ECEN 615
Methods of Electric Power Systems Analysis

Lecture 14: Power Flow Sensitivities, August 14, 2003 Blackout

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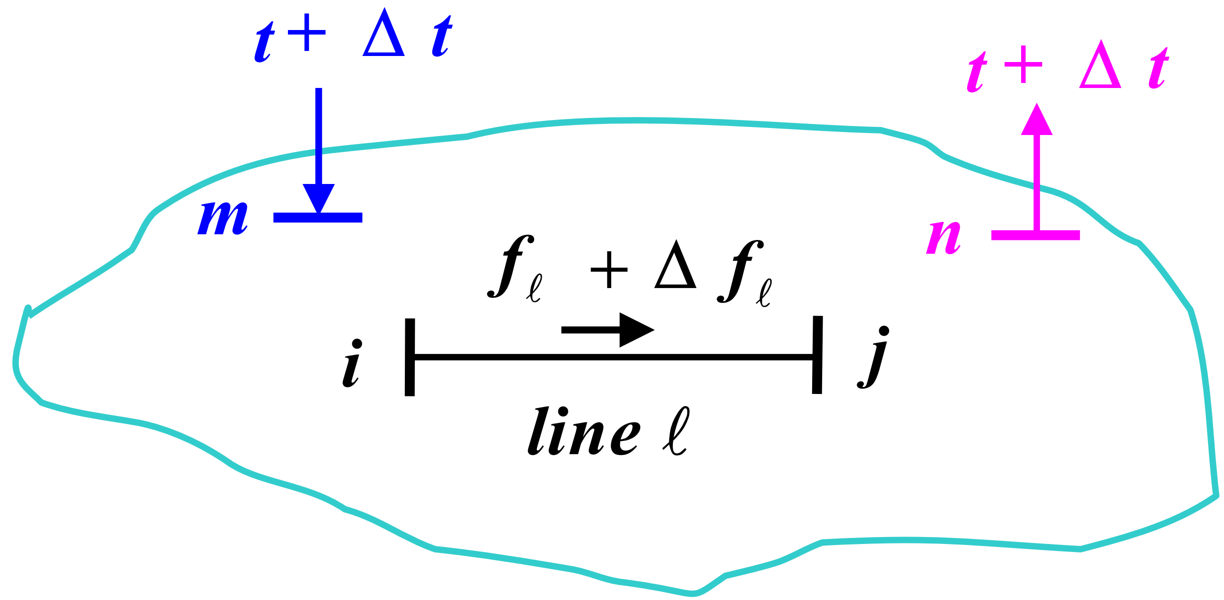
Announcements

- Read Chapter 7

Definition: PTDF

- NERC defines a PTDF as
  - "In the pre-contingency configuration of a system under study, a measure of the responsiveness or change in electrical loadings on transmission system Facilities due to a change in electric power transfer from one area to another, expressed in percent (up to 100%) of the change in power transfer"
  - Transaction dependent
- We'll use the notation $\varphi_{\ell}^{(w)}$ to indicate the PTDF on line ℓ with respect to basic transaction w
- In the lossless formulation presented here (and commonly used) it is slack bus independent

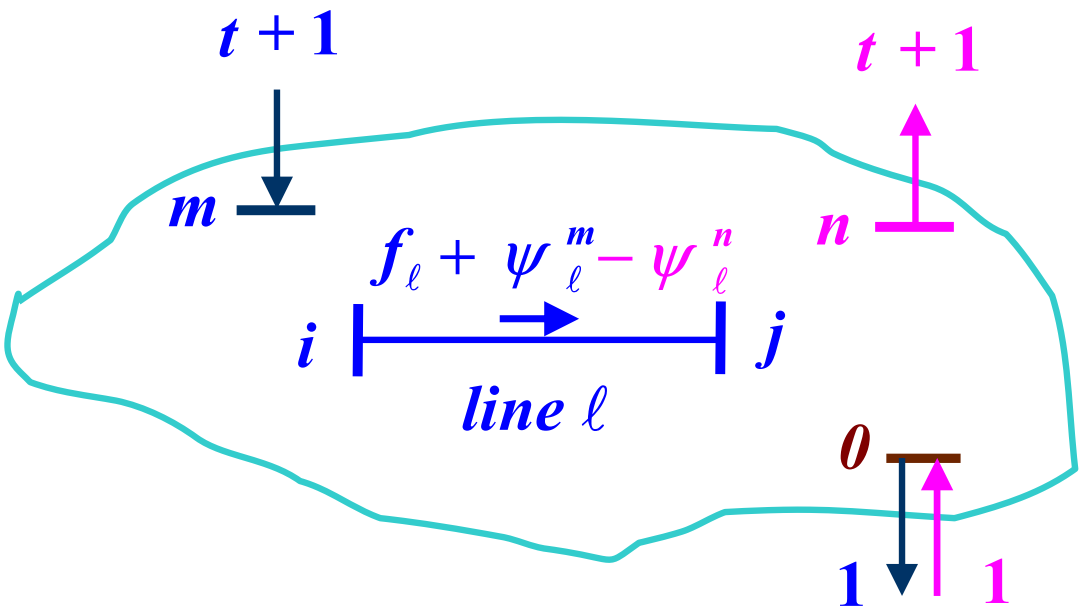
PTDFs



$$\varphi_{\ell}^{(w)} \triangleq \frac{\Delta f_{\ell}}{\Delta t}$$

Note, the PTDF is independent of the amount Δt; which is often expressed as a percent

PTDF Evaluation



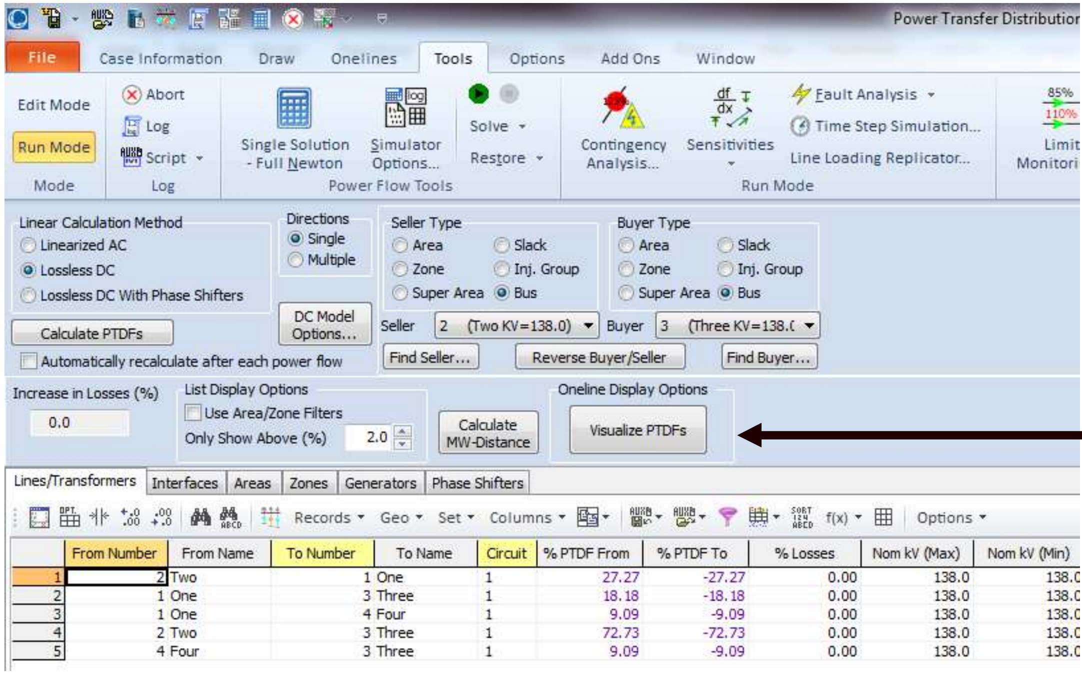
Defined in terms of the injection shift factors (ISFs); the slack bus dependence in each cancels out

$$\varphi_\ell^{(w)} = \psi_\ell^m - \psi_\ell^n$$

The PTDFs to the slack bus are the ISFs

Calculating PTDFs in PowerWorld

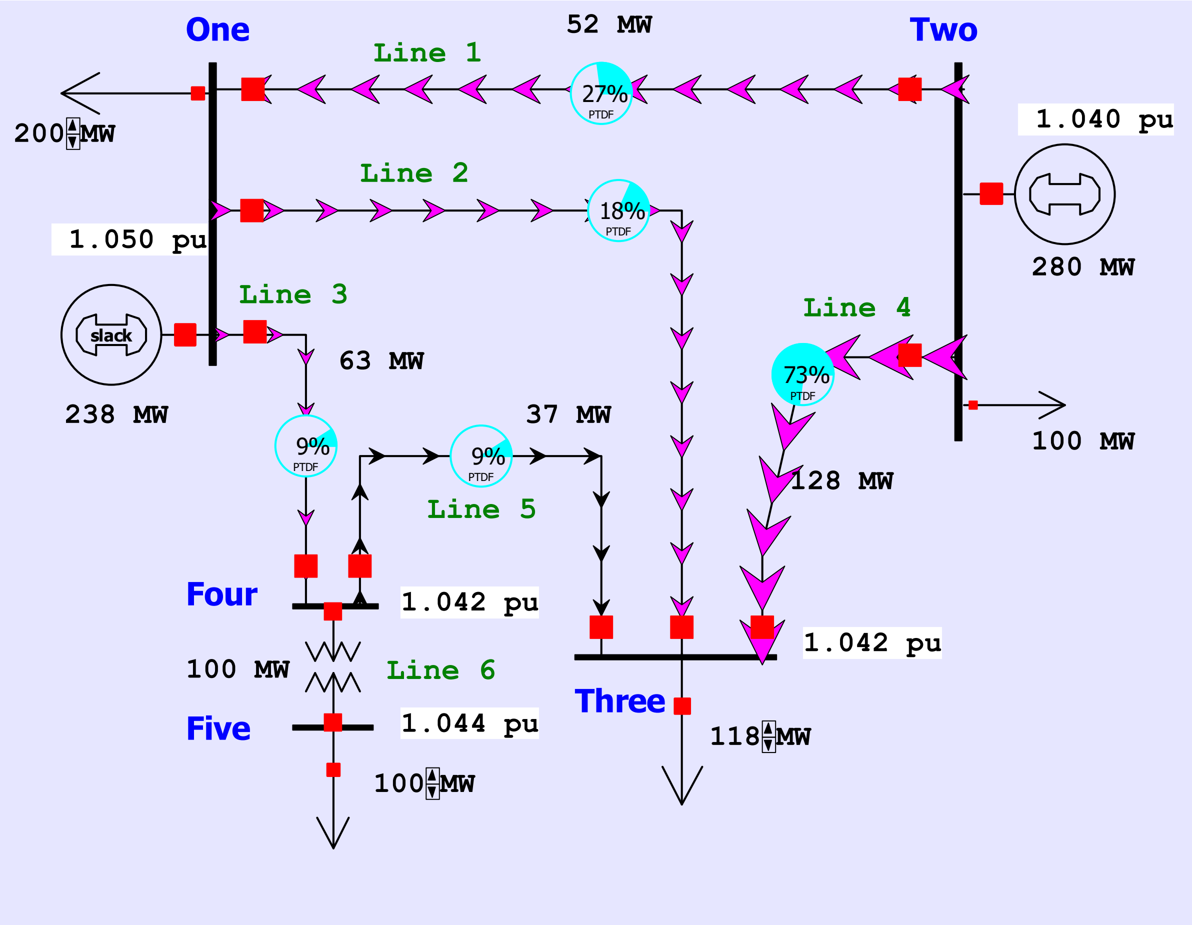
- PowerWorld provides a number of options for calculating and visualizing PTDFs
  - Select Tools, Sensitivities, Power Transfer Distribution Factors (PTDFs)



Results are shown for the five bus case for the Bus 2 to Bus 3 transaction

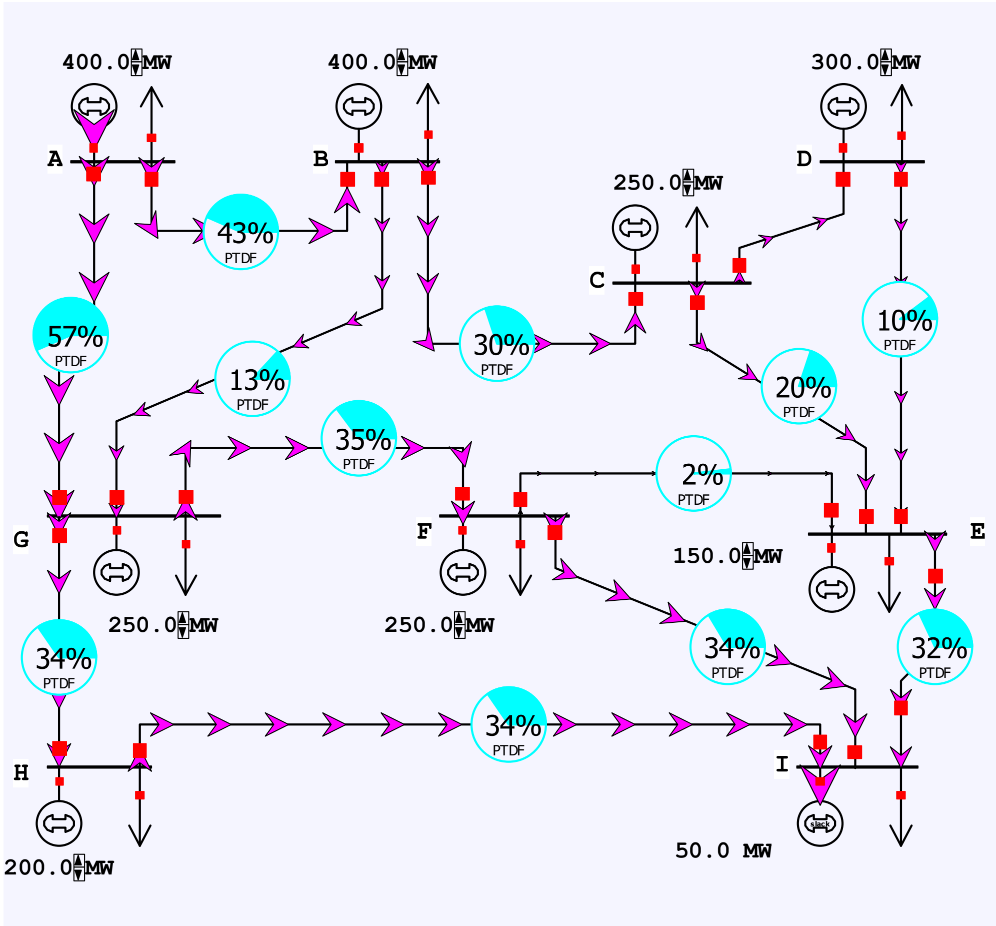
There is a button to visualize the PTDFs

Five Bus PTDF Visualization



PowerWorld Case: **B5_DistFact_PTDF**

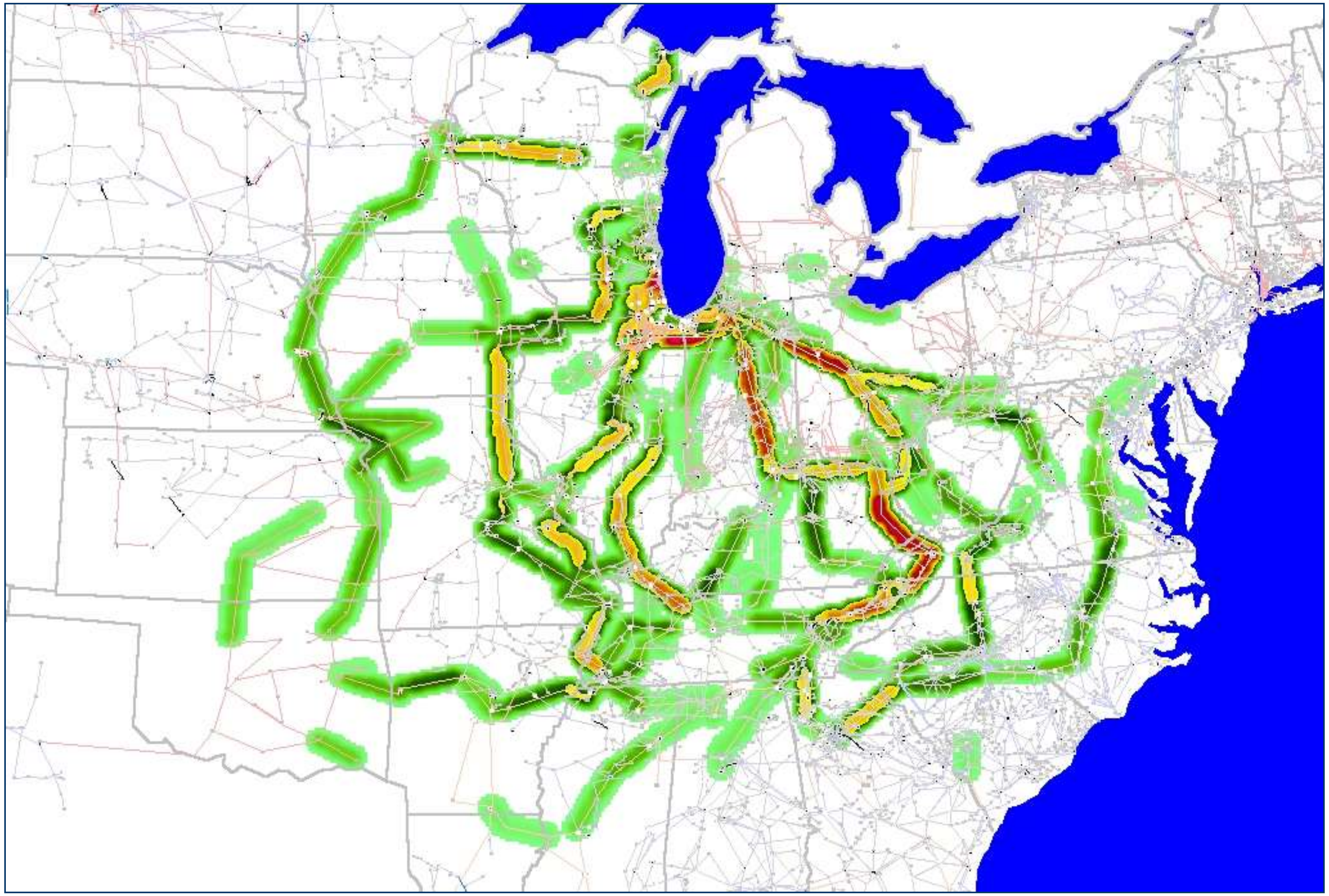
Nine Bus PTDF Example



Display shows the PTDFs for a basic transaction from Bus A to Bus I. Note that 100% of the transaction leaves Bus A and 100% arrives at Bus I

PowerWorld Case: **B9_PTDF**

Eastern Interconnect Example: Wisconsin Utility to TVA PTDFs



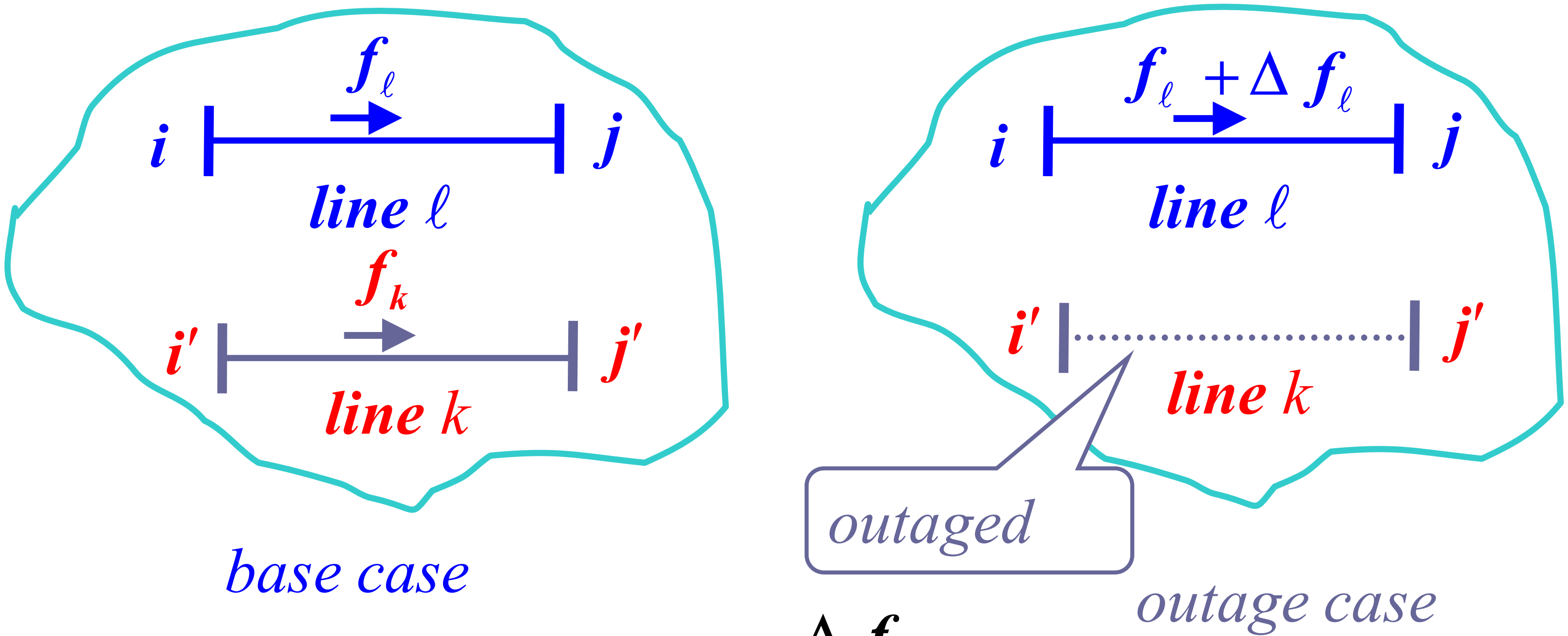
In this example multiple generators contribute for both the seller and the buyer

Contours show lines that would carry at least 2% of a power transfer from Wisconsin to TVA

Line Outage Distribution Factors (LODFs)

- Power system operation is practically always limited by contingencies, with line outages comprising a large number of the contingencies
- Desire is to determine the impact of a line outage (either a transmission line or a transformer) on other system real power flows without having to explicitly solve the power flow for the contingency
- These values are provided by the LODFs
- The LODF d_{ℓ}^{k} is the percentage of the pre-outage real power line flow on line k that is redistributed to line ? as a result of the outage of line k

LODFs

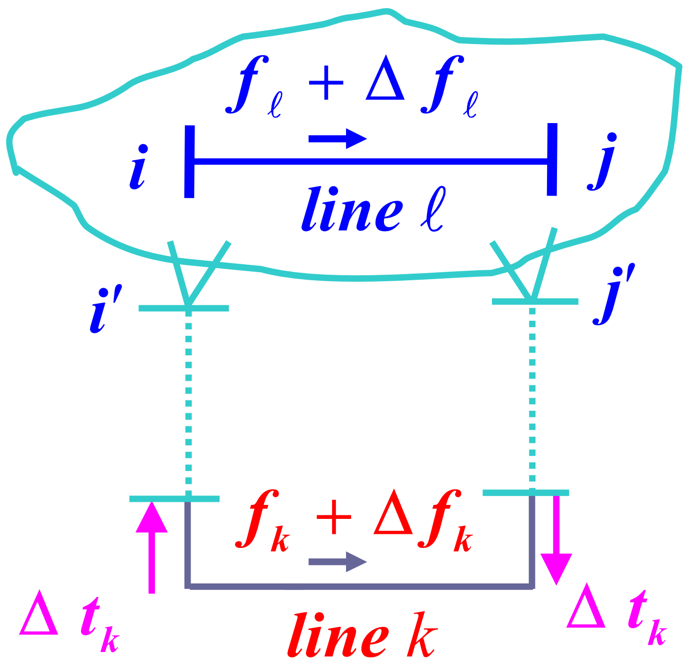


$$d_\ell^k = \frac{\Delta f_\ell}{f_k} = d_{\ell,k}$$

Best reference is Chapter 7 of the course book

LODF Evaluation

We simulate the impact of the outage of line k by adding the basic transaction $w_k = \{i', j', \Delta t_k\}$



and selecting Δt_k in such a way that the flows on the dashed lines become exactly zero

In general this Δt_k is not equal to the original line flow

LODF Evaluation

- We select Δt_k to be such that

$$f_k + \Delta f_k - \Delta t_k = 0$$

where Δf_k is the active power flow change on the line k due to the transaction w_k

- The line k flow from basic transaction w_k depends on its PTDF

$$\Delta f_k = \varphi_k^{(w_k)} \Delta t_k$$

it follows that

$$\Delta t_k = \frac{f_k}{1 - \varphi_k^{(w_k)}} = \frac{f_k}{1 - \left(\psi_k^{i'} - \psi_k^{j'} \right)}$$

LODF Evaluation

- For the rest of the network the impacts of the outage of line k are the same as the impacts of the additional basic transaction w_k

$$\Rightarrow \quad \Delta f_\ell = \varphi_\ell^{(w_k)} \Delta t_k = \frac{\varphi_\ell^{(w_k)}}{1 - \varphi_k^{(w_k)}} f_k$$

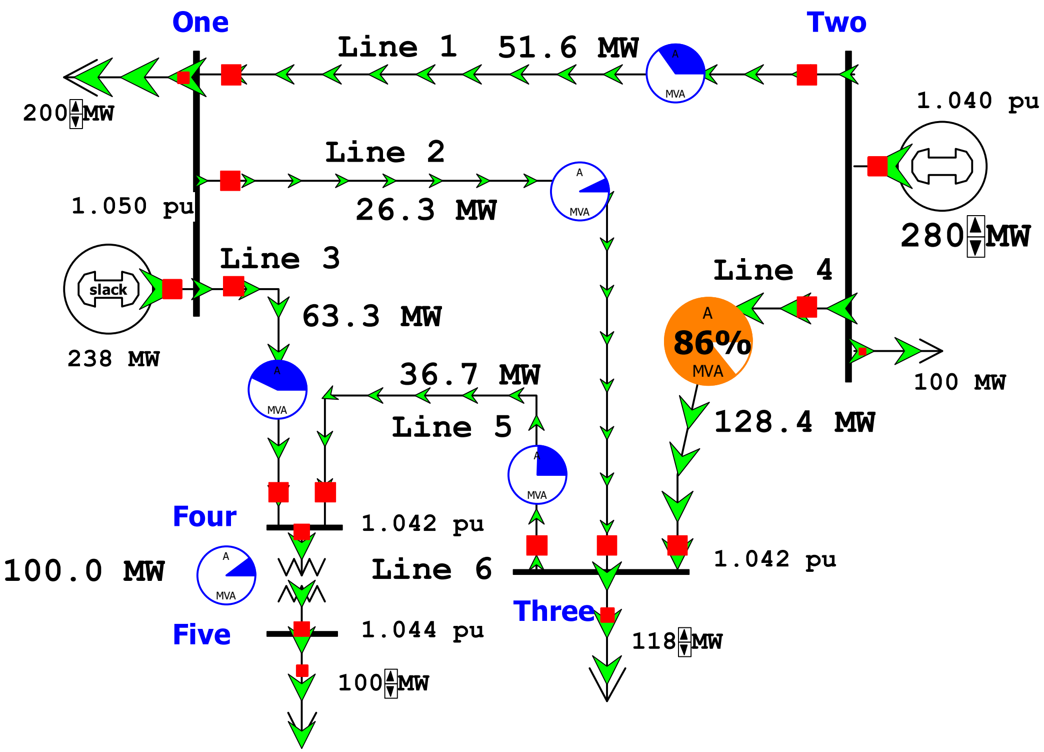
- Therefore, by definition the LODF is

$$d_\ell^k = \frac{\Delta f_\ell}{f_k} = \frac{\varphi_\ell^{(w_k)}}{1 - \varphi_k^{(w_k)}}$$

Recall that k is the line being outaged

Five Bus Example

- Assume we wish to calculate the values for the outage of line 4 (between buses 2 and 3); this is line *k*



Say we wish to know the change in flow on the line 3 (Buses 3 to 4). PTDFs for a transaction from 2 to 3 are 0.7273 on line 4 and 0.0909 on line 3

PowerWorld Case:
B5_DistFact_LODF

Five Bus Example

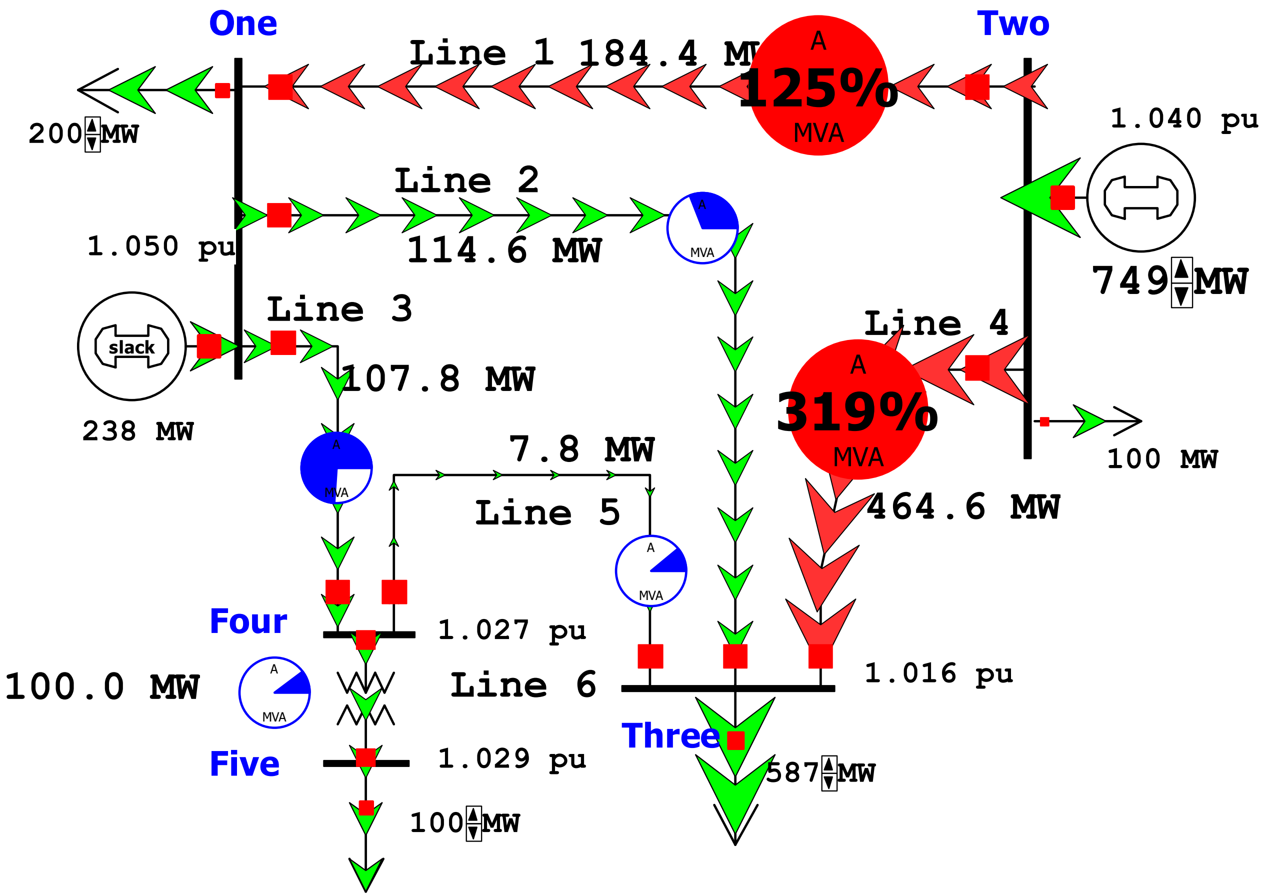
- Hence we get

$$\Delta t_k = \frac{f_k}{1-\varphi_k^{(w_k)}} = \frac{128}{1-0.7273} = 469.4$$

$$d_3^4 = \frac{\Delta f_3}{f_4} = \frac{\varphi_3^{(w_4)}}{1-\varphi_4^{(w_4)}} = \frac{0.0909}{1-0.7273} = 0.333$$

$$\Delta f_3 = (0.333) f_4 = 0.333 \times 128 = 42.66 \text{ MW}$$

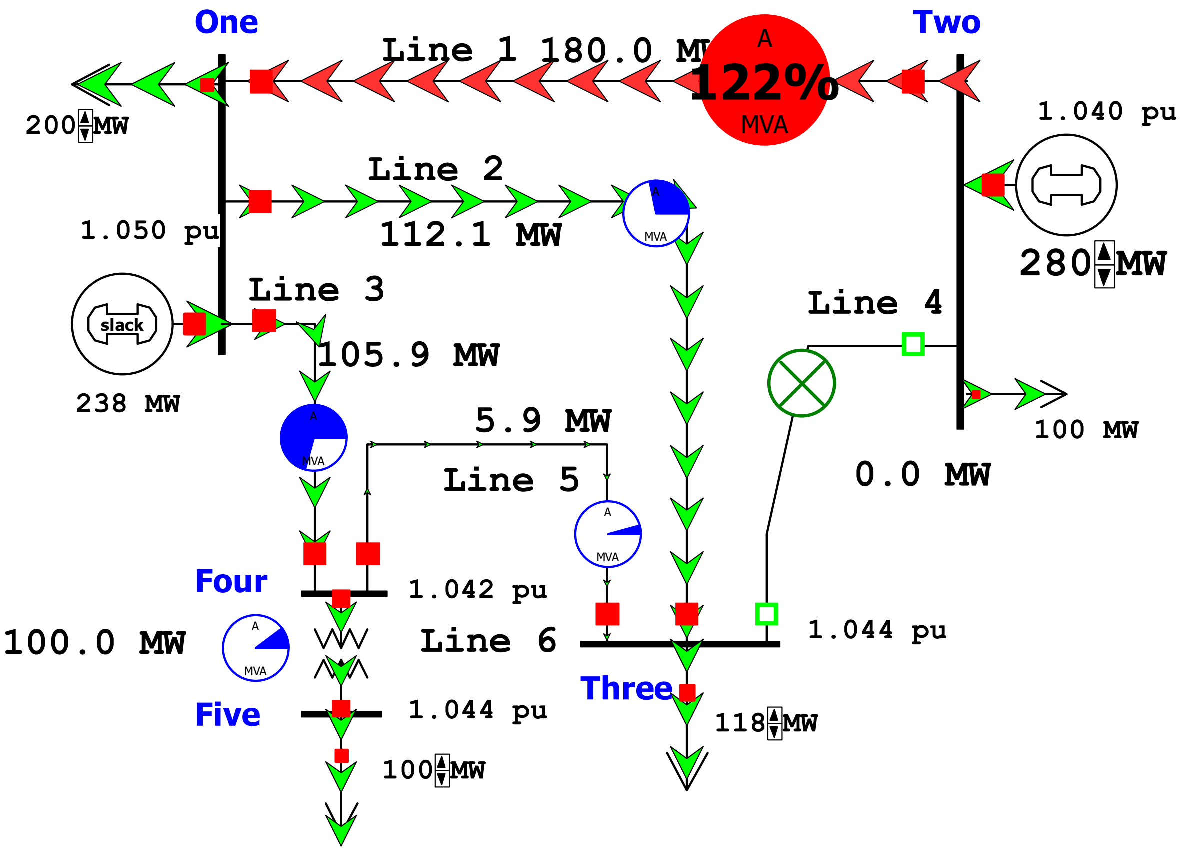
Five Bus Example Compensated



Here is the system with the compensation added to Bus 2 and removed at Bus 3; we are canceling the impact of the Line 4 flow for the reset of the network.

Five Bus Example

- Below is the network with the line actually outaged



The Line 3 flow changed from 63 MW to 106 MW, an increase of 43 MW, matching the LODF value

Developing a Critical Eye

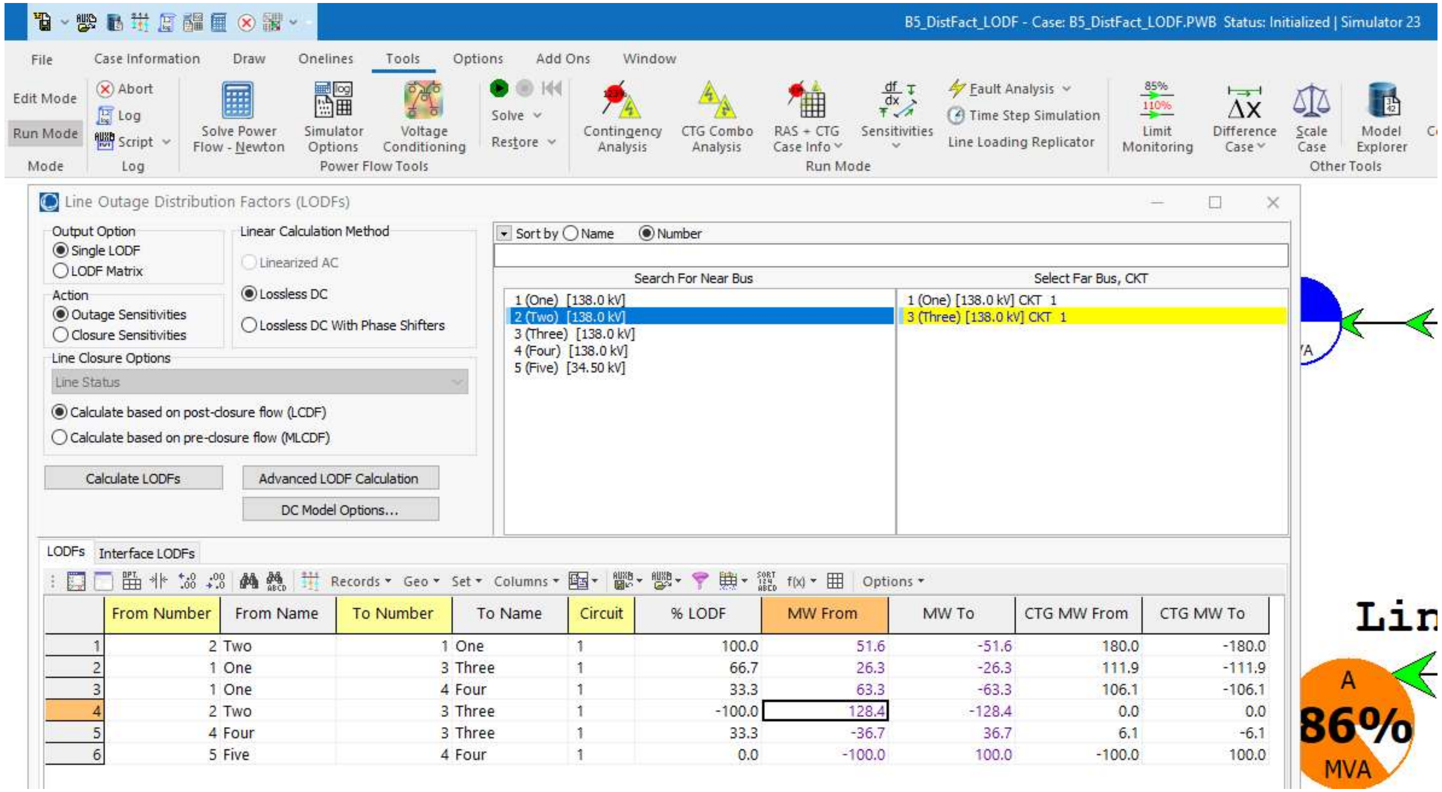
- In looking at the below formula you need to be thinking about what conditions will cause the formula to fail

$$\Rightarrow \quad \Delta f_\ell = \varphi_\ell^{(w_k)} \Delta t_k = \frac{\varphi_\ell^{(w_k)}}{1 - \varphi_k^{(w_k)}} f_k$$

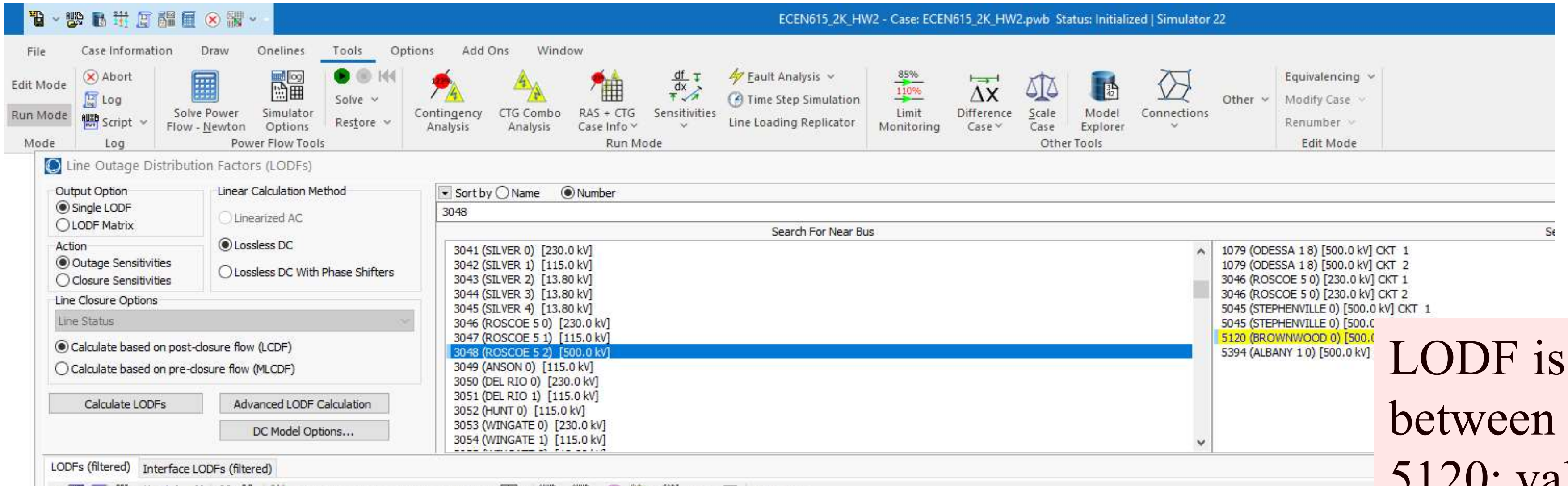
  Here the obvious situation is when the denominator is zero
- That corresponds to a situation in which the contingency causes system islanding
  - An example is line 6 (between buses 4 and 5)
  - Impact modeled by injections at the buses within each viable island

Calculating LODFs in PowerWorld

- Select **Tools, Sensitivities, Line Outage Distribution Factors**
  - Select the Line using the dialogs on the right, and click **Calculate LODFs**; the image shows values for Line 4 for the **B5_DistFact_LODF** case



2000 Bus LODF Example



	From Number	From Name	To Number	To Name	Circuit	% LODF	MW From	MW To	CTG MW From	CTG MW To
6	5451	COPPERAS COVE	5239	GOLDTHWAITE 1	1	21.2	-761.3	764.8	-666.7	670.2
7	3048	ROSCOE 5 2	5394	ALBANY 1 0	1	14.6	-144.5	144.7	-79.1	79.3
8	5137	WACO 1 0	5388	WACO 2 0	1	-12.3	535.0	-534.5	480.3	-479.7
9	5236	OLNEY 1 0	5394	ALBANY 1 0	1	-12.2	-759.0	765.7	-813.6	820.3
10	5137	WACO 1 0	5451	COPPERAS COVE	1	12.0	-679.5	684.5	-625.7	630.7
11	5260	GLEN ROSE 1 0	5045	STEPHENVILLE 0	1	-11.5	-1646.6	1659.6	-1698.2	1711.1
12	5239	GOLDTHWAITE 1	6210	MARBLE FALLS 2	1	-10.5	-791.1	798.2	-837.8	844.9
13	5358	RIESEL 1 0	5179	CORSICANA 2 0	1	-10.1	1317.1	-1308.4	1271.8	-1263.1
14	5388	WACO 2 0	5317	GRANBURY 1 0	1	-9.6	204.4	-203.9	161.4	-160.9
15	5279	TEMPLE 1 0	5358	RIESEL 1 0	1	-7.6	380.4	-379.4	346.6	-345.6
16	5410	KILLEEN 3 0	5451	COPPERAS COVE	1	7.6	115.5	-115.4	149.2	-149.1

LODF is for line between 3048 and 5120; values will be proportional to the PTDF values; case is **ECEN615_2K_HW2**

2000 Bus LODF Example

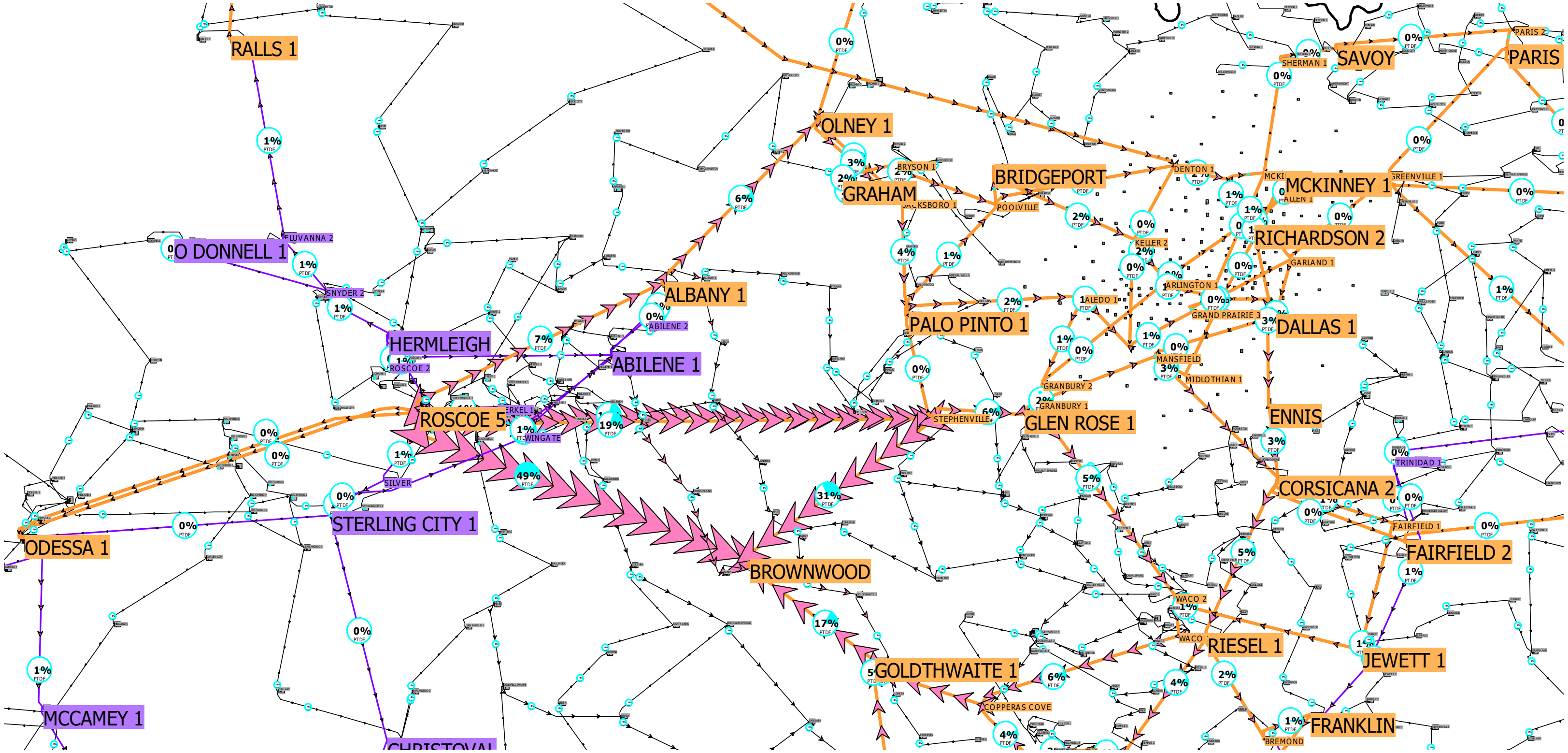


Image visualizes the PTDFs between buses 3048 and 5120

Multiple Line LODFs

- LODFs can also be used to represent multiple device contingencies, but it is usually more involved than just adding the effects of the single device LODFs
- Assume a simultaneous outage of lines k_1 and k_2
- Now setup two transactions, w_{k1} (with value Δt_{k1})and w_{k2} (with value Δt_{k2}) so

$$f_{k1} + \Delta f_{k1} + \Delta f_{k2} - \Delta t_{k1} = 0$$

$$f_{k2} + \Delta f_{k1} + \Delta f_{k2} - \Delta t_{k2} = 0$$

$$f_{k1} + \varphi_{k1}^{(w_{k1})} \Delta t_{k1} + \varphi_{k1}^{(w_{k2})} \Delta t_{k2} - \Delta t_{k1} = 0$$

$$f_{k2} + \varphi_{k2}^{(w_{k1})} \Delta t_{k1} + \varphi_{k2}^{(w_{k2})} \Delta t_{k1} - \Delta t_{k2} = 0$$

Multiple Line LODFs

- Hence we can calculate the simultaneous impact of multiple outages; details for the derivation are given in C. Davis, T.J. Overbye, "Linear Analysis of Multiple Outage Interaction," *Proc. 42nd HICSS*, 2009
- Equation for the change in flow on line ℓ for the outage of lines k_1 and k_2 is

$$\Delta f_{\ell} = \begin{bmatrix} d_{\ell}^{k1} & d_{\ell}^{k2} \end{bmatrix} \begin{bmatrix} 1 & -d_{k1}^{k2} \\ -d_{k2}^{k1} & 1 \end{bmatrix}^{-1} \begin{bmatrix} f_{k1} \\ f_{k2} \end{bmatrix}$$

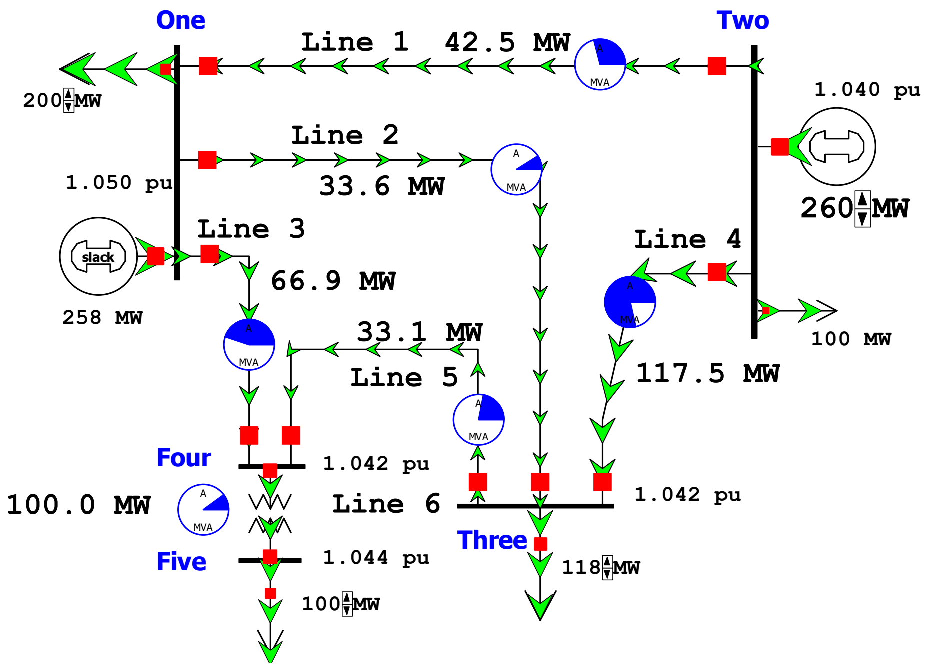
Multiple Line LODFs

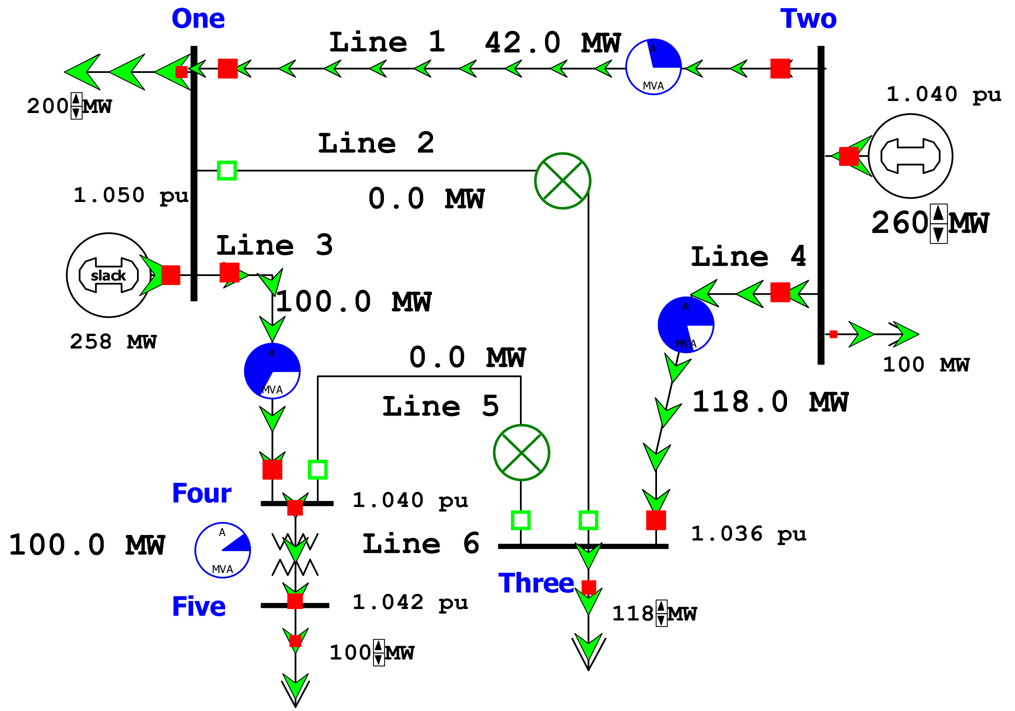
- Example: Earlier five bus case, outage of Lines 2 and 5 to flow on Line 4.

$$\Delta f_\ell = \begin{bmatrix} d_\ell^{k1} & d_\ell^{k2} \end{bmatrix} \begin{bmatrix} 1 & -d_{k1}^{k2} \\ -d_{k2}^{k1} & 1 \end{bmatrix}^{-1} \begin{bmatrix} f_{k1} \\ f_{k2} \end{bmatrix}$$

$$\Delta f_\ell = \begin{bmatrix} 0.4 & 0.25 \end{bmatrix} \begin{bmatrix} 1 & -0.75 \\ -0.6 & 1 \end{bmatrix}^{-1} \begin{bmatrix} 0.336 \\ -0.331 \end{bmatrix} = 0.005$$

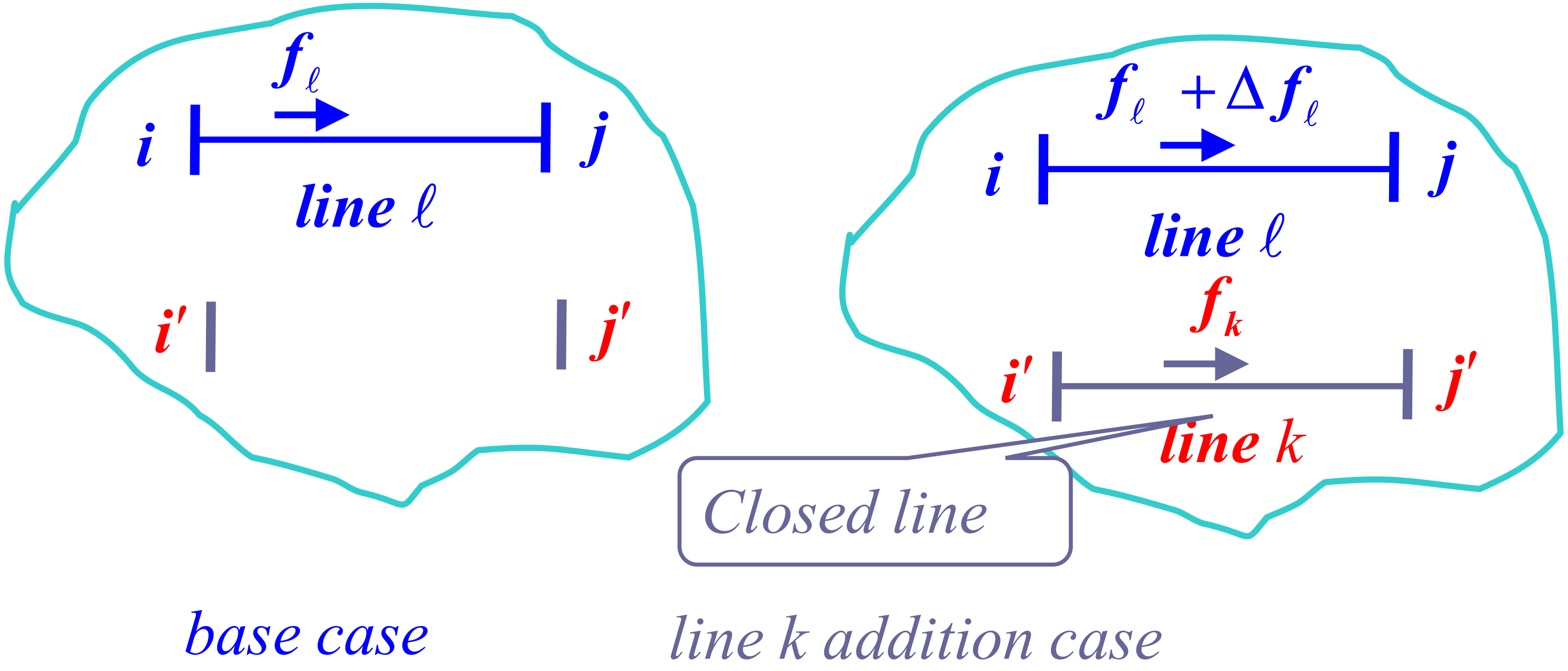
Multiple Line LODFs





Line 4 flow goes from 117.5 MW to 118.0 MW

Line Closure Distribution Factors (LCDFs)



$$LCDF_{\ell}^{k} = \frac{\Delta f_{\ell}}{f_{k}} = LCDF_{\ell,k}$$

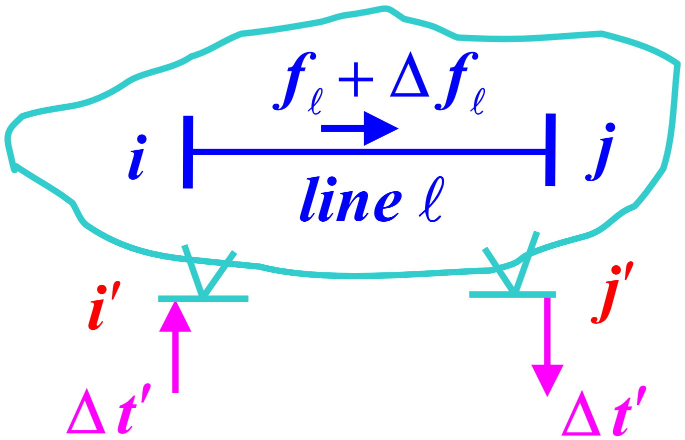
LCDF Definition

- The line closure distribution factor (LCDF), $LCDF_{\ell,k}$, for the closure of line k (or its addition if it does not already exist) is the portion of the line active power flow on line k that is distributed to line ℓ due to the closure of line k
- Since line k is currently open, the obvious question is, "what flow on line k?"
- Answer (in a dc power flow sense) is the flow that will occur when the line is closed (which we do not know)

LCDF Evaluation

- We simulate the impact of the closure of line k by imposing the additional basic transaction

$$w_k = \{ i', j', \Delta t_k \}$$



on the base case network and we select Δt_k so that

$$\Delta t_k = - f_k$$

LCDF Evaluation

- For the other parts of the network, the impacts of the addition of line k are the same as the impacts of adding the basic transaction w_k

$$\Delta \boldsymbol{f}_{\ell} = \varphi_{\ell}^{(\boldsymbol{w}_k)} \Delta \boldsymbol{t}_{\boldsymbol{k}} = -\varphi_{\ell}^{(\boldsymbol{w}_k)} \boldsymbol{f}_{\boldsymbol{k}}$$

- Therefore, the definition is

$$\boldsymbol{LCDF}_{\ell,\boldsymbol{k}} = \frac{\Delta \boldsymbol{f}_{\ell}}{\boldsymbol{f}_{\boldsymbol{k}}} = -\varphi_{\ell}^{(\boldsymbol{w}_k)}$$

- The post-closure flow f_k is determined (in a dc power flow sense) as the flow that would occur from the angle difference divided by $(1 + \varphi_{\boldsymbol{k}}^{(\boldsymbol{w}_k)})$

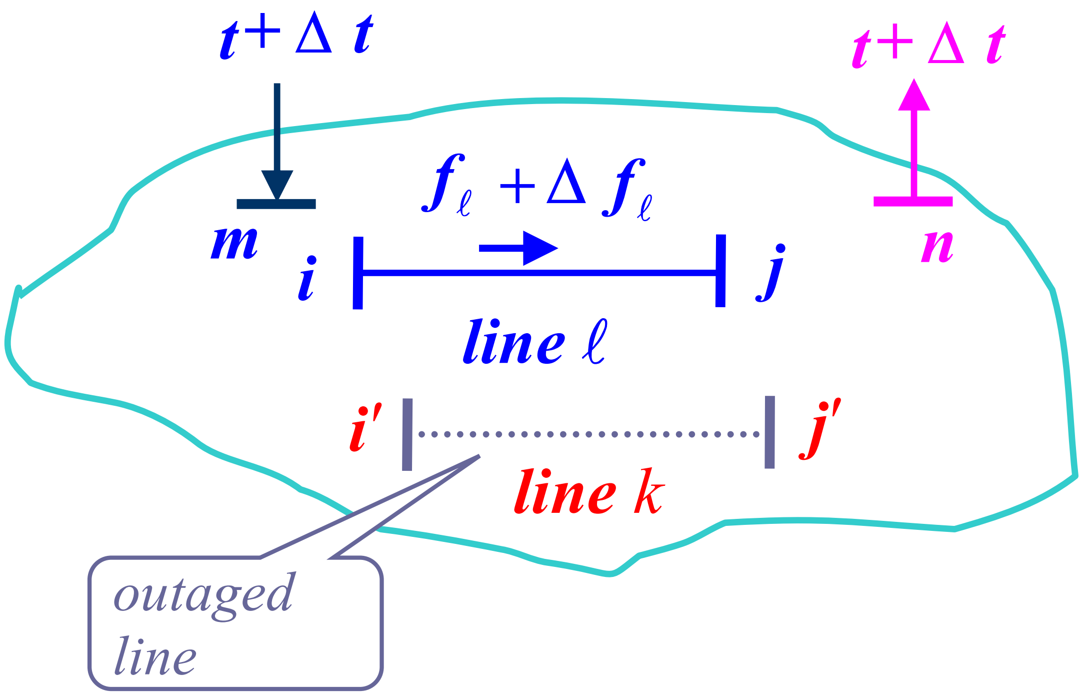
Outage Transfer Distribution Factor

- The outage transfer distribution factor (OTDF) is defined as the PTDF with the line k outaged
- The OTDF applies only to the post-contingency configuration of the system since its evaluation explicitly considers the line k outage

$$\left(\varphi_{\ell}^{(w)}\right)^{k}$$

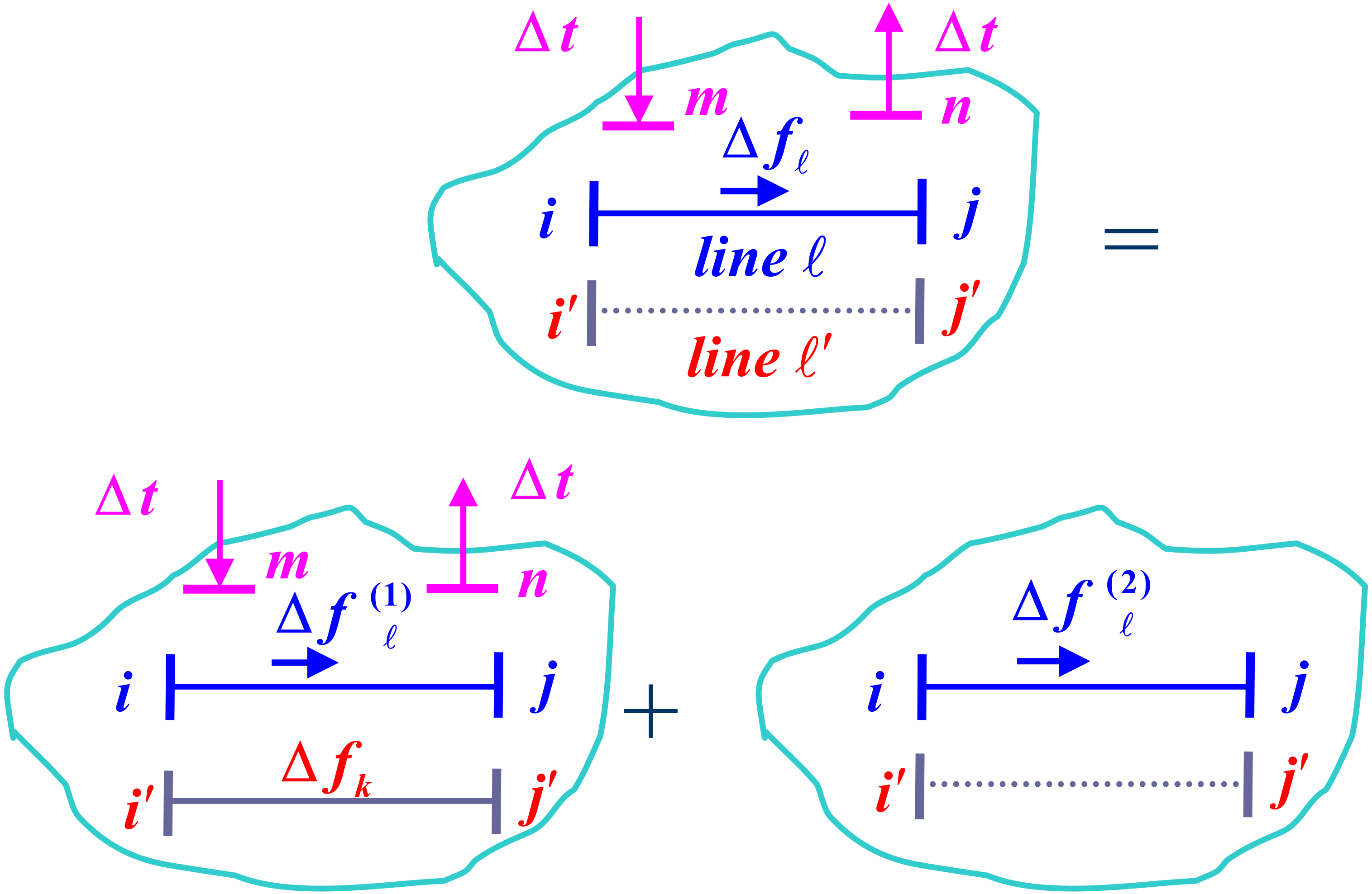
- This is a quite important value since power system operation is usually contingency constrained

Outage Transfer Distribution Factor (OTDF)



$$\left(\varphi_{\ell}^{(w)}\right)^{k} @ \left.\frac{\Delta f_{\ell}}{\Delta t}\right|_{k\ outaged}$$

OTDF Evaluation



OTDF Evaluation

- Since $\Delta \boldsymbol{f}_{\ell}^{(1)} = \varphi_{\ell}^{(w)} \Delta \boldsymbol{t}$

  and $\Delta \boldsymbol{f}_{\boldsymbol{k}} = \varphi_{\boldsymbol{k}}^{(w)} \Delta \boldsymbol{t}$

  then $\Delta \boldsymbol{f}_{\ell}^{(2)} = \boldsymbol{d}_{\ell}^{\boldsymbol{k}} \Delta \boldsymbol{f}_{\boldsymbol{k}} = \boldsymbol{d}_{\ell}^{\boldsymbol{k}} \varphi_{\boldsymbol{k}}^{(w)} \Delta \boldsymbol{t}$

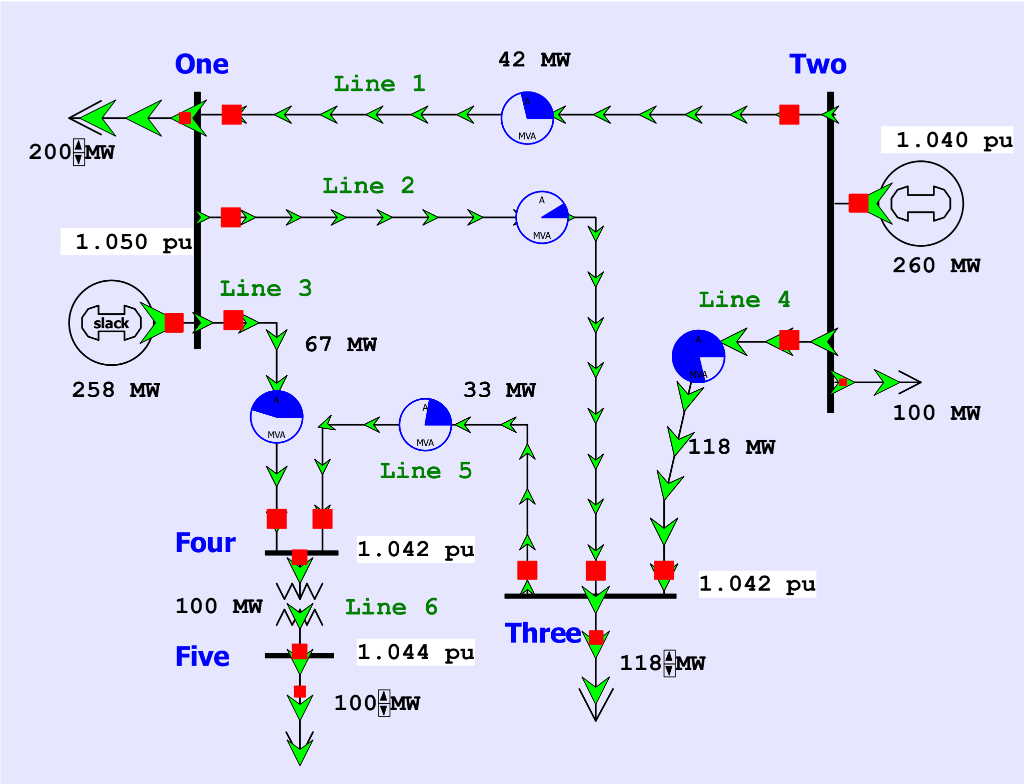
  so that

$$\Delta \boldsymbol{f}_{\ell} = \Delta \boldsymbol{f}_{\ell}^{(1)} + \Delta \boldsymbol{f}_{\ell}^{(2)} = \left[\varphi_{\ell}^{(w)} + \boldsymbol{d}_{\ell}^{\boldsymbol{k}} \varphi_{\boldsymbol{k}}^{(w)} \right] \Delta \boldsymbol{t}$$

$$\left(\varphi_{\ell}^{(w)} \right)^{\boldsymbol{k}} = \varphi_{\ell}^{(w)} + \boldsymbol{d}_{\ell}^{\boldsymbol{k}} \varphi_{\boldsymbol{k}}^{(w)}$$

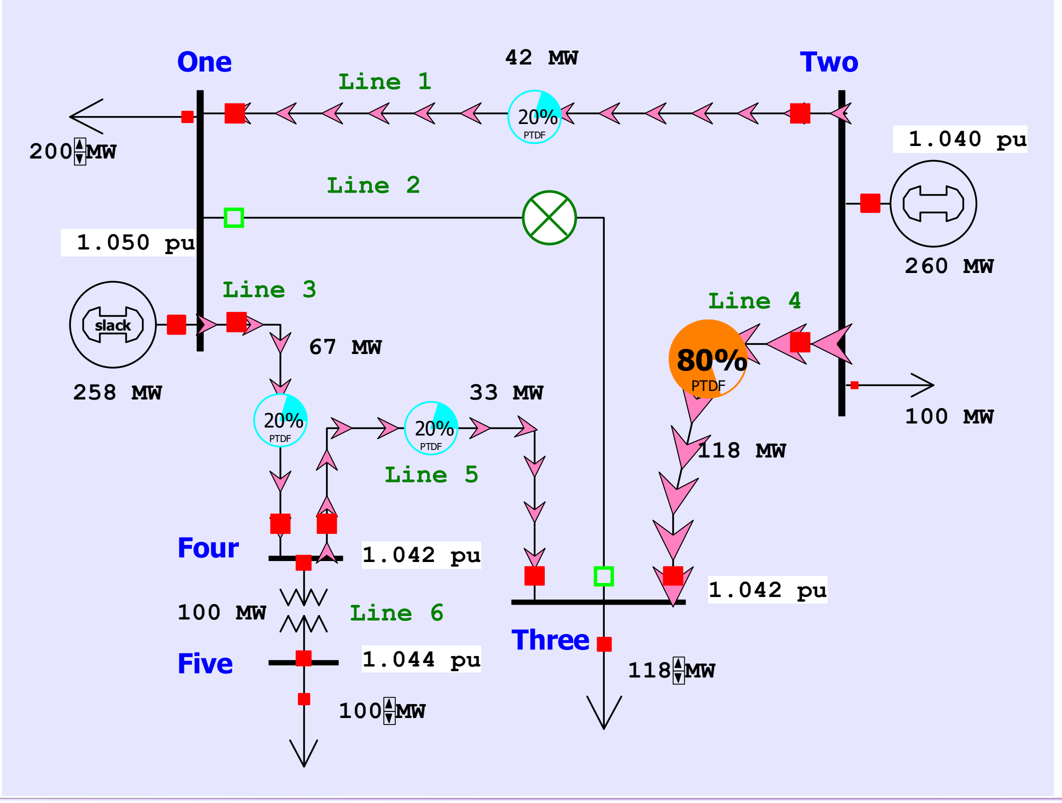
Five Bus Example

- Say we would like to know the PTDF on line 1 for a transaction between buses 2 and 3 with line 2 out



Five Bus Example

- Hence we want to calculate these values without having to explicitly outage line 2



Hence the value we are looking for is 0.2 (20%)

Five Bus Example

- Evaluating: the PTDF for the bus 2 to 3 transaction on line 1 is 0.2727; it is 0.1818 on line 2 (from buses 1 to 3); the LODF is on line 1 for the outage of line 2 is -0.4
- Hence

$$\left(\varphi_{\ell}^{(w)}\right)^{k} = \varphi_{\ell}^{(w)} + d_{\ell}^{k}\,\varphi_{k}^{(w)}$$

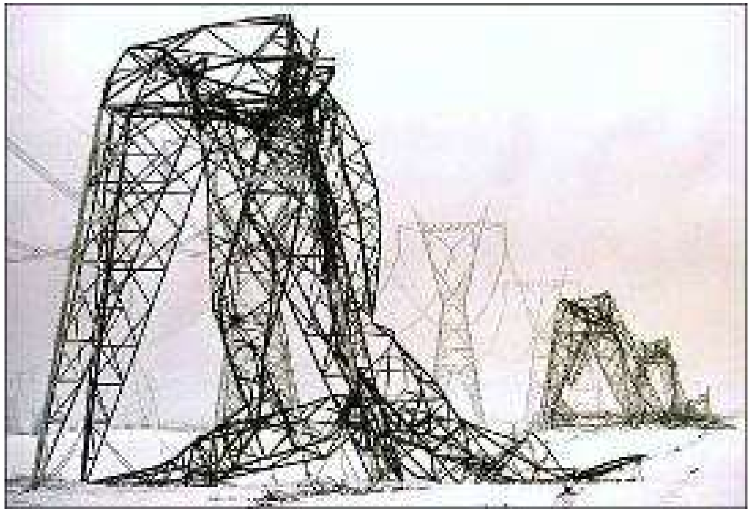
$$\mathbf{0.2727 + (-0.4) \times (0.1818) = 0.200}$$

- For line 4 (buses 2 to 3) the value is

$$\mathbf{0.7273 + (0.4) \times (0.1818) = 0.800}$$

Blackouts

- Blackouts are costly, with some estimates of costs above $100 billion per year.
- But blackouts are not created equal. Some are unavoidable due to large scale system damage (hurricanes, tornados and ice storms). Most are local, distribution issues.



More than 200 transmission towers damaged or destroyed

Right image source: entergynewsroom.com (Hurricane Laura damage)

Some Electric Grid Risks

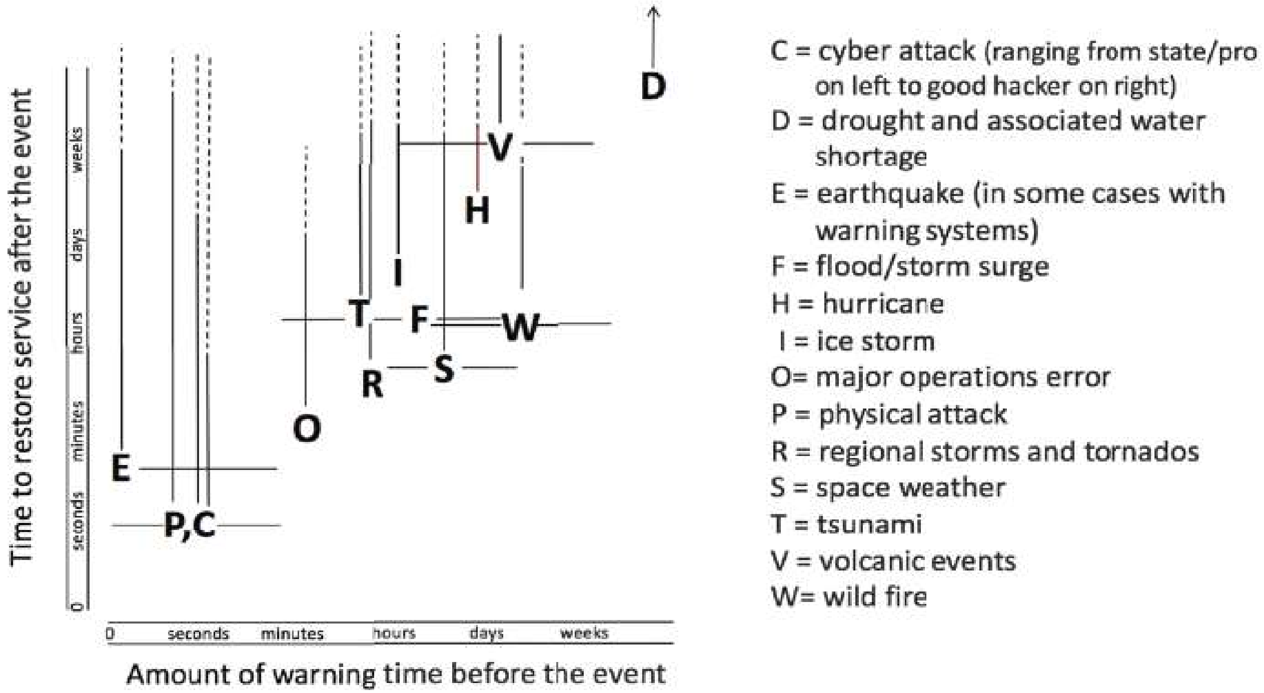


FIGURE 3.1 Mapping of events that can cause disruption of power systems. The horizontal placement provides some indication of how much warning time there may be before the event. The vertical axis provides some indication of how long it may take to recover after the event. Lines provide a representation

Image Source: Enhancing the Resilience of the Nation's Electricity System, US National Academies Press, 2017

The Real Cause of Most Blackouts!

Photo source: http://save-the-squirrels.com

But mostly only the small ones in the distribution system

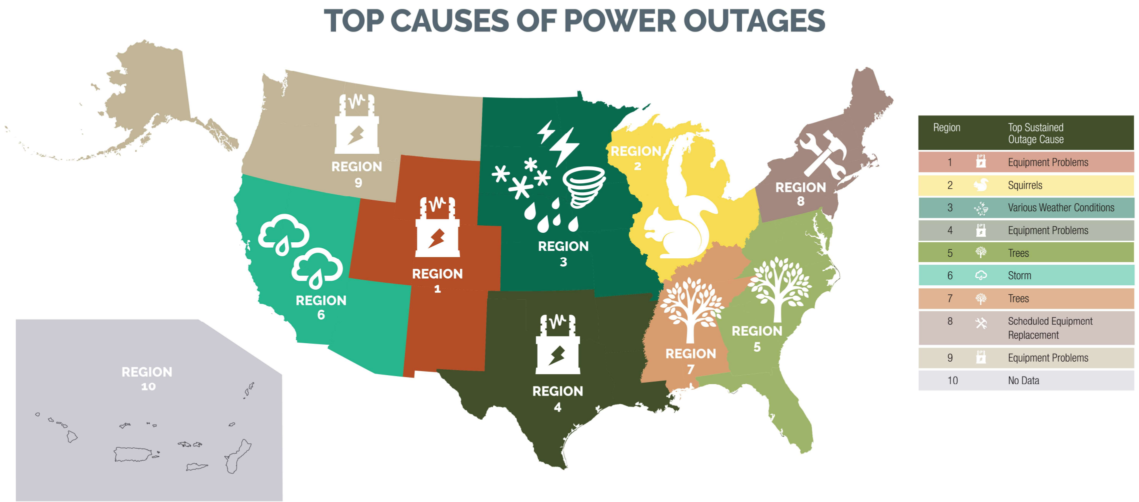


Image source: publicpower.org

High-Impact, Low-Frequency Events

- In order to enhance electric grid resiliency, we need to consider the almost unthinkable events
- These include what the North American Electric Reliability Corporation (NERC) calls High-Impact, Low-Frequency Events (HILFs); others call them black sky days

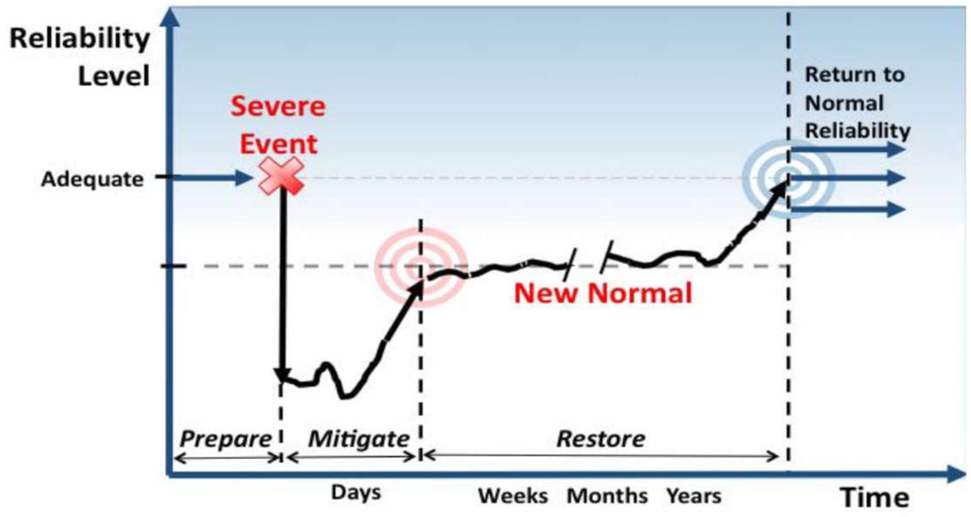


Image Source: NERC, 2012

  - Large-scale, potentially long duration blackouts
  - HILFs identified by NERC were 1) a coordinated cyber, physical or blended attacks, 2) pandemics, 3) geomagnetic disturbances (GMDs), and 4) HEMPs

Avoidable Transmission Level Blackouts

- Many major blackouts can be prevented.
- Time frames of the blackouts, minutes to hours, allow for human intervention
  - Tokyo 1987 (20 minutes), WECC 1996 (six minutes), Eastern Interconnect 2003 (about an hour), Italy 2003 (25 minutes), India 2012 (affecting 600 million people), South America (2019)
- And of course many are prevented, and hence do not make the news. For example, near voltage collapse in Delmarva Peninsula, 1999.
- The 2021 Texas event, which we'll cover later, was caused by a generator capacity shortage not the transmission system

Going Back in Time

- The August 14th 2003 blackout is rapidly moving from being a "recent event" into history; yet it still has much to teach us
  - IEEE Power and Energy Magazine will have a special edition on blackouts in 2023 for the 20th year anniversary
- This talk is about the past and the future: what can we learn from the past to help us prepare for the future
  - But not so much about what are the immediate lessons from the Blackout since many recommendations have already been put into practice.
- The blackout final report is very readable and available by googling "August 14 2003 Blackout Report"

Blackout misery

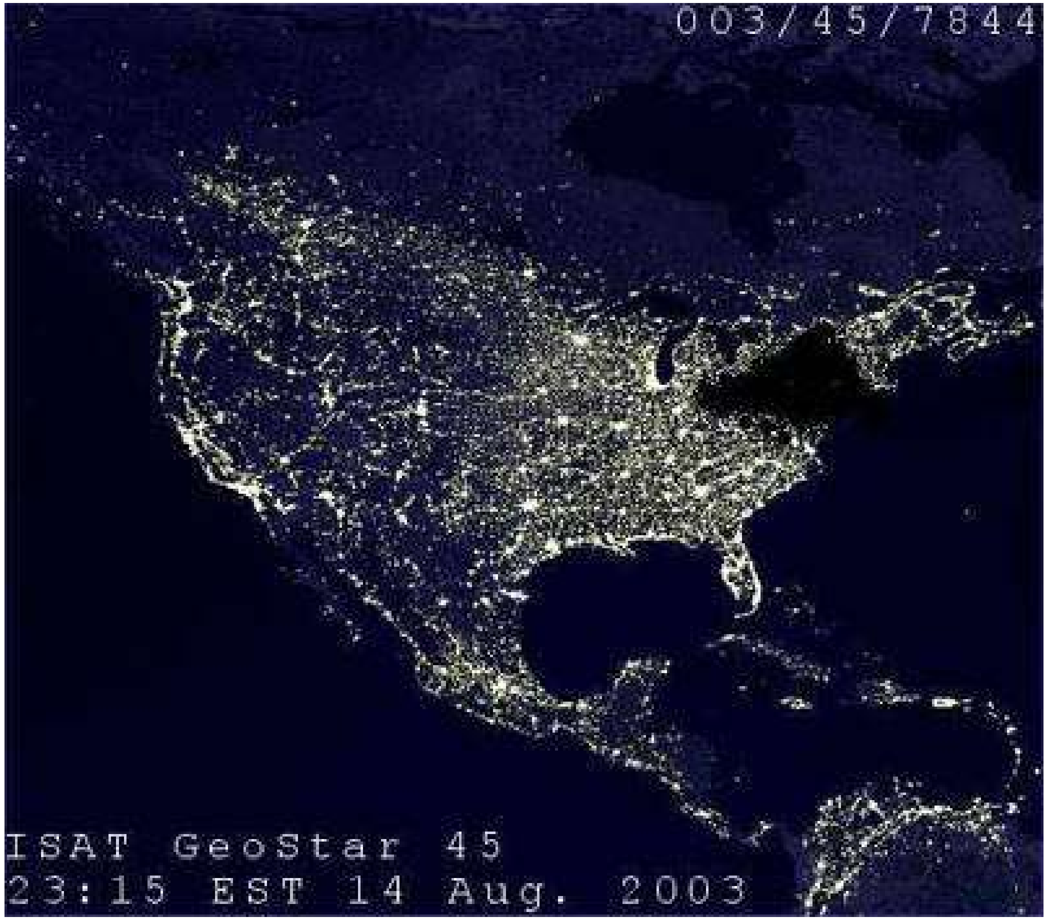
50 million affected in Northeast and beyond as power grid fails

Transportation Many 'wait it out,' by air and land ■ 4A | **Scenes** Moms in labor, cars stuck in car washes ■ 5A | **Impact** Offices close, ATMs idle, cellphones jam ■ 1B

Brooklyn Bridge: Thousands of commuters in New York took to their feet Thursday evening after a major power outage hit the city and much of the Northeast.

In contrasting numbers, the August 14, 2003 Blackout hit about 50 million people, while Hurricane Ian (2022) caused power outages affecting perhaps 2.7 million. The 2021 Texas blackout affected more than 10 million people with at least some outages at a time when temperatures were quite low.

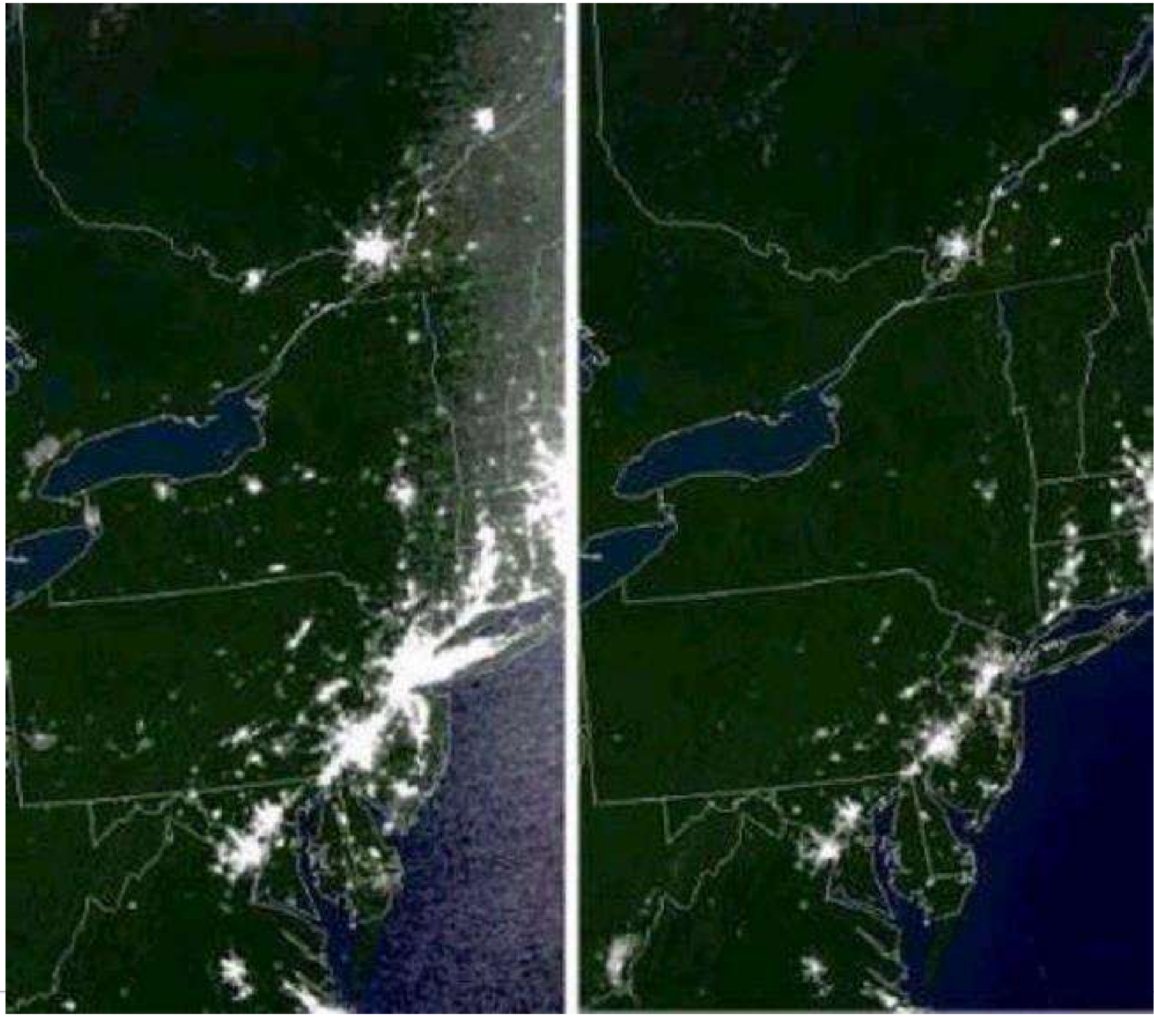
August 14, 2003 Hoax Image



This image was widely circulated immediately after the blackout, even appearing for a time on a DOE website. It was quickly shown to be a hoax.

What might immediately give it away?

Actual Before and After Images

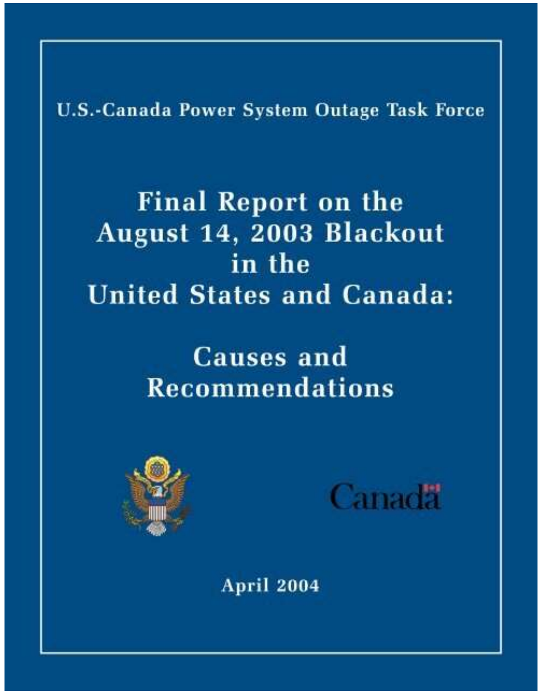


My Favorite August 14, 2003 Cartoon

Suddenly, knowing a lot about the U.S. power grid became sexy at cocktail parties.

Causes of the Blackout

- Blackout Final Report listed four causes
  - FirstEnergy (FE) did not understand inadequacies of their system, particularly with respect to voltage instability.
  - Inadequate situational awareness by FE
  - FE failed to adequately manage their tree growth
  - Failure of the grid reliability organizations (primarily MISO) to provide effective diagnostic support
- Human/cyber interactions played a key role



We’ve Come Quite a Ways Since 2003

- Report included 46 recommendations, many of which have dramatically changed the operation of the interconnected power grid
  - Thirteen were focused on physical and cyber security
- Focus here is what can 8/14/03 teach us to help with the grid in 2022 (and beyond)
- Need to keep in mind economic impact of 8/14/03 was above $5 billion; yearly impact of blackouts could be above $100 billion

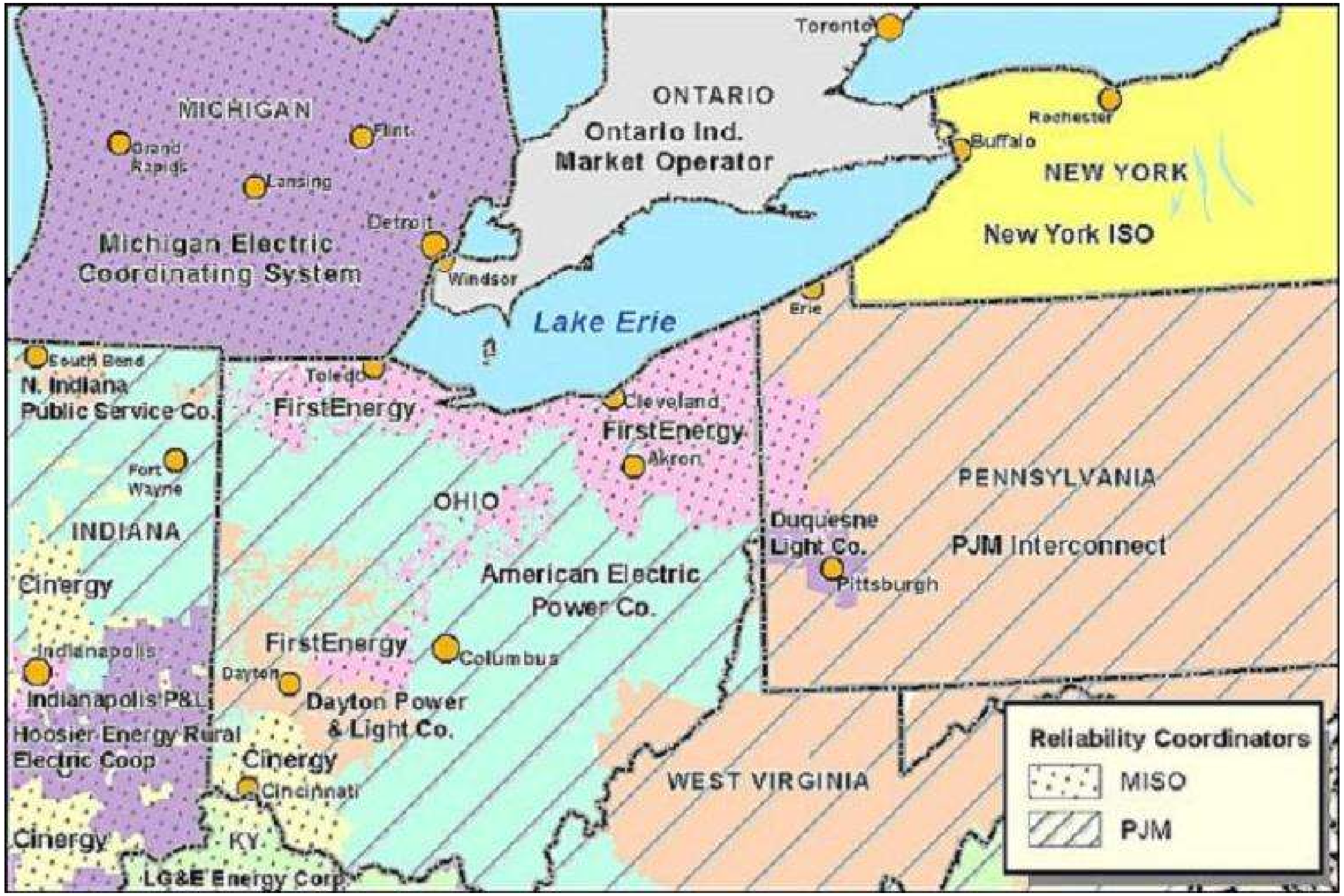
First Energy Control Center, Recent (2013)

Image Source: www.wksu.org/news/story/365

My Involvement in Blackout Investigation

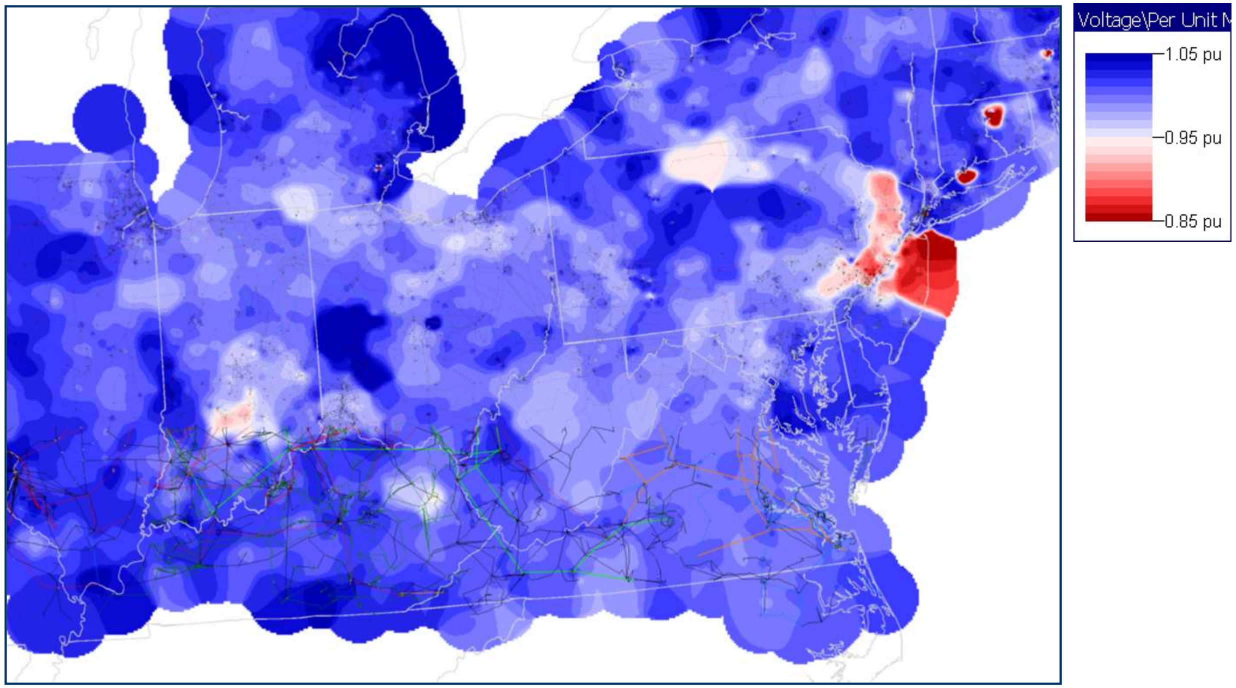
- I spend a lot of time talking to reporters on 8/14 to 8/16, before I knew what happened
- Tasked by DOE to do onsite visit to FE on 8/19 to 8/21 with Doug Wiegmann; did a similar visit to MISO the next week (right as classes were starting for us at UIUC)
- Did return visit in Oct with many others involved in the investigation; we also then talked with Cinergy
- Many folks played far larger roles; I was only involved extensively early on

Footprints of Reliability Coordinators in Midwest



August 13, 2003

- It is important to realize that immediately before the blackout few people thought the system was on the verge of a catastrophe.
- NERC 2003 Summer Assessment did not list Ohio as an area of particular concern



NERC 2003 Summer Assessment is available at http://www.nerc.com/files/summer2003.pdf

August 14, 2003: Pre-blackout (before 14:30 EDT)

- It had mostly been a normal summer day at First Energy
  - Most generation was available though the 883 MW Davis-Besse Nuclear unit was on a long-term outage
  - At 13:31 EDT the Eastlake 5 unit (a 597 MW plant on Lake Erie) tripped when the operator tried to up is reactive output, but this was not seen as a severe event
- It had been a busy day at MISO, with their reliability coordinators dealing with a small outage in Indiana around noon
  - Their state estimator failed at 1215 EDT but no one knew

Figure 4.1. August 2003 Temperatures in the U.S. Northeast and Eastern Canada

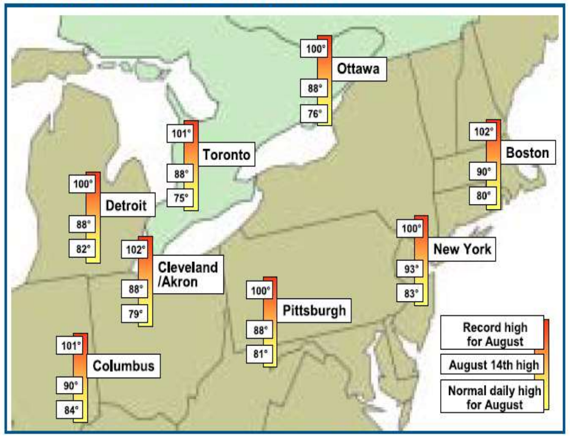
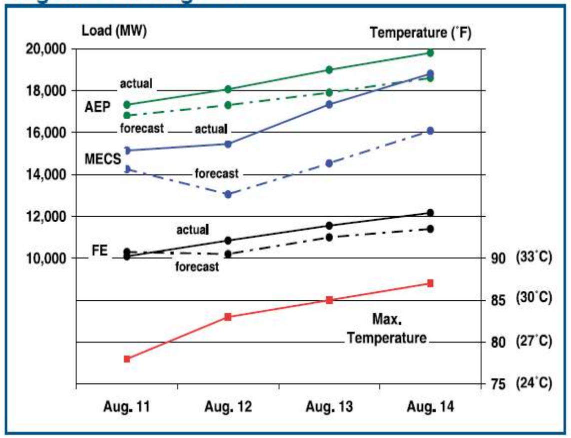


Figure 4.2. Load Forecasts Below Actuals, August 11 through 14



Cinergy Bedford-Columbus 345 kV Line Tree Contact at 12:08 EDT

Trees were Finally "Trimmed" Two Months Later