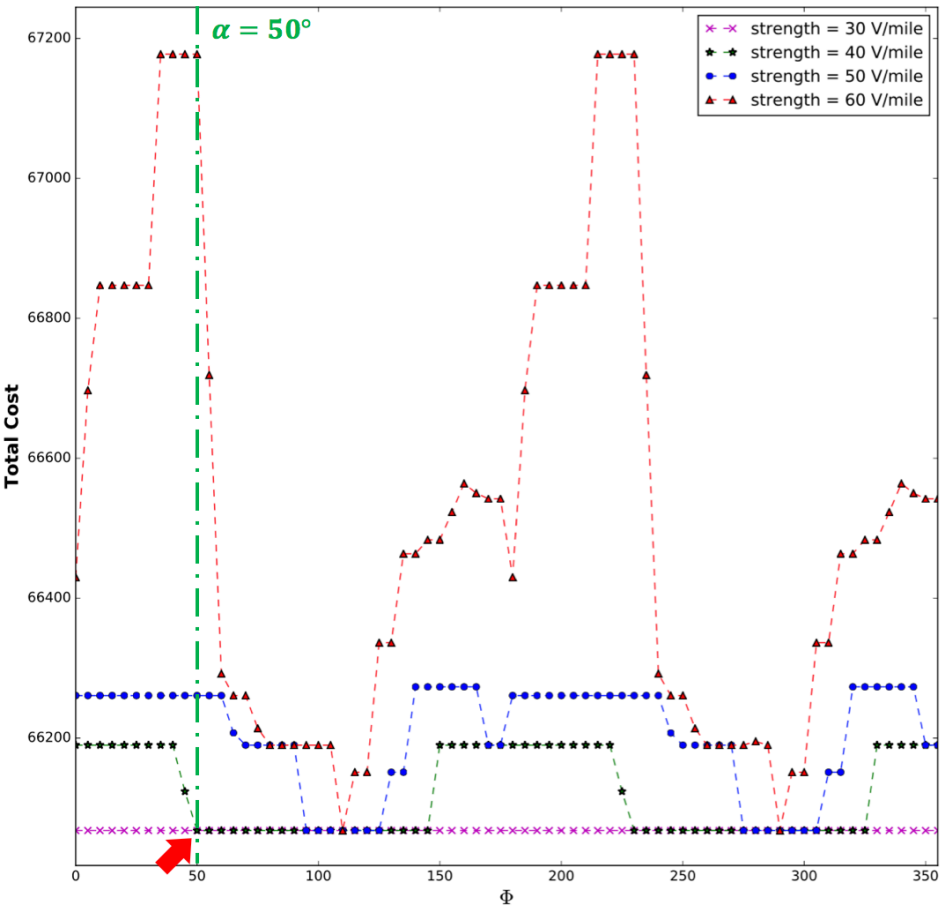


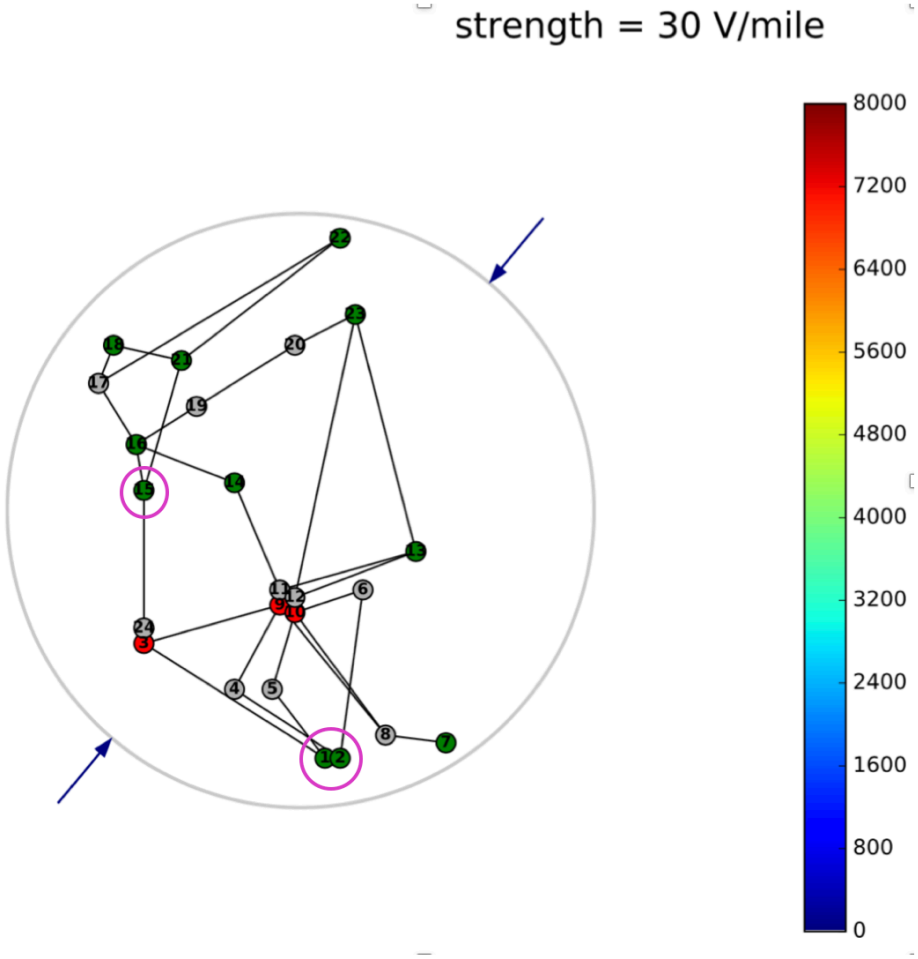
Needs more expensive generation

Forces lines to open

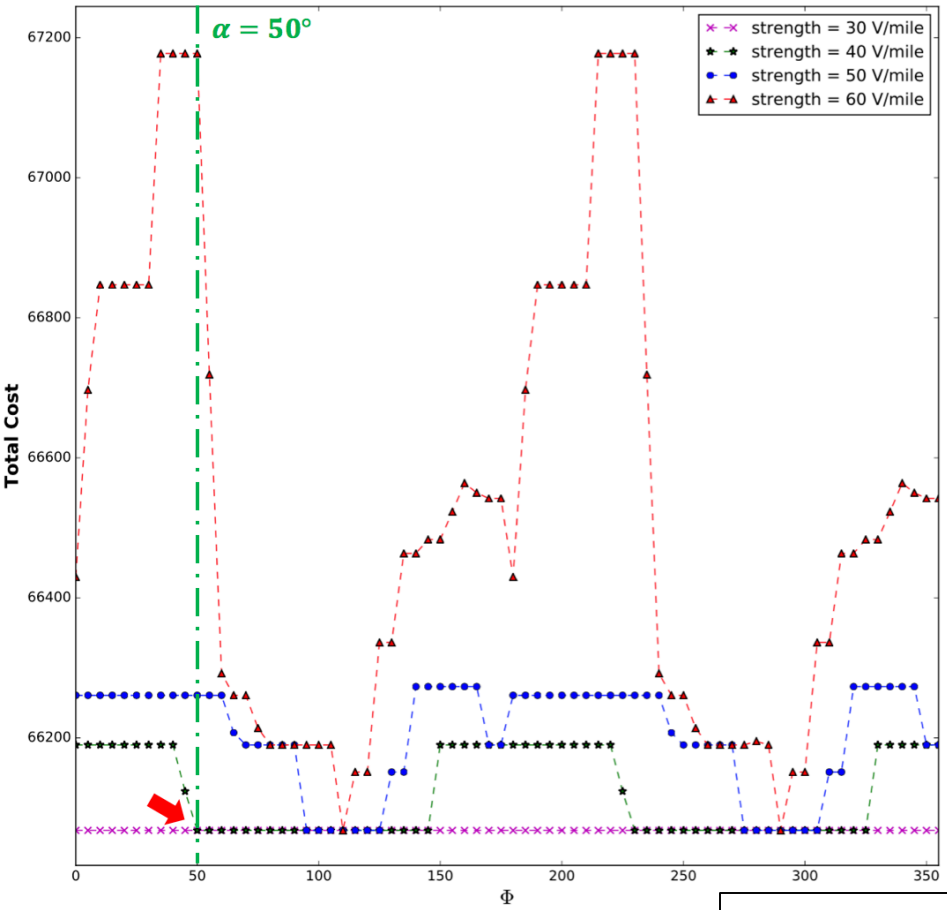
Transformer approaching heating limits

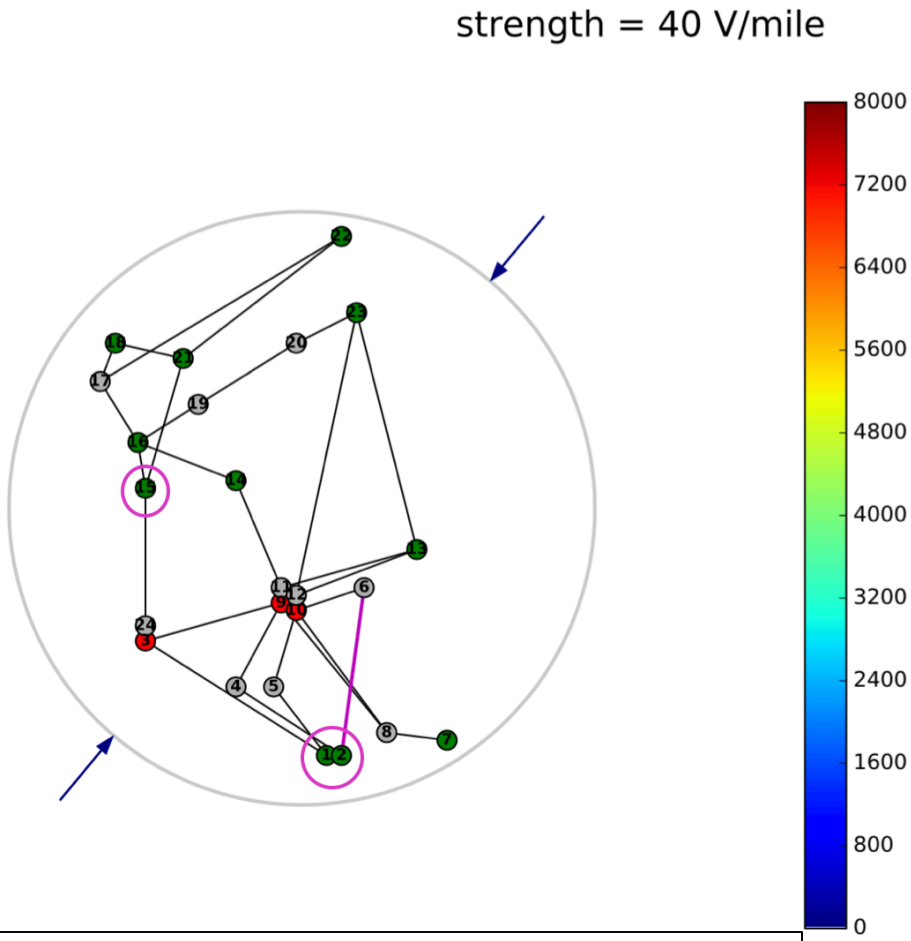
Analysis of Switching Needs: Event Strength





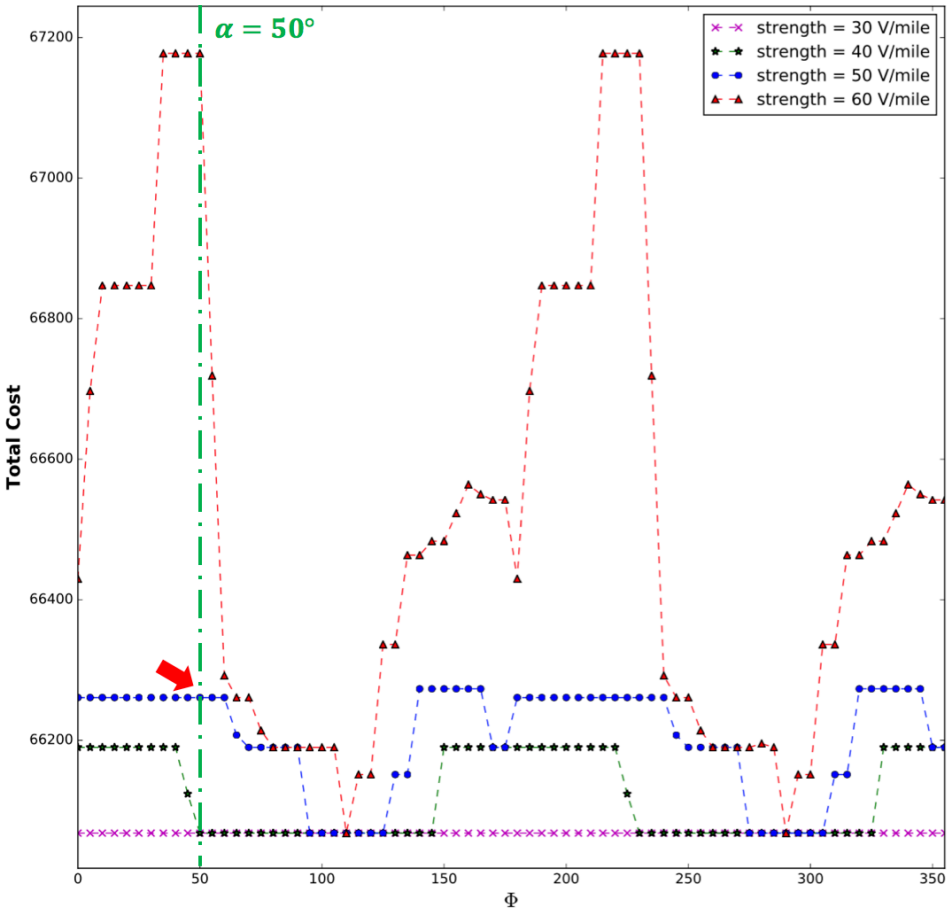
Analysis of Switching Needs: Event Strength

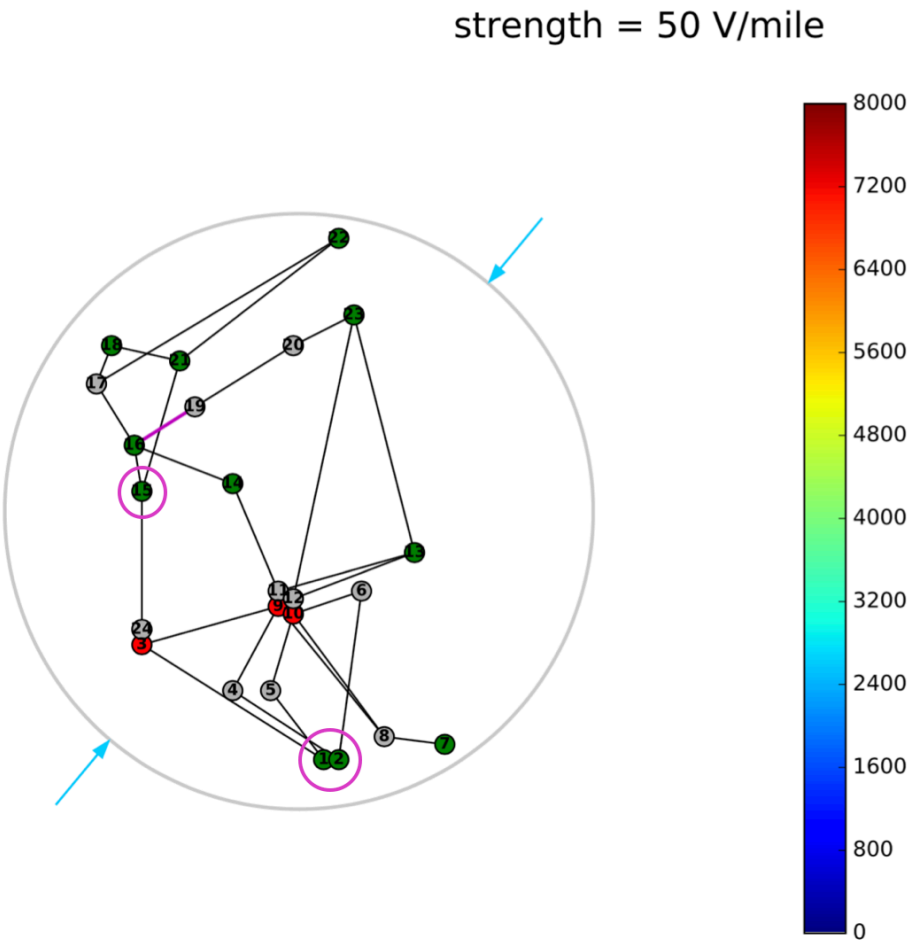




Able to maintain system performance, but a line must be switched

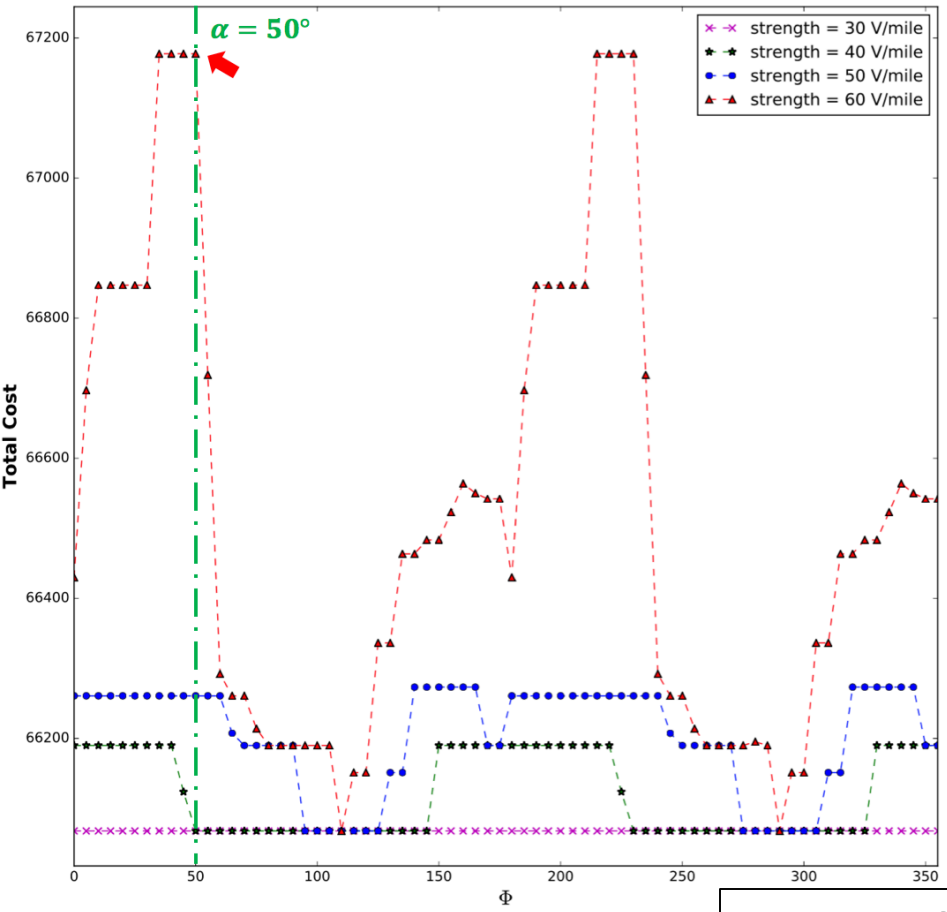
Analysis of Switching Needs: Event Strength

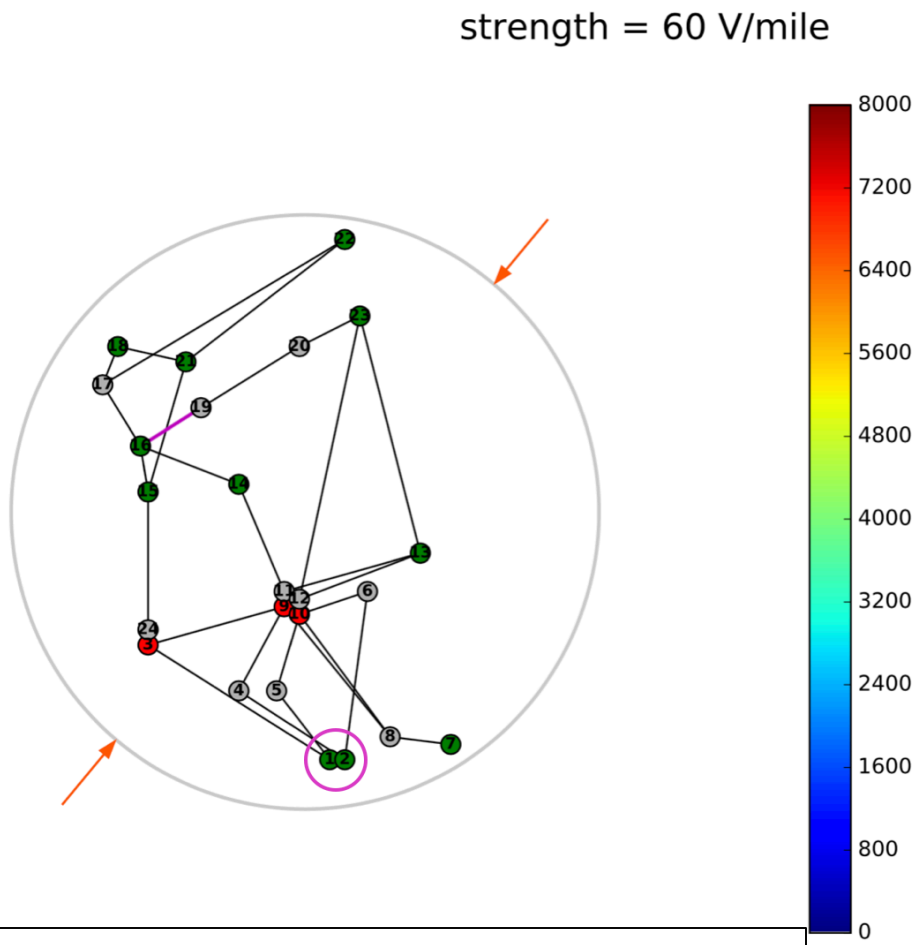




System performance starts to degrade

Analysis of Switching Needs: Event Strength





System forced to dispatch expensive generation

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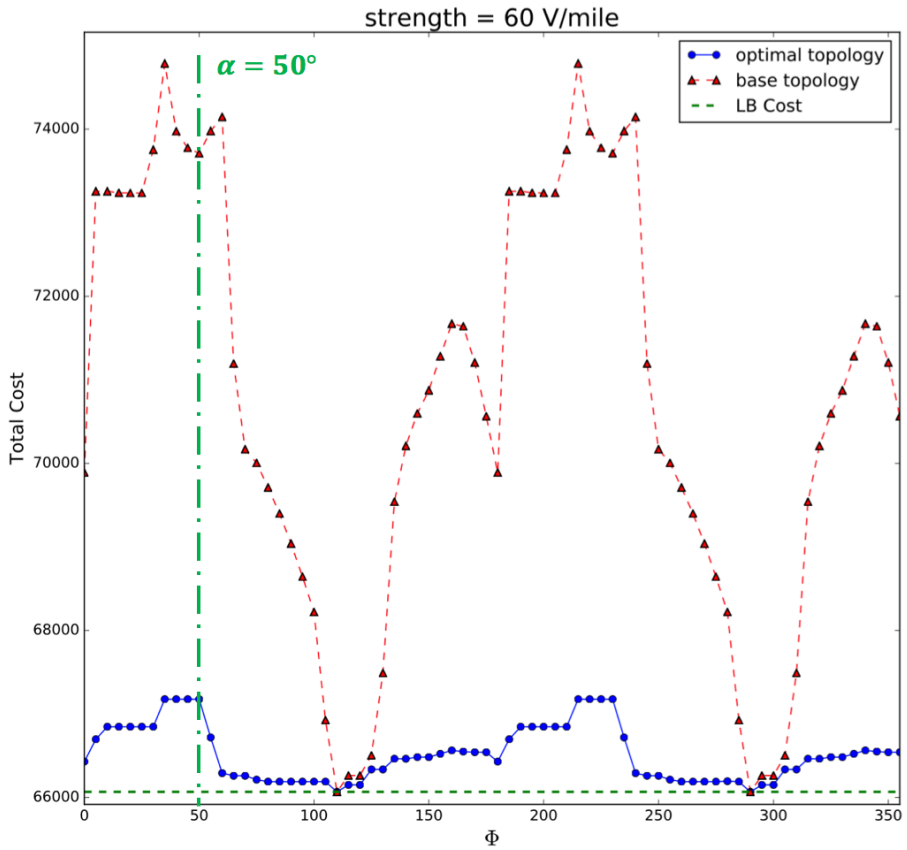
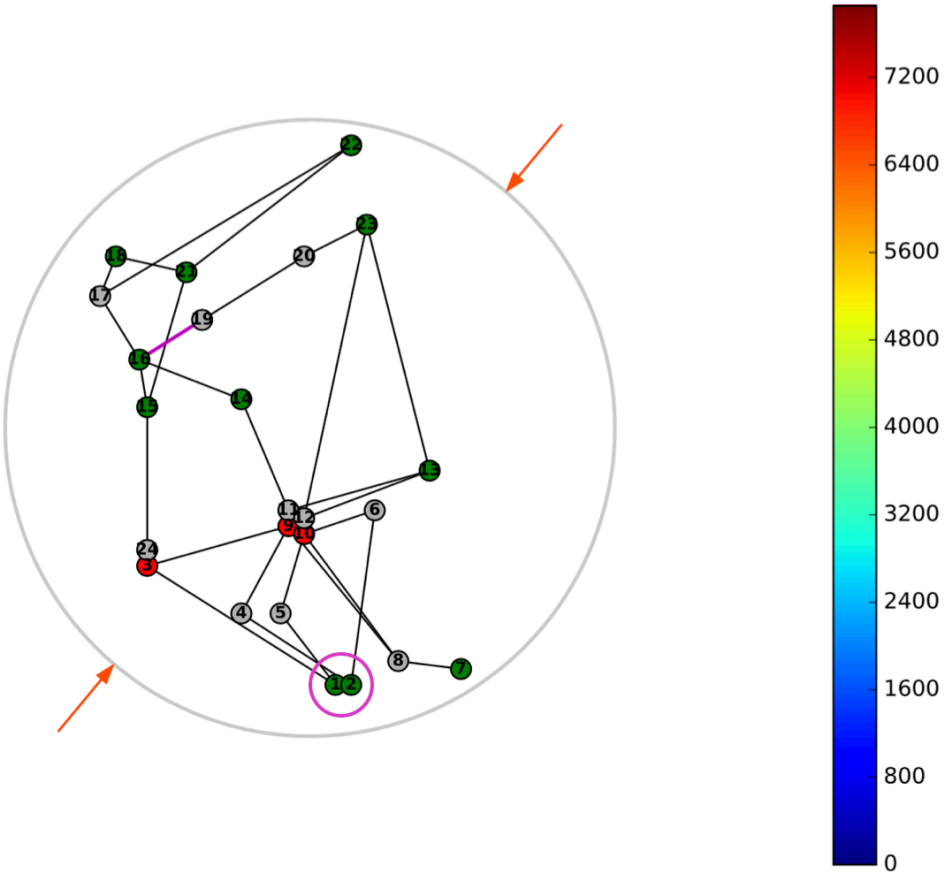
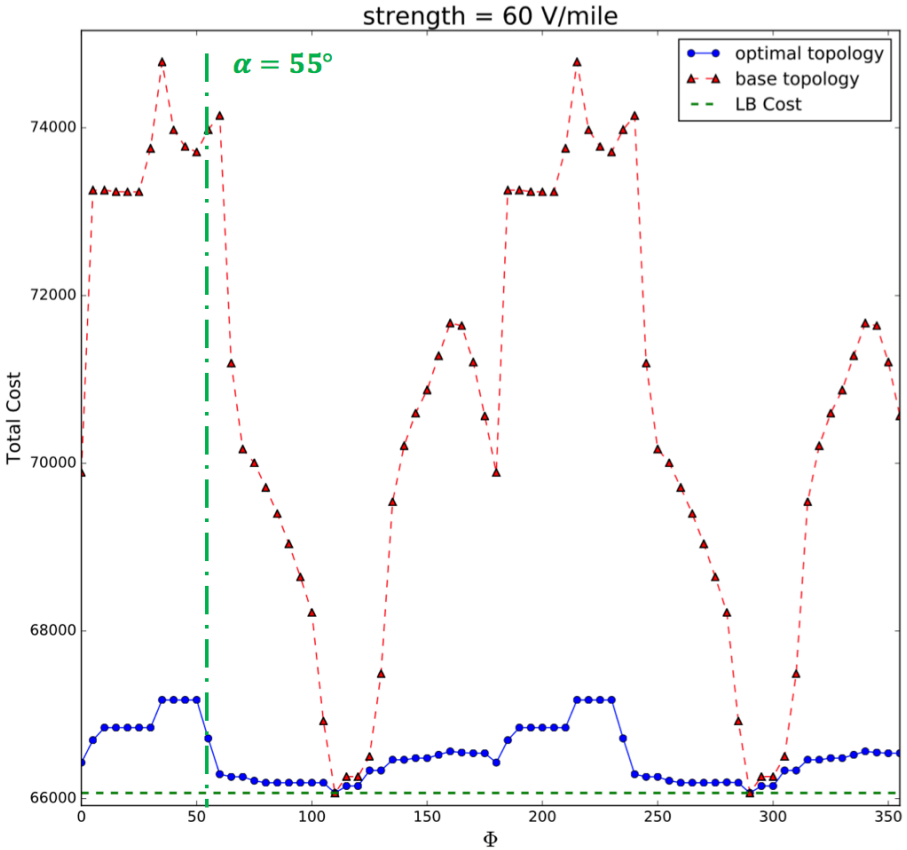
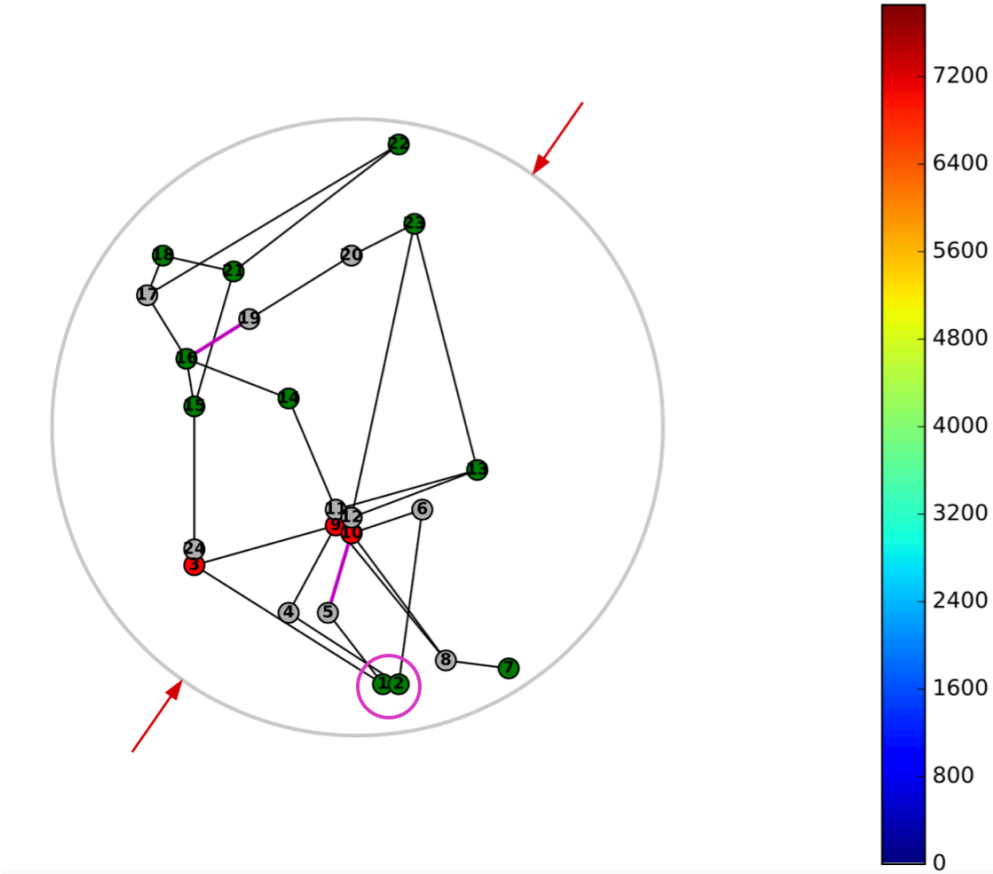
Analysis of Switching Needs: Event Direction





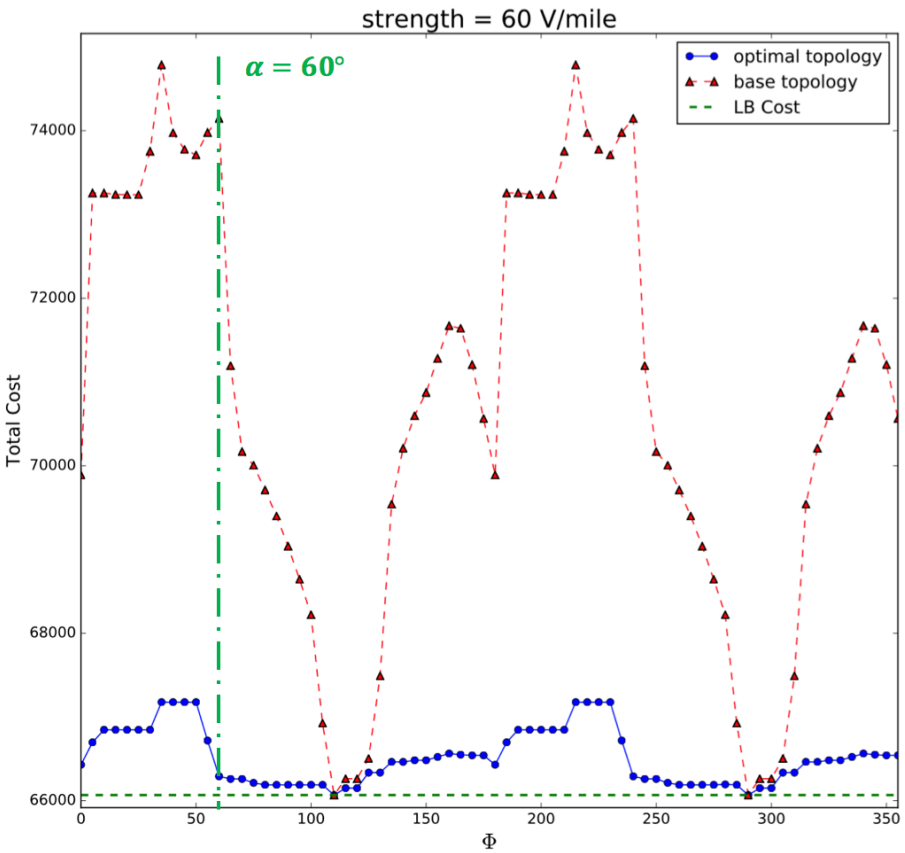
Analysis of Switching Needs: Event Direction

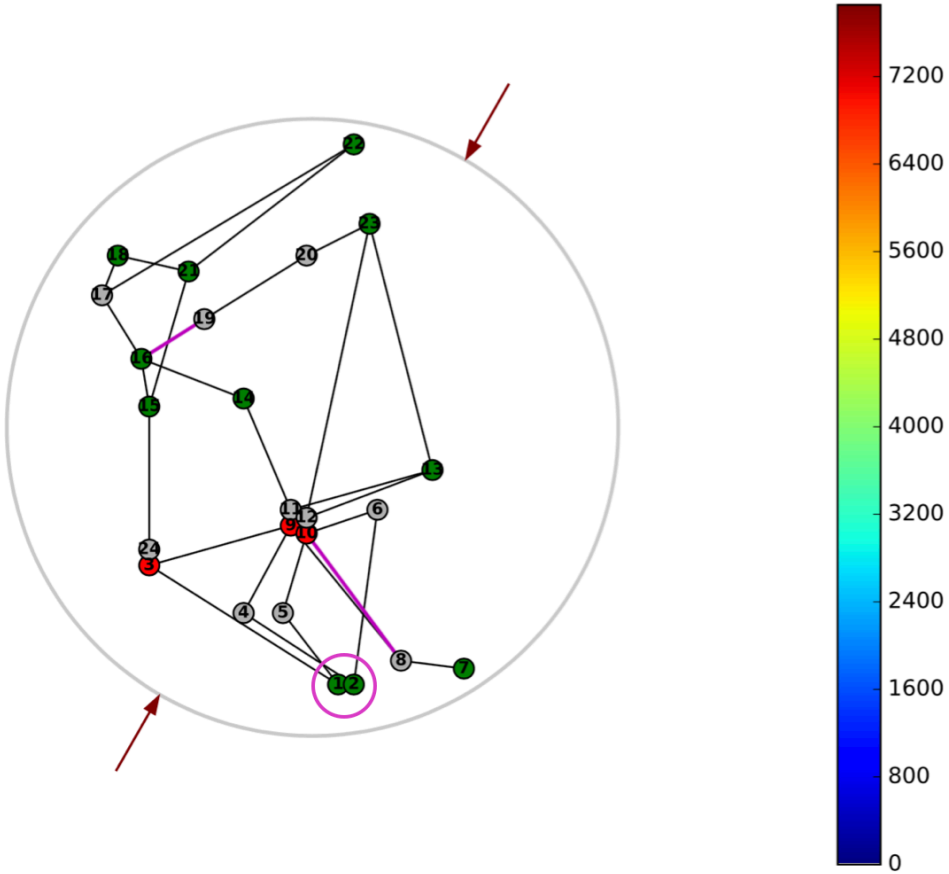




System performance starts to degrade

Analysis of Switching Needs: Event Direction

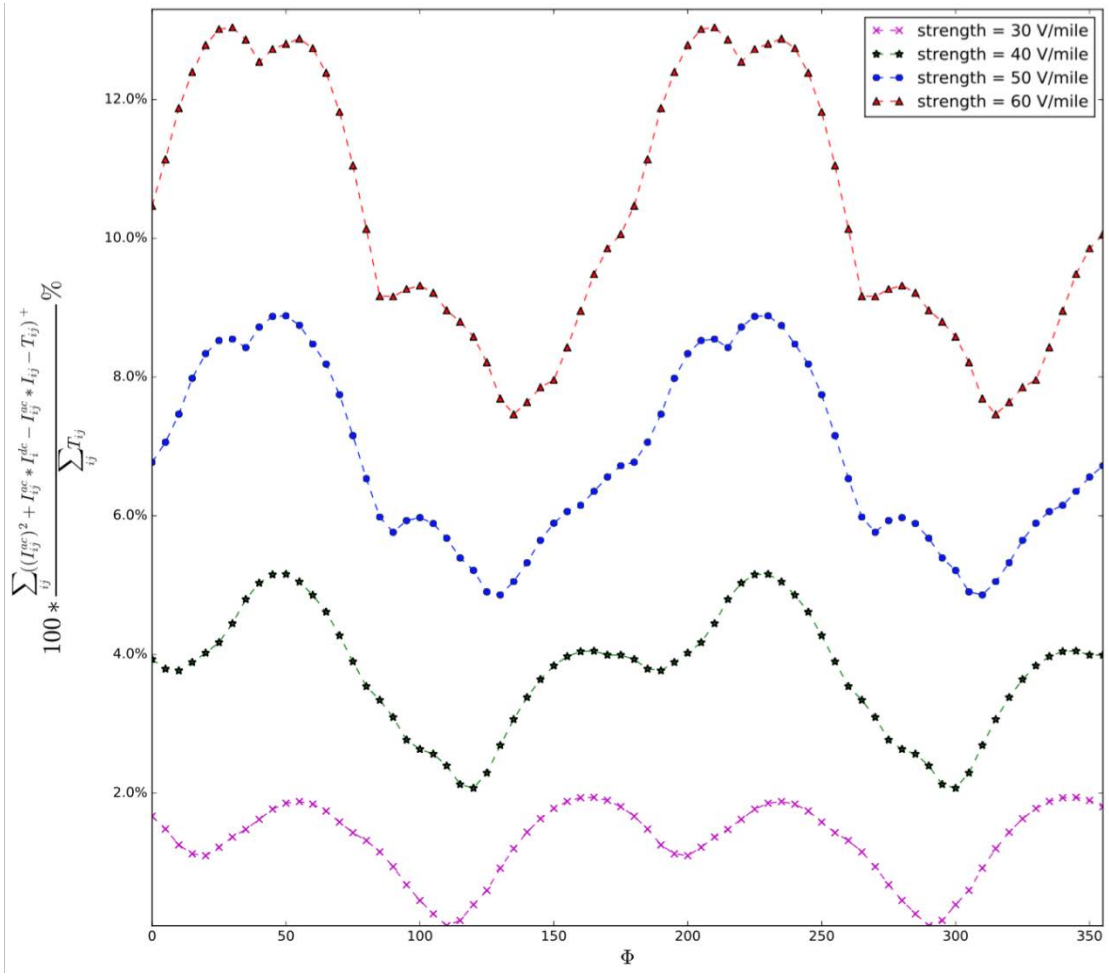




System performance continues to degrade, and line is forced to be switched

Analysis of Switching Needs: How much does it matter?

- **Assume base topology**
- **How much thermal overheating is experienced?**
- **As the event magnitude increases, the overheating risk increases**



Conclusions and Future Work

Conclusions and Contributions

- **A model of GIC physics combined with AC power flow physics**
  - A model of power system component safety margins
  - Optimized the operations to stay within safety margins
- **Builds on previous work**
  - Focus on placing blocking devices
  - Minimized a safety metric (reactive power loading at transformers)
    - Overbye et al., 13, 15
  - To the best of our knowledge, we have the first model that builds in the safety margins directly

Future Work

- **Stochastic events**
  - We assume the characteristics of the event are known
    - Connection to space weather and earth modeling and prediction
  - Robust operations
- **Modeling**
  - Improved algorithms
  - Other GMD impacts
  - Real system studies