ECEN 460
Power System Operation and Control
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Lecture 15: Power Flow Sensitivities, Transmission Issues

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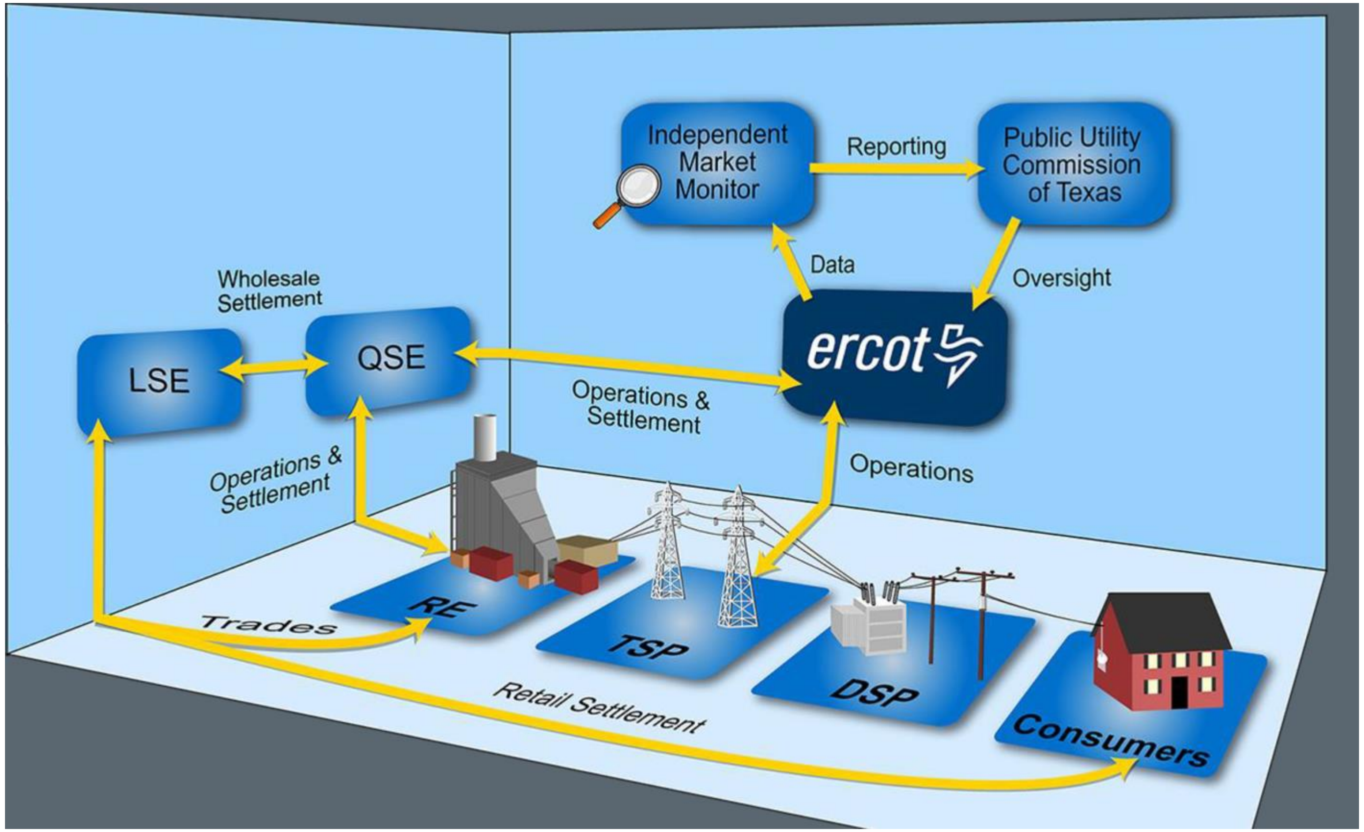
The ERCOT Wholesale Markets

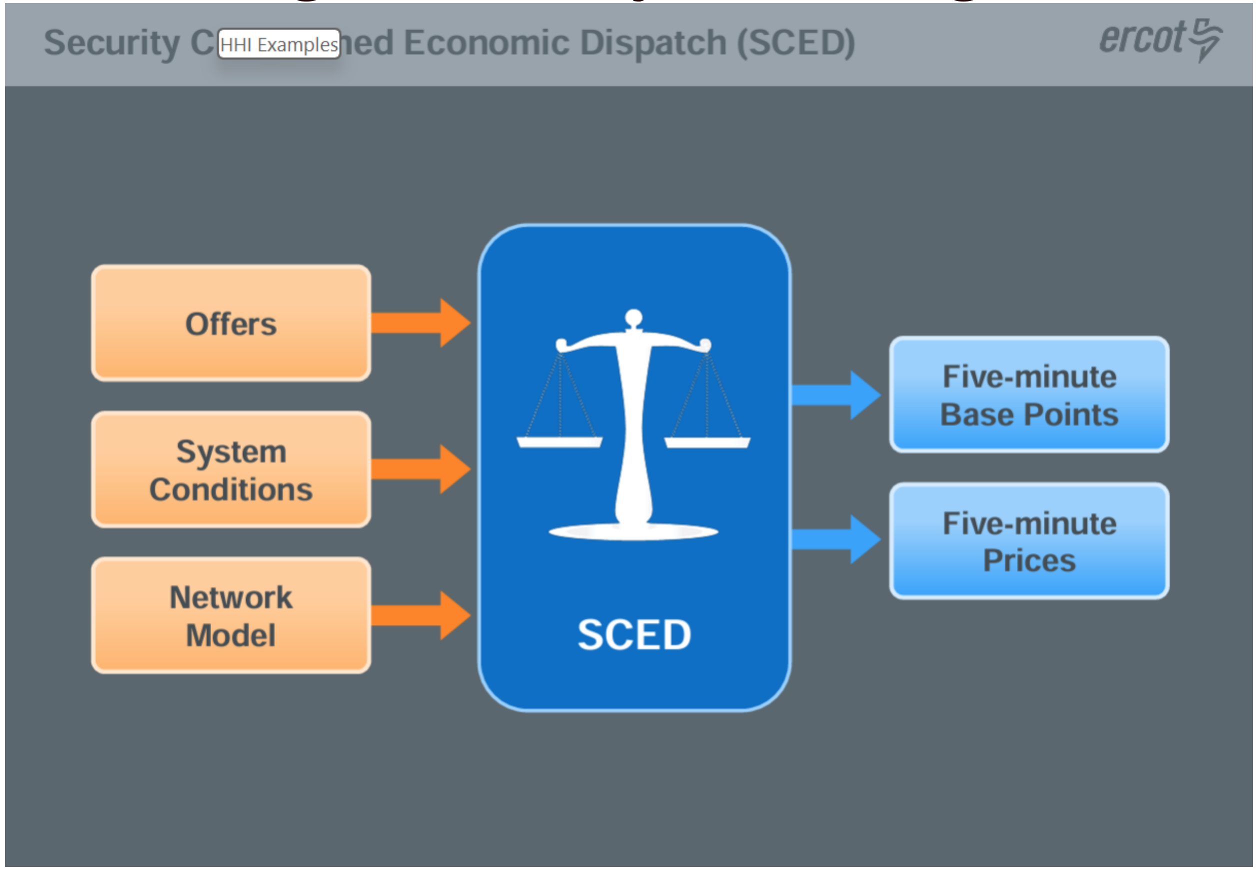
- The overall structure of the ERCOT market is given below
  - There is a day-ahead time market, an adjustment period, hour ahead, and then the operating hour
  - LSE is a Load Serving Entity (e.g., a utility; there are > 400 in ERCOT)
  - RE is a Resource Entity (> 950)
  - QSE is a Qualified Scheduling Entity (there are > 1200)
  - TSP is Transmission Service Provider, DSP is Distribution Service Provider



Material partially from www.ercot.com/files/docs/2023/07/07/2023_07-wholesale-101.pdf

ERCOT Real-Time Dispatch and Pricing

- The goal of real-time dispatch is to manage reliability, matching the generation with the load, ensuring the transmission flows and voltages stay within limits, and operate the system at least cost



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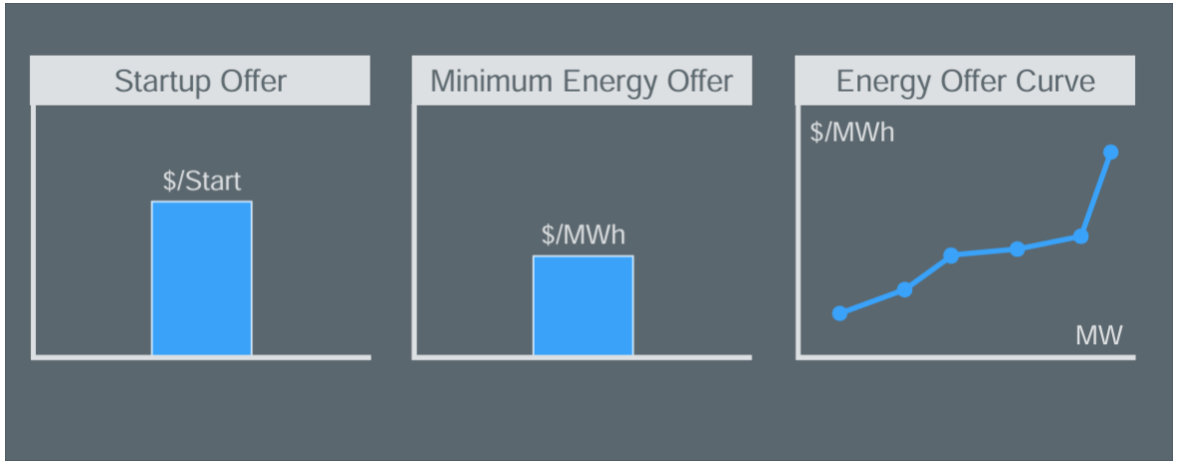
ERCOT Forward Markets

- Since the electric load for tomorrow can be well estimated, the goal is to determine next day dispatch as accurately as possible
  - Hedging is transacting at a known price now to protect from having to transact at an unknown price later
- Forward energy markets in ERCOT include a centralized day-ahead market (DAM) conducted by ERCOT and bilateral trades
- An offer to sell energy in the DAM includes three parts



Material partially from www.ercot.com/files/docs/2023/07/07/2023_07-wholesale-101.pdf

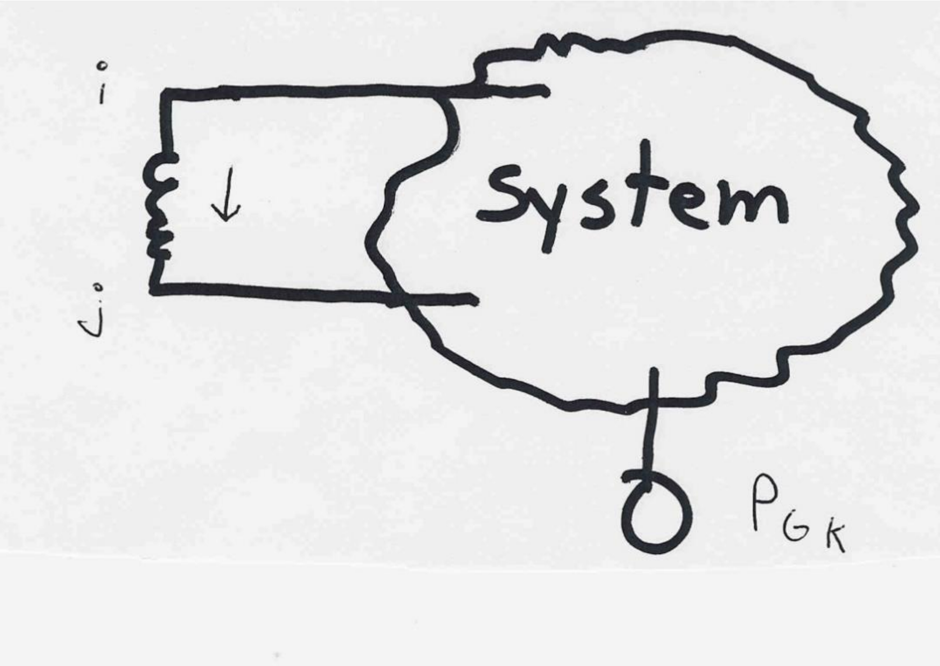
ERCOT Energy Settlements

- The energy settlements provides the dollars to the entities that provided electric energy
- It consist of three parts: 1) the bilateral trades, 2) the day-ahead market (DAM), and 3) real—time
- In the DAM, the settlement is based on the Day-Ahead Settlement Point Price (DASPP) and the amount of power
- The real-time energy settlement is based on the difference between what is scheduled in the DAM, and the actual metered generation and load
  - The price is based on the Real-Time Settlement Point Price (RTSPP)
- We’ll talk about the impact of congestion after the test

Material partially from www.ercot.com/files/docs/2023/07/07/2023_07-wholesale-101.pdf

Power System Control and Sensitivities

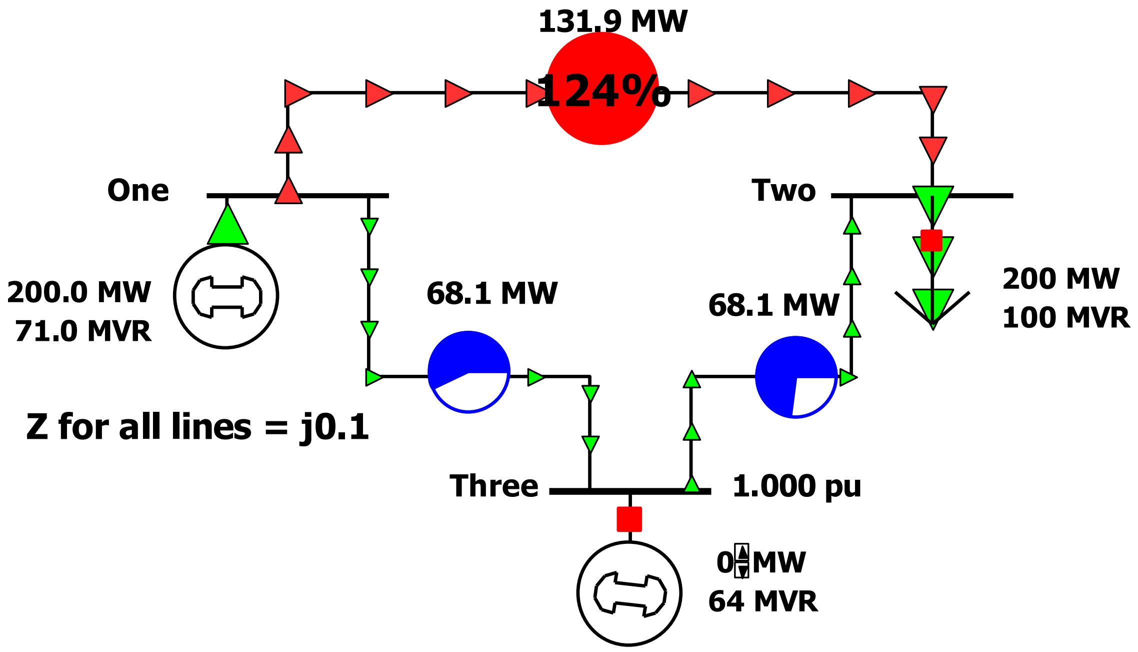
- In order to optimize the grid, the OPF and SCOPF need to have sensitivity information on how a change in control affects a constraint
- An example would be to determine is how a change in generation at bus k affects the power flow on a line from bus i to bus j.



The assumption is that the change in generation is absorbed by the slack bus

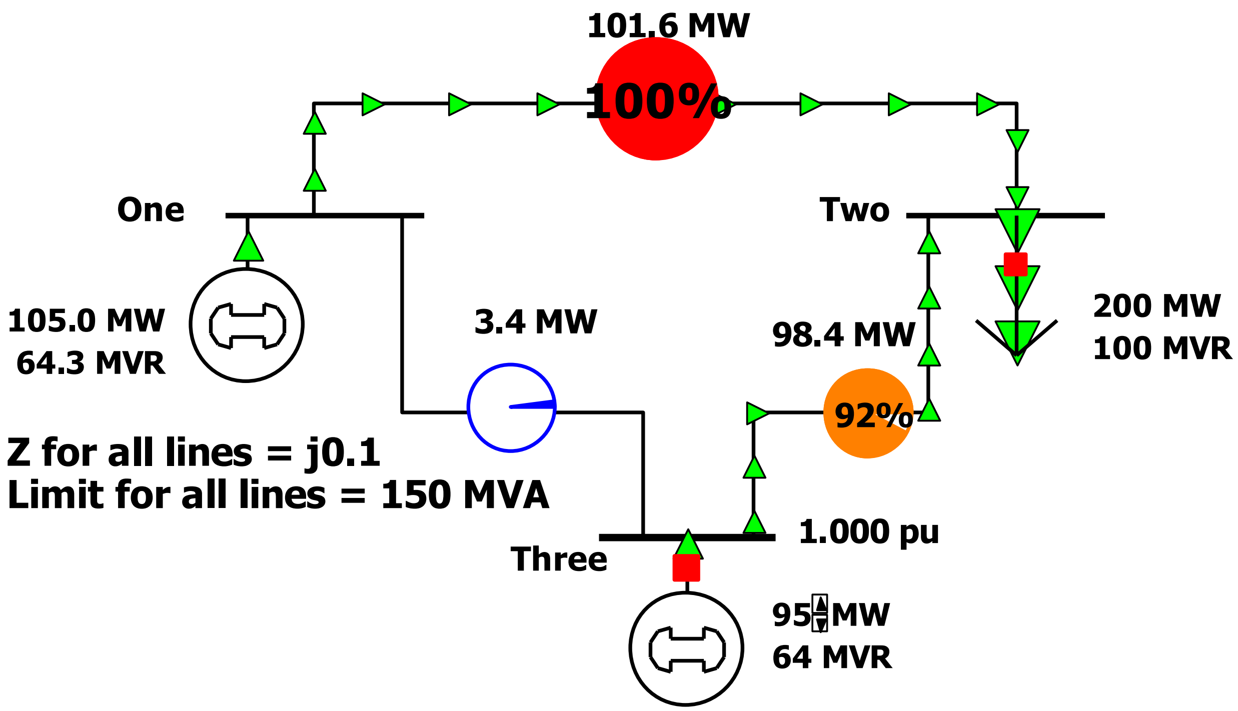
Power Flow Simulation - Before

- One way to determine the impact of a generator change is to compare a before/after power flow.
- For example below is a three bus case with an overload



Power Flow Simulation - After

- Increasing the generation at bus 3 by 95 MW (and hence decreasing it at bus 1 by a corresponding amount), results in a 30.3 MW drop in the MW flow on the line from bus 1 to 2, and a 64.7 MW drop on the flow from 1 to 3.



Expressed as a percent, 30.3/95 =32% and 64.7/95=68%

Analytic Calculation of Sensitivities

- Calculating control sensitivities by repeat power flow solutions is tedious and would require many power flow solutions. An alternative approach is to analytically calculate these values

The power flow from bus i to bus j is

$$P_{ij} \approx \frac{|V_i||V_j|}{X_{ij}} \sin(\theta_i - \theta_j) \approx \frac{\theta_i - \theta_j}{X_{ij}}$$

So $\Delta P_{ij} \approx \dfrac{\Delta\theta_i - \Delta\theta_j}{X_{ij}}$ We just need to get $\dfrac{\Delta\theta_{ij}}{\Delta P_{Gk}}$

Analytic Sensitivities

From the fast decoupled power flow we know

$$\Delta\boldsymbol{\theta} = \mathbf{B}^{-1}\Delta\mathbf{P}(\mathbf{x})$$

So to get the change in $\Delta\boldsymbol{\theta}$ due to a change of generation at bus k,

just set $\Delta\mathbf{P}(\mathbf{x})$ equal to all zeros except a minus one at position k.

$$\Delta\mathbf{P} = \begin{bmatrix} 0 \\ \vdots \\ -1 \\ 0 \\ \vdots \end{bmatrix} \begin{array}{l} \\ \\ \leftarrow \text{ Bus k} \\ \\ \\ \end{array}$$

Three Bus Sensitivity Example

For a three bus, three line case with $Z_{line} = j0.1$

$$\mathbf{Y}_{bus} = j\begin{bmatrix} -20 & 10 & 10 \\ 10 & -20 & 10 \\ 10 & 10 & -20 \end{bmatrix} \rightarrow \mathbf{B} = \begin{bmatrix} -20 & 10 \\ 10 & -20 \end{bmatrix}$$

Hence for a change of generation at bus 3

$$\begin{bmatrix} \Delta\theta_2 \\ \Delta\theta_3 \end{bmatrix} = \begin{bmatrix} -20 & 10 \\ 10 & -20 \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ -1 \end{bmatrix} = \begin{bmatrix} 0.0333 \\ 0.0667 \end{bmatrix}$$

Then $\Delta P_{3\text{ to }1} = \dfrac{0.0667 - 0}{0.1} = 0.667$ pu

$\Delta P_{3\text{ to }2} = 0.333$ pu $\quad \Delta P_{2\text{ to }1} = 0.333$ pu

Sensitivity Comments

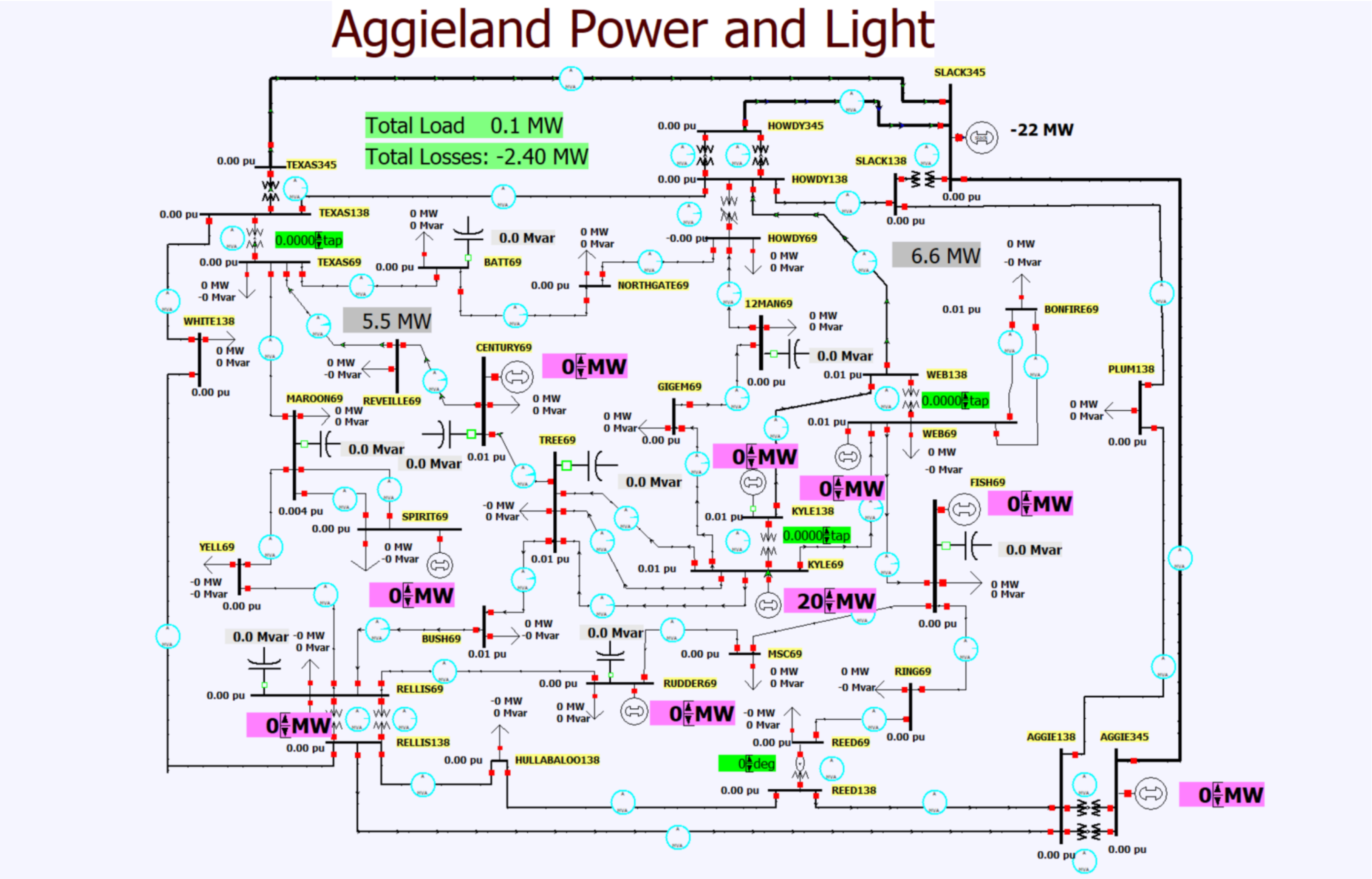
- In ECEN 615 the methods for quickly calculating sensitivities are developed. Here the focus is just on their application
- Sensitivities can (relatively) easily be calculated even for large systems, and can be calculated for a variety of different power system controls, such as phase shifting transformers
- Sensitivities are dependent upon the operating point
  - They also include the impact of marginal losses

A Sensitivity Example in Simulator

- Open the Lab2_Bus37_Start (from Lab 2). To optimally remove the overloads it is important to know how changing a particular control (say the KYLE69 MW generation) affects the line flows
  - A common assumptions is the opposite generation change occurs at the slack bus
- These sensitivity values can be approximated by solving a power flow, noting the flows, changing the power flow (e.g., increasing the KYLE69 generation), resolving, and looking at the flow differences
- Simulator allows a comparison of two cases using Difference Flows
  - Solve the case, then select **Tools, Difference Case, Set Present as Base**
  - Change the case (e.g., increase KYLE69 from 60 to 80 MW), resolve

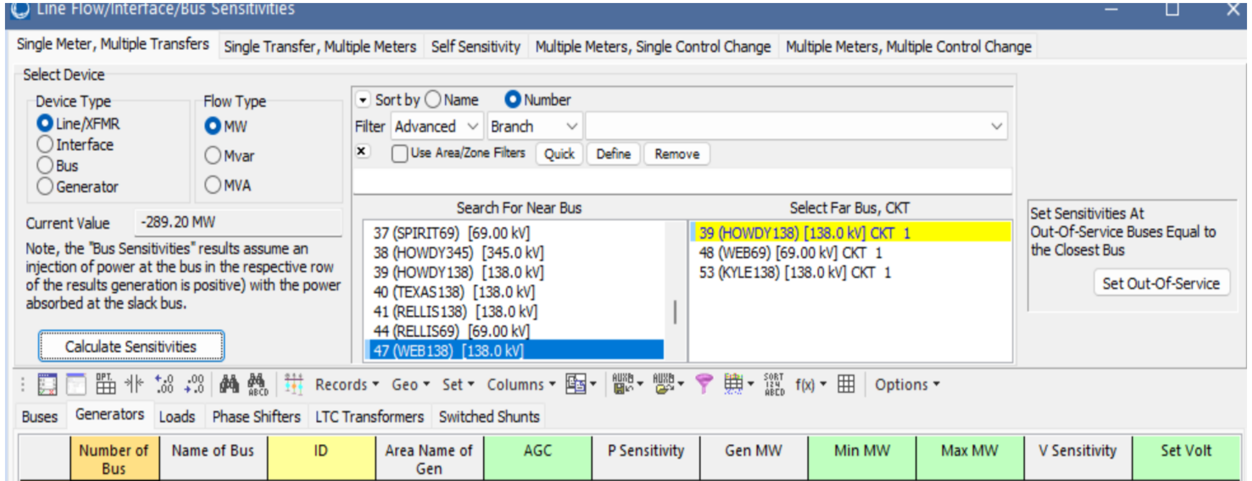
Lab 2 37 Bus Case Difference Flows

- The image shows the difference flows for the 20 MW generation change at KYLE 69; note the flow on the line from WEB138 to HOWDY138 has increased by 6.6 MW
  - Its sensitivity to this generation change it 6.6/20 = 0.33



Showing Sensitivities in PowerWorld

- PowerWorld has a number of different ways to show sensitivities. One approach is to show all the sensitivities for a single device (e.g., a line) to multiple controls (e.g., generator changes); the other is the sensitivities for many devices to a single control
- To see the sensitivity for a line flow to generation changes select **Tools, Flow and Voltage Sensitivities, Single Meter, Multiple Transfers**
  - Select the WEB138 (bus 47) to HOWDY138 (bus 39) line

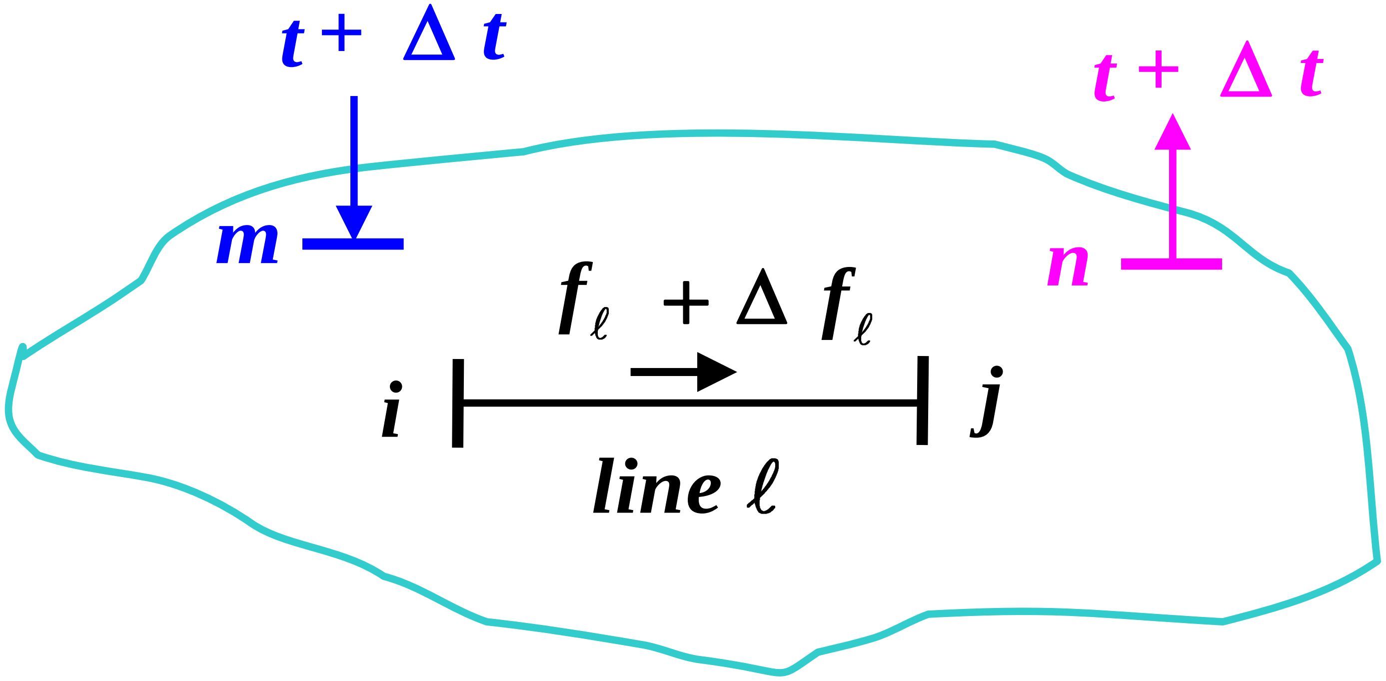


	Number of Bus	Name of Bus	ID	Area Name of Gen	AGC	P Sensitivity	Gen MW	Min MW	Max MW	V Sensitivity	Set Volt
1	14	RUDDER69	1	1	YES	0.264300	10.0	10.0	40.0		1.02000
2	16	CENTURY69	2	1	YES	0.335097	50.0	0.0	100.0		1.03000
3	20	FISH69	2	1	NO	0.344090	50.0	0.0	110.0		1.03000
4	28	AGGIE345	1	1	NO	0.032367	200.0	0.0	250.0		1.03000
5	31	SLACK345	1	1	YES	0.000000	938.4	0.0	1000.0	-0.02817	1.03000
6	37	SPIRIT69	1	1	NO	0.158717	110.0	15.0	140.0		1.01000
7	44	RELLIS69	1	1	NO	0.195458	45.0	20.0	60.0		1.02000
8	48	WEB69	1	1	NO	0.415047	5.0	5.0	30.0		1.00000
9	53	KYLE138	1	1	NO	0.529700	0.0	0.0	250.0		1.02000
10	54	KYLE69	1	1	NO	0.353665	60.0	15.0	200.0		1.01000

Power Transfer Distribution Factors (PTDFs)

- PTDFs are a common sensitivity values that are used to show how a particular power transfer (i.e., from a source to a sink) will affect the grid
- 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"
- In the lossless formulation presented here (and commonly used) it is slack bus independent

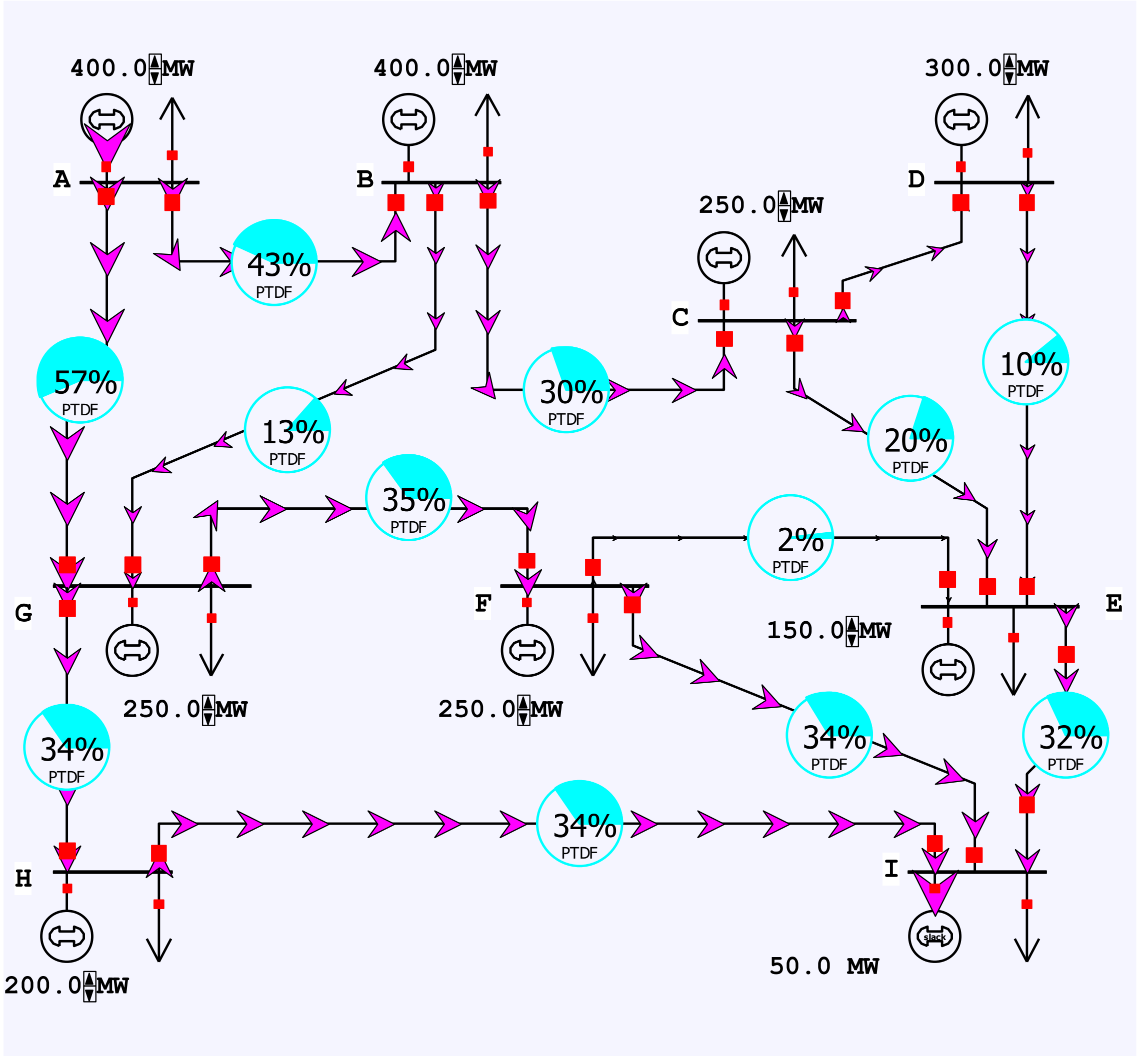
PTDFs



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

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

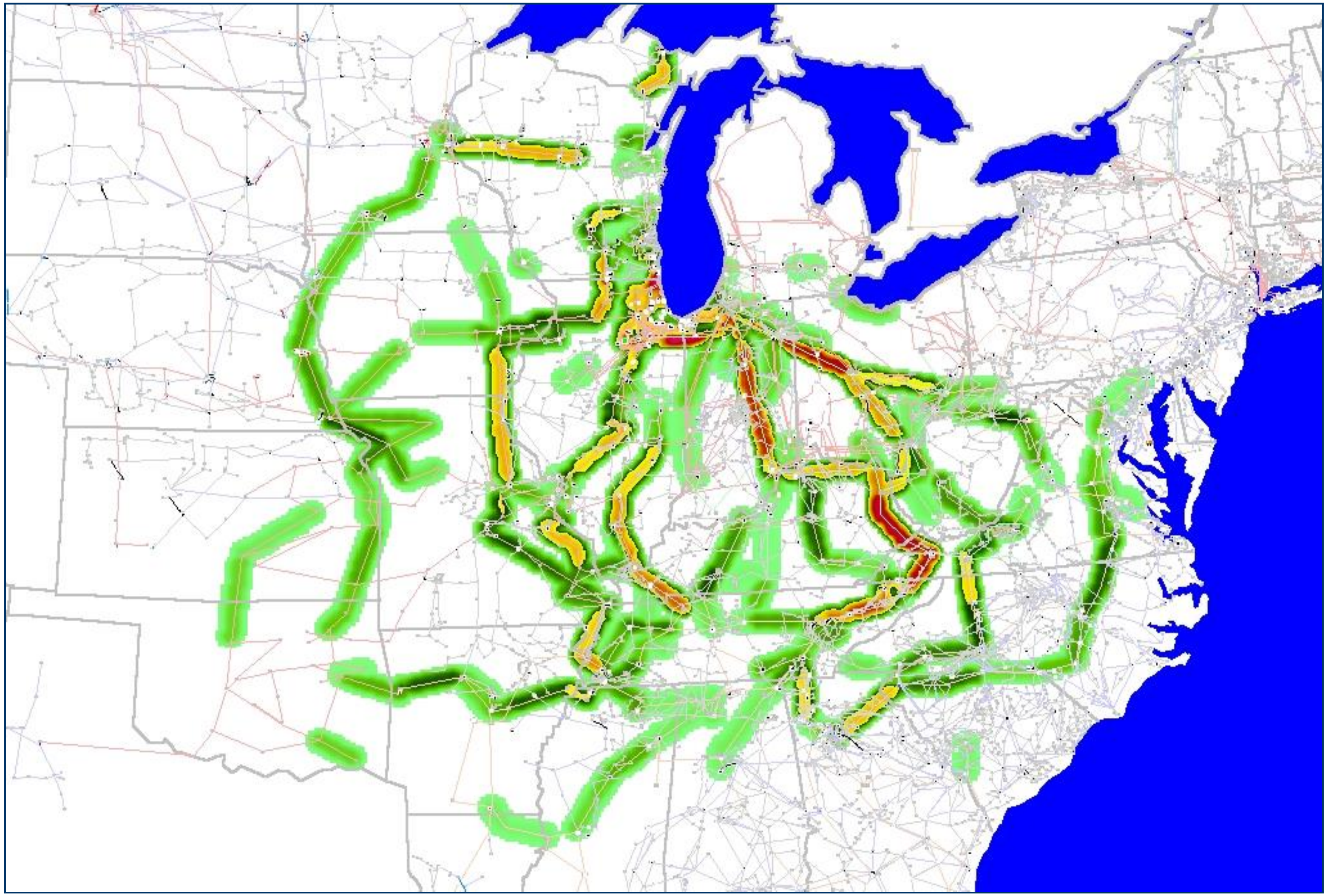
Nine Bus PTDF Example



Display shows the PTDFs for a 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

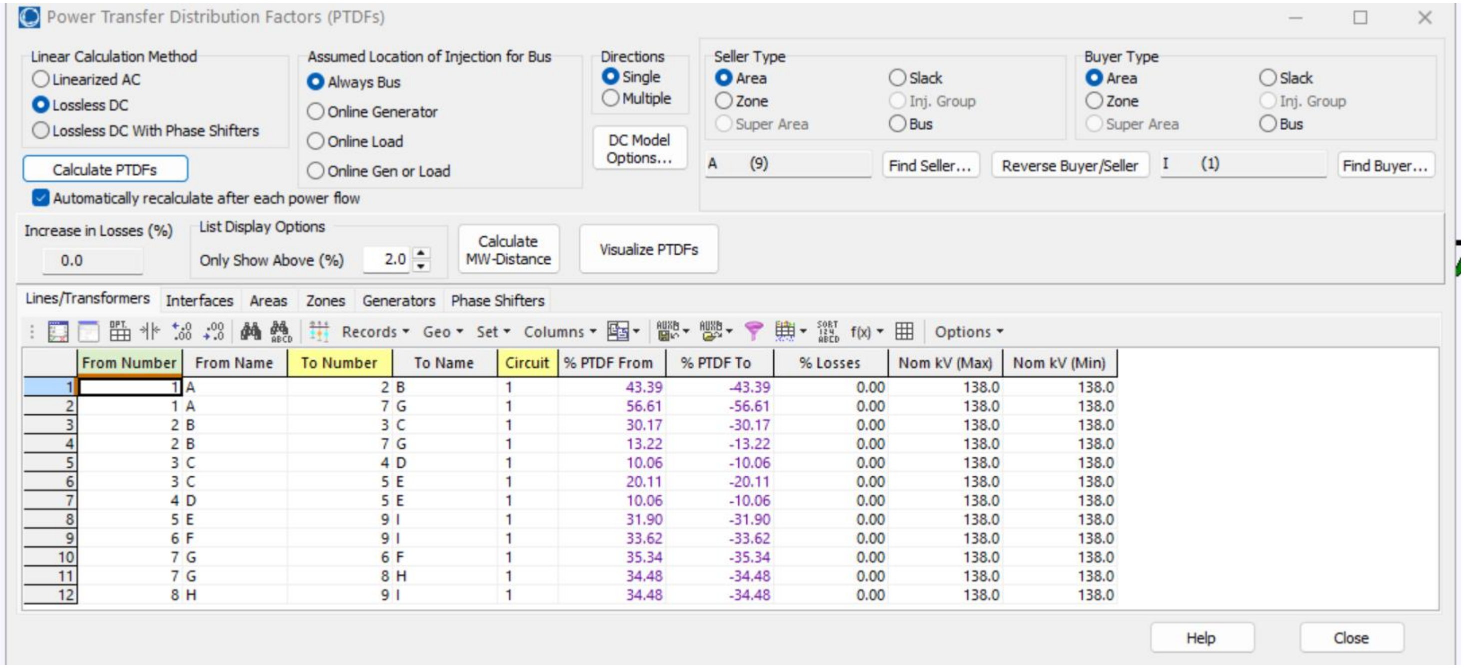


In this example multiple generators contribute for both the seller and the buyer

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

Calculating PTDFs in PowerWorld

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



	From Number	From Name	To Number	To Name	Circuit	% PTDF From	% PTDF To	% Losses	Nom kV (Max)	Nom kV (Min)
1	1	A	2	B	1	43.39	-43.39	0.00	138.0	138.0
2	1	A	7	G	1	56.61	-56.61	0.00	138.0	138.0
3	2	B	3	C	1	30.17	-30.17	0.00	138.0	138.0
4	2	B	7	G	1	13.22	-13.22	0.00	138.0	138.0
5	3	C	4	D	1	10.06	-10.06	0.00	138.0	138.0
6	3	C	5	E	1	20.11	-20.11	0.00	138.0	138.0
7	4	D	5	E	1	10.06	-10.06	0.00	138.0	138.0
8	5	E	9	I	1	31.90	-31.90	0.00	138.0	138.0
9	6	F	9	I	1	33.62	-33.62	0.00	138.0	138.0
10	7	G	6	F	1	35.34	-35.34	0.00	138.0	138.0
11	7	G	8	H	1	34.48	-34.48	0.00	138.0	138.0
12	8	H	9	I	1	34.48	-34.48	0.00	138.0	138.0

Results are shown for the nine bus case for the Area A to Area I transaction

Transmission Ownership

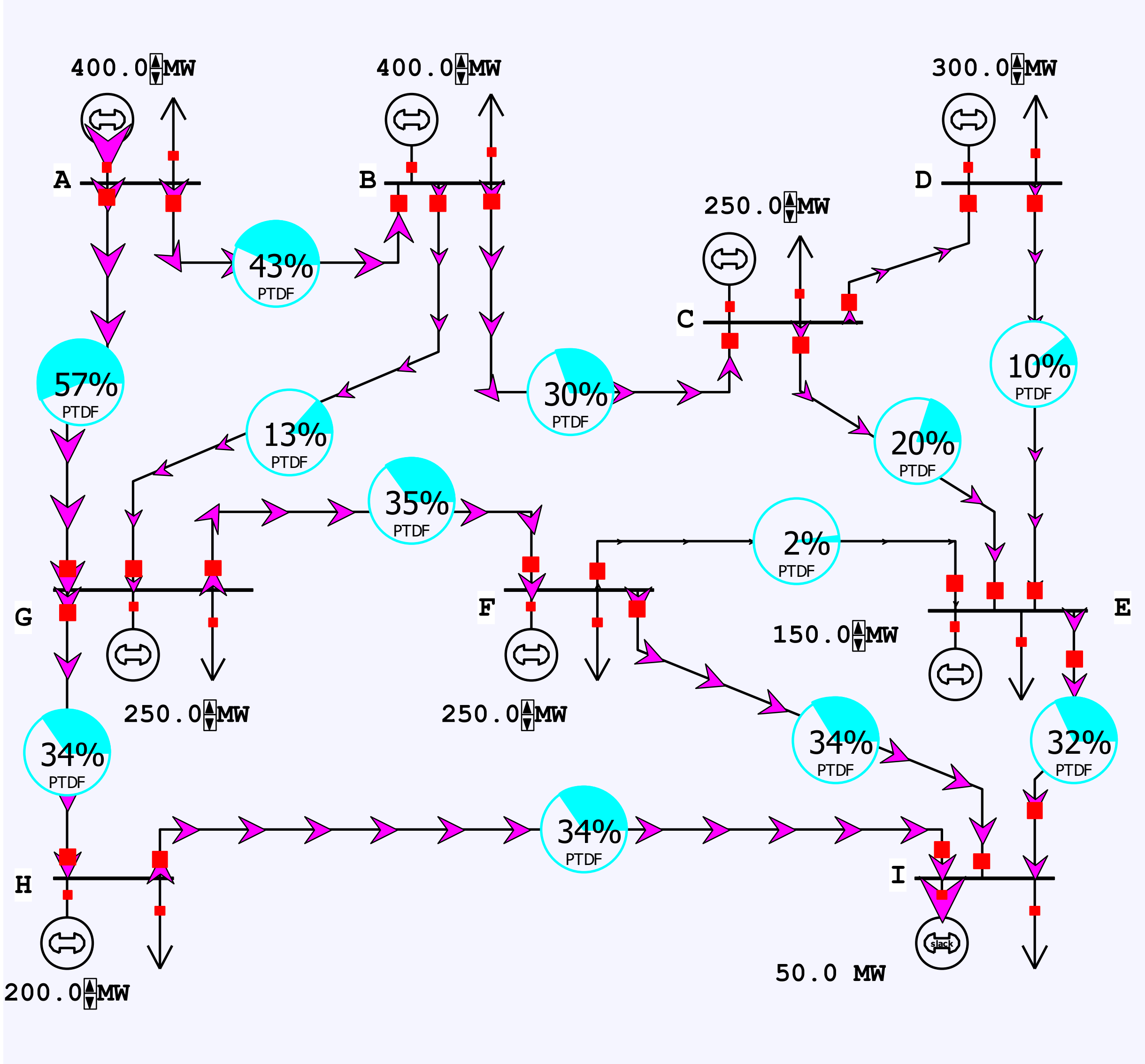
- The vast majority of the US transmission grid is privately owned, mostly by investor owned utilities; almost all is ac, with a small amount of HVDC
  - There are some transmission only companies like ATC (mostly in Wisconsin)
- Normally property ownership includes several rights including
  - The right to use the property
  - The right to allow others to use the property, often for a fee
  - The right to exclude others from using the property
  - The right to transfer the property to others such as by selling it
- With ac transmission because of its nature (e.g., loop flow) some of these rights need to be modified; how they are modified can be market specific

Historical Transmission Usage and Expansion

- When most electric utilities were vertically integrated monopolies the costs and benefits associated with operating and expanding the transmission system did not need to be precisely determined since a single entity controllable all aspects of electricity supply, and could do joint generation, load and transmission planning
- There could still be (and were) disputes between adjoining utilities since loop flows still existed
- The most common way of providing another utility access to the transmission to transact with more distant utilities was through a notion known as the “contract path”

Contract Path Nine Bus Example

- If **A** wished to transact with **I**, using the contract path approach they just needed to get some of the intermediate areas to agree (say **G** and **H**)
- This did not account for the loop flows
- This led to the creation of larger ISOs to manage issues



Transmission Challenges

- The main challenges with transmission are
  - Compensating existing transmission line owners
  - Ensuring sufficient new transmission is constructed
- Different markets use different rules to achieve this
- For current transmission there are 1) maintenance costs, 2) operating costs, 3) depreciation expenses, and 4) financing costs; state regulators usually approve these charges
- New transmission needs are usually determined by a regional planning organization (e.g., ERCOT) working with existing transmission line owners with the states approving the new transmission lines

General Economics: Types of Goods

- In economics goods (products or services) are often differentiated based on whether they are excludable and rivalrous
  – Excludable is the degree to which a good can be prevented from being used
  – Rivalrous is the degree to which consumption by one prevents consumption by others
  – Public goods are non-excludable and non-rivalrous; examples are official statistics, national defense, public radio and TV
  – Private goods are excludable and rivalrous; most things are in this category
  – Common goods are non-excludable and rivalrous; many free public services fall in this category, like roads and electric transmission access; the "tragedy of the commons" refers to common goods.
  – Club goods are excludable and non-rivalrous; examples are private parks and satellite TV

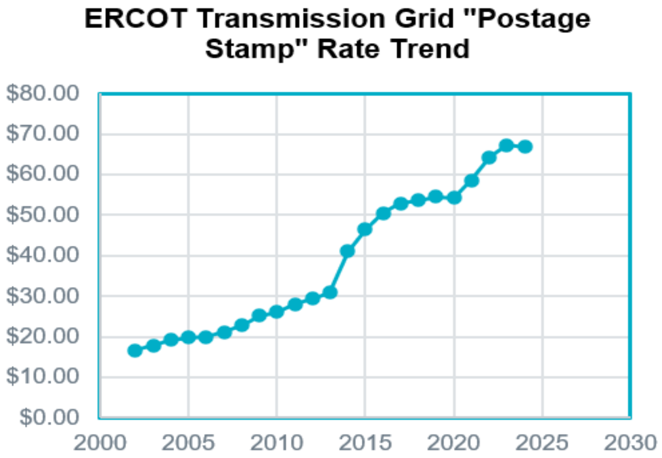
Paying for the Transmission Grid

- Paying for the transmission grid involves a number of different factors, including perceived fairness and simplicity
- ERCOT uses a "postage stamp" approach, in which the total transmission costs are paid by each of the load serving entities (LSEs) based on their load usage during the 15 minute period in which ERCOT sets its maximum demand during each of the four summer months (the 4CP approach) (June, July, August, September)
  - This is a relatively simple approach, and benefits from just having a single state involved
  - A criticism of this approach is it could certainly be possible for larger loads to deliberately reduce their demand during these periods

ERCOT Transmission Cost of Service (TCOS)

Wholesale Transmission Rates and Charges in ERCOT

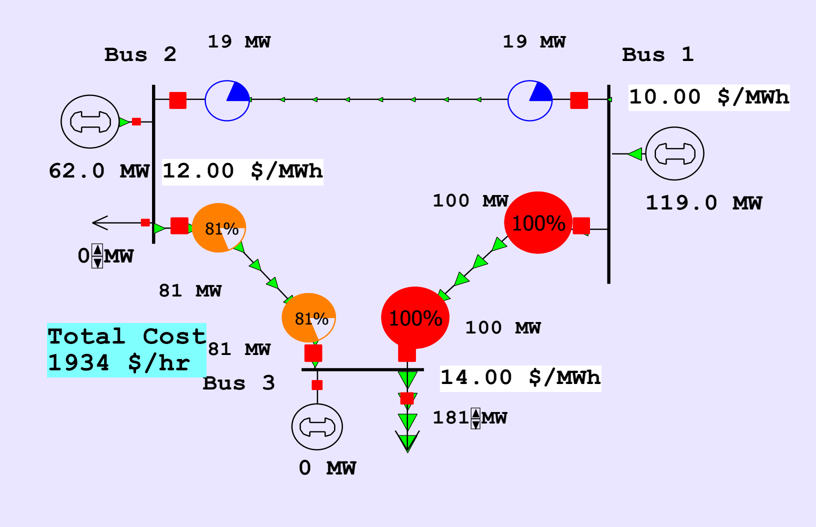
Matrix DN	Matrix Year	Postage Stamp Rate (a)	% Rate Change	4CP Load (b)	% Load Change	Transmission Charges (c) = (a) * (b)	% Charges Change
56050	2024	**$66.76**	-0.8%	83,685,241.4	8.9%	**$5,586,575,524**	8.0%
54507*	2023	**$67.30**	4.7%	76,848,305.7	6.0%	**$5,171,739,736**	11.0%
52989	2022	**$64.29**	10%	72,490,325.3	2.2%	**$4,660,557,131**	12.3%
51612*	2021	**$58.50**	7.8%	70,937,625.2	-0.1%	**$4,149,860,060**	7.7%
50333	2020	**$54.28**	-0.5%	70,980,872.4	2.3%	**$3,852,813,554**	1.8%
48928	2019	**$54.57**	1.8%	69,368,963.5	3.1%	**$3,785,308,370**	5.0%
47777	2018	**$53.58**	1.3%	67,273,101.1	-0.6%	**$3,604,682,776**	0.6%
46604	2017	**$52.91**	4.8%	67,690,205.6	2.5%	**$3,581,817,753**	7.4%
45382	2016	**$50.48**	8.8%	66,036,438.6	3.7%	**$3,333,519,422**	12.8%
43881	2015	**$46.40**	13.0%	63,680,709.6	-2.4%	**$2,955,016,343**	10.2%
42062	2014	**$41.08**	32.7%	65,250,196.8	-1.2%	**$2,680,360,767**	31.2%
40946	2013	**$30.95**	5.4%	66,014,375.9	1.6%	**$2,043,144,934**	7.1%
39916	2012	**$29.36**	4.5%	64,992,452.1	5.9%	**$1,908,411,522**	10.7%
38900	2011	**$28.09**	7.8%	61,368,962.6	0.8%	**$1,723,854,160**	8.7%
37680	2010	**$26.05**	3.7%	60,858,331.4	1.7%	**$1,585,268,854**	5.5%
36374	2009	**$25.13**	10.5%	59,819,399.9	3.8%	**$1,502,986,350**	14.7%
35011	2008	**$22.73**	7.8%	57,650,014.9	-3.3%	**$1,310,253,397**	4.3%
33550	2007	**$21.08**	5.9%	59,611,096.1	1.3%	**$1,256,430,226**	7.3%
32084	2006	**$19.90**	0.3%	58,858,282.1	5.0%	**$1,171,039,672**	5.3%
30474	2005	**$19.85**	3.1%	56,040,200.6	2.3%	**$1,112,159,251**	5.5%
28937	2004	**$19.25**	8.2%	54,788,344.7	2.4%	**$1,054,657,555**	10.8%
26950	2003	**$17.78**	7.1%	53,520,537.1	1.5%	**$951,854,189**	8.7%
25002	2002	**$16.61**		52,727,134.8		**$875,986,472**	



The "postage stamp" rate represents the sum of the wholesale transmission rates of the TSPs in ERCOT. It is an annual rate per kilowatt of ERCOT average 4CP demand for access to the Texas transmission grid. The rates and charges change with each wholesale transmission rate proceeding, the amounts shown represent a snapshot of the rates and charges in effect at the time of the corresponding annual "matrix" docket.

Congestion Revenue Rights (CRRs)

- In LMP markets congestion causes price differences. Markets provide financial instruments to hedge against the uncertainty associated with these price differences
  - In ERCOT and CAISO (California) they are known as Congestion Revenue Rights (CRRs); in PJM, MISO and ISO-NE they are Financial Transmission Rights (FTRs)
  - They are not a right to deliver physical electric energy
  - In ERCOT they apply in the day ahead market
- In ERCOT there are two types
  - Point-to-Point Options
    - Owners only get paid based upon the price difference
  - Point-to-Point Obligations
    - Owners might have to pay

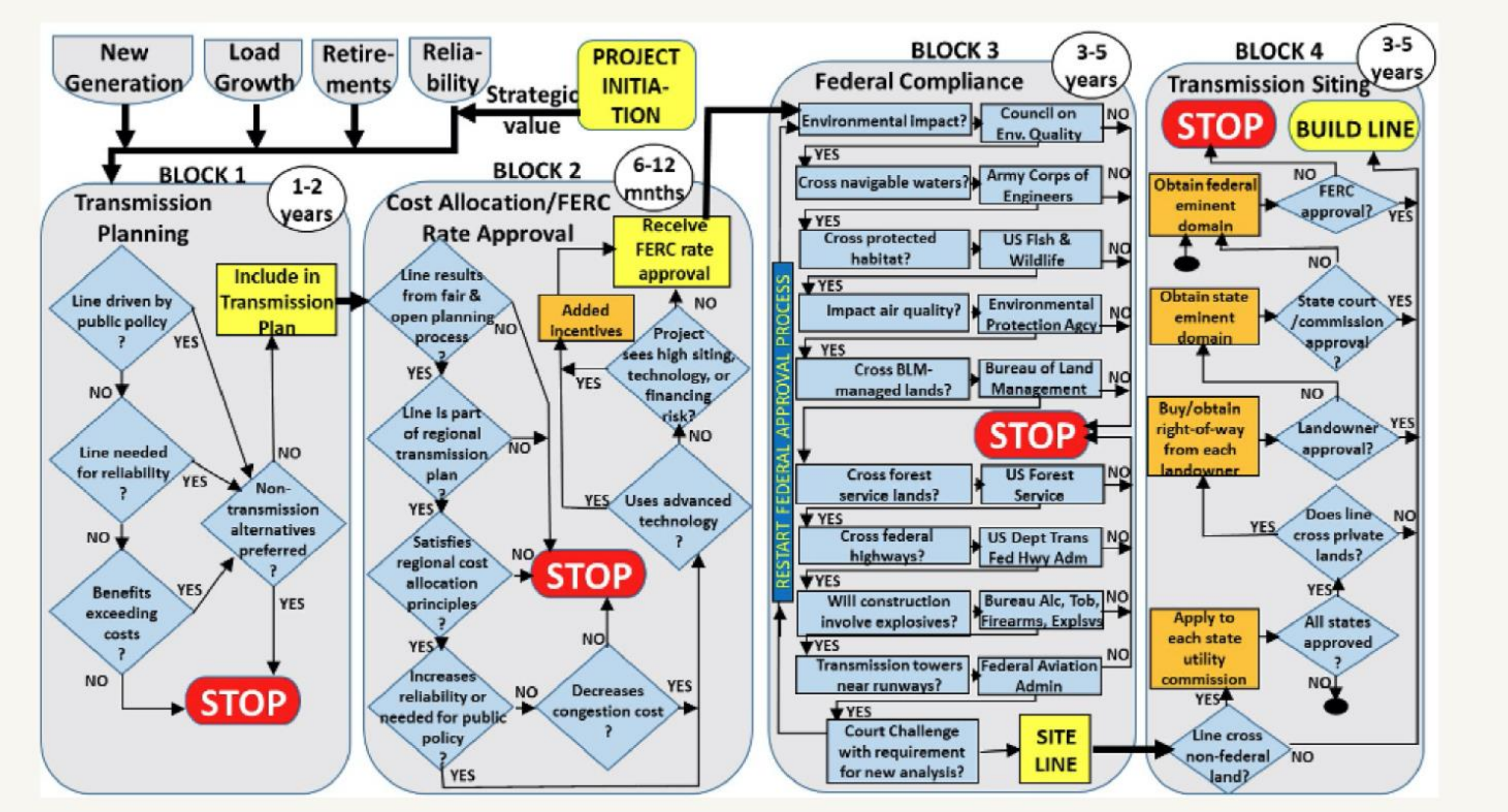


Congestion Revenue Rights (CRRs), cont.

- CRRs can be bought in the CRR auction, traded, or awarded by allocation
  - Allocations are given to Non-Opt-In Entities (NOIEs) are municipally owned utilities or electric cooperatives that have chosen not to participate in the competitive retail electricity markets
  - There are monthly auctions and auctions for six-month periods; CRRs have different time periods including off-peak, peak weekday and peak weekend
- Information on ERCOTs CRRs is available at www.ercot.com/mktinfo/crr
  - As of March 1, 2025 there were about 685,000 open CRRs! Many are for just a few MWs
- Additional information is available from the ERCOT State of the Market Report; the value of congestion in 2023 for ERCOT is $2.3 billion
- Nationwide an estimate of congestion costs is about $12 billion in 2023

Building New Transmission Lines

- In general, getting new transmission build can be a very involved process, particularly if it crosses state lines; the below image summarizes the process



The process is somewhat similar in Texas since just a single state is involved, with the Public Utility Commission of Texas (PUCT) approving new lines by issuing a Certificate of Convenience and Necessity (CCN)

Image source: www.breakthroughenergy.org/newsroom/articles/transmissiondeployment/

Who Gets to Build New Transmission

- In many locations, including Texas, Right of First Refusal (ROFR) laws give the incumbent utilities the first right to construct and operate new transmission lines
- In October 2024 a US district court ruled that this Texas law was invalid because if violated the Dormant Commerce Clause of the US Constitution since the court viewed the Texas law as restricting interstate commerce
  - This ruling did not apply to the ERCOT portion of Texas since its electricity is not considered interstate commerce

Getting Transmission Line Right-of-Ways

- Determining the path for a new transmission line is an involved process, with the PUCT ultimately giving final approval
- For new right-of-ways that involve private land, the entity constructing the line (usually a utility) contacts the landowners to obtain easements
  - An easement provides rights for the utility to use the land for the transmission line, and restricts what the property owner can do with the land; payment is usually up front, though annual payments are common with wind turbines; the price is negotiable
- In an easement agreement cannot be obtained, it can be obtained through eminent domain, which is ultimately a legal process in which the landowner gets a court determined payment

EIA US Real-Time Electric Grid Information

- Information about the real-time status of the US electric grid is available at www.eia.gov/electricity/gridmonitor/dashboard/electric_overview/US48/US48