

ECEN 615

Methods of Electric Power Systems Analysis

Lecture 8: Advanced Power Flow, Sparsity

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Announcements



- Start reading Chapter 7 (the term reliability is now often used instead of security).
- Homework 2 is due on Thursday Sept 25; use the five bus power system that was given in lecture 5, except to simplify your power flow algorithm you should assume that all the resistance values are zero. This gives the Ybus shown below.

	Number	Name	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5
1	1	One	$0.00 - j50.00$				$-0.00 + j50.00$
2	2	Two		$0.00 - j28.70$		$-0.00 + j10.00$	$-0.00 + j20.00$
3	3	Three			$0.00 - j100.00$	$-0.00 + j100.00$	
4	4	Four		$-0.00 + j10.00$	$-0.00 + j100.00$	$0.00 - j148.92$	$-0.00 + j40.00$
5	5	Five	$-0.00 + j50.00$	$-0.00 + j20.00$		$-0.00 + j40.00$	$0.00 - j109.34$

Special Speaker on Friday at 1130 am in Zach 241



Title: Translating the Grid: How the Press Tells the Stories of the Texas Electric Power Sector

Date: Friday, September 19, 2025 at 11:30am Central Time

Abstract

The goal of this presentation is to help graduate students and faculty better understand how the electric power industry is discussed in the mainstream media and why their field matters to everyday people. The Texas power grid has been under heavy scrutiny since failing in the February 2021 freeze, which killed at least 246 people across the state. The crisis illuminated a contradiction that many are still frustrated by: Why does the energy capital of the world sometimes struggle to keep the lights on for its own residents? At the same time, Texas has been held up as a model of how states can ease the build-out of renewable energy, and as a hub for the development of next-generation technologies such as enhanced geothermal and small modular reactors. Now, with the emergence of AI, Texas is again in the spotlight as one of the regions with the fastest-growing electricity demand in the country.

This presentation discusses the main storylines playing out in the Texas electric power sector, as well as why the road to the country's energy transition necessarily runs through the Lone Star State. It highlights the questions and concerns top-of-mind for everyday readers, and how this reporter tries to explain a complicated, highly technical industry to a general audience. Included in the presentation is a brief overview of how the media industry has grappled with financial challenges and digital transformation, and how those changes impact local news coverage. Time will be left at the end for any questions.

Biography

Claire Hao is an energy & power grid reporter at the Houston Chronicle. She covers the growth and politics of renewable energy in the country's leading state for utility-scale wind and solar, the complexities of the Texas power grid as extreme weather repeatedly tests its aging infrastructure, the expected energy demand from AI and more. Most anything that has to do with how electricity is produced, transmitted, distributed and consumed is fair game. She can be reached at claire.hao@houstonchronicle.com.

Before joining the Houston Chronicle in 2023, Claire spent a year on the climate team of the San Francisco Chronicle, where she also covered power grid & energy transition, as well as wildfire, drought, earthquake readiness and California's home insurance crisis. Claire has also written for the news desks of Bloomberg Law and the Chicago Tribune, as well as for the editorial board of the Washington Post.

Claire was raised in the metro Detroit area and graduated from the University of Michigan in 2022. She was born in Bryan, Texas, as her father pursued his electrical engineering PhD at Texas A&M University.

ERCOT College Days: Either October 3 or 17



ercot 

COLLEGE DAY 2025

Register now!

Registration Deadline:
October 2, 2025, at 2 p.m.

Speakers and Topics

- Engineer Development Program
 - Large Load Interconnection Process
 - Energy Storage Resources
 - Artificial Intelligence

Location

ERCOT Taylor Center (TCC1)
800 Airport Rd.
Taylor, TX 76574

IN-PERSON

October 3
9:30 a.m. – 2 p.m.

- Resumé Reviews*
- Lunch Provided*

* Available for in-person attendees only

VIRTUAL

October 17
1 p.m. – 2 p.m.

SCAN ME
to register



Event Registration QR Code:



Event Registration Link:

<https://cvent.me/QAv7gR>

Power System Terminology: Reliability vs Security



- Prior to 9/11/2001 the power industry used the term “security” to mean that the grid was being operated in a reliable manner.
- A description of this change is given in [a] (page 61)

The World Trade Center and the Pentagon were attacked by terrorists on September 11, 2001. Shortly after the attack, Mr. Richard Clarke, then national coordinator for Security, Infrastructure Protection, and Counterterrorism, met with NERC officials to discuss ways of protecting the electric system from acts of terrorism. After hearing NERC references to “security coordinators,” Mr. Clarke interrupted to say, “Wait a minute— I’m the security coordinator.” Shortly thereafter, NERC began to use the term “operating reliability” in place of “security,” and “Reliability Coordinators” in place of “security coordinators.”
- If you are interested in reading the complete set of the NERC Reliability Standards, all 1700 plus pages are available at www.nerc.com/pa/stand/reliability%20standards%20complete%20set/rscompleteset.pdf

[a] Quote from *The History of the North American Electric Reliability Corporation* by David Nevius, NERC, 2020
www.nerc.com/news/Documents/NERCHistoryBook.pdf

Transformer Vector Groups



- Transformer vector groups are used to fully specify the connections between the windings on a three or two winding transformer.
- Vector groups are not needed for power flow, but they are needed if the power flow is used to initialization fault analysis or harmonics, and are a needed input for geomagnetic disturbance (GMD) analysis.
- A vector group consists of symbols in capital letters telling the connection type for the high-voltage winding (Y,D, or Z for zigzag) and small letters for the intermediate and low-voltage winding.
 - If a neutral point is brought out an N or n is used; for auto transformers the lower voltage symbol is replaced by an “a”
 - Phase displacement is given by clock numbers (0 to 11) indicating 30 degree intervals of lag from the high voltage winding

Transformer Vector Groups, Example



- The table gives examples of vector groups used in a 10,000 bus industry power flow model.
 - Note the table contains a mixture of vector groups for three winding and two winding transformers
 - Such metrics are easy to obtain from data on any PowerWorld Case Info display by right-clicking on the field and selecting **Set/Toggle/Columns, Get Column Metrics**, to display the Grid Metrics, and then selecting the **Histograms and Groupings** page

	Text Value	Percent ▼	Count	Cumulative Count	Cumulative Percent
1	YNyn0	36.622	683	683	36.622
2	YNd1	25.094	468	1151	61.716
3	YNa0d1	16.783	313	1464	78.499
4	YNa0	11.260	210	1674	89.759
5	Dyn1	3.753	70	1744	93.512
6	YN0d1d1	1.609	30	1774	95.121
7	Dd0	1.072	20	1794	96.193
8	YN0yn0yn0	0.590	11	1805	96.783
9	YN0yn0d1	0.536	10	1815	97.319
10	D0d2	0.483	9	1824	97.802
11	YNd11	0.429	8	1832	98.231
12	YNa	0.214	4	1836	98.445
13	Dy1	0.214	4	1840	98.660
14	D1y0y0	0.214	4	1844	98.874
15	YNd5	0.214	4	1848	99.088
16	Yyn0	0.161	3	1851	99.249
17	D1yn0yn0	0.161	3	1854	99.410
18	Yy0	0.107	2	1856	99.517
19	YNynd1	0.107	2	1858	99.625
20	Ynyn	0.107	2	1860	99.732
21	YNd5d5	0.107	2	1862	99.839
22	Dyn	0.054	1	1863	99.893
23	Yd1	0.054	1	1864	99.946
24	Dyn11	0.054	1	1865	100.000

Transformer Vector Groups, Standards

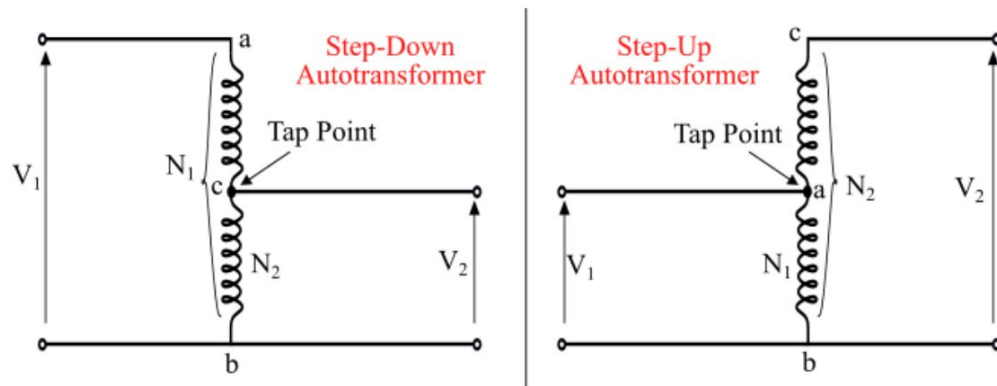


- The complete format for the vector groups is given in either IEEE Std C57.12.70-2020 or IEC 60076-1.
 - Both of these standards require that the first field in the vector group is the high voltage winding, followed by the medium voltage winding, and then the lowest voltage winding (for a three winder)
 - The standards also specify that the high-voltage winding has a phase displacement of 0 (12 o'clock position)
- Other software packages use a slightly different format in which the symbols are organized base on the From/To bus values, and the first phase displacement does not need to be zero.
- Simulator supports both formats including for input and output.

Autotransformers



- In an autotransformer part of the winding is common to both the primary and the secondary windings.
- Advantages are they more cost effective with smaller size and higher efficiency; a disadvantage is they do not provide electrical isolation.
- Autotransformers are widely used including in the transmission system.



Modeling Transformer Wye-Delta Phase Shifts



- In three-phase power systems it is very common to have two winding transformers that employ wye-connected windings on one side and delta-connected windings on the other, or to have three winding transformers with a combination of wye and delta windings.
 - Such connections introduce phase shifts with multiples of 30°
- In a standard (positive sequence) power flow these phase shifts do not need to be modeled; however, increasingly they are being modeled by explicitly adding multiple of 30° phase shifts to the transformers.
 - This results in corresponding phase shifts in the solution angles
- To help keep track of these phase shifts, PowerWorld has introduced a new data type known as Phase Shift Groups (PSGs).

Phase Shift Groups (PSGs)



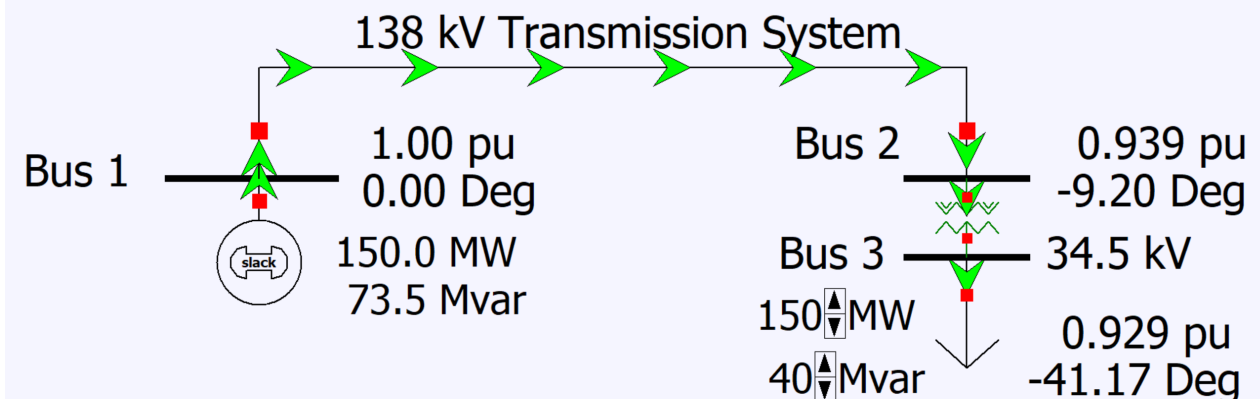
- A PSG is defined as the set of boundary transformers that are modeled as having a specific phase shift, and the lower voltage, radial subnetwork buses affected by this phase shift.
 - A simple, and quite common example, is single generator connected to the transmission system through a generator step-up transformer (GSU) that is grounded-wye on the high side, and delta on the low side
 - Another simple example is a radial load modeled with a step-down transformer
 - However, PSGs can contain larger subnetworks with many buses and several boundary transformers (e.g., a 34.5 kV network)
- A PSG can contain another PSG, having an even lower voltage.
- Transformers can only be part of the boundary for a single PSG, but buses can be in multiple PSGs.

Simple PSG Example



- The below oneline shows an example in which a load is served through a 138/34.5 kV transformer (connected delta-grounded wye) in which the lower voltage lags the transmission system by 30 degrees
 - This is modeled in the power flow by having a 30 degree phase shift the Bus 2 (From) to Bus 3 (To) transformer
 - This phase shift does not need to be modeled, and has no impact on the power flow solution other than shifting the Bus 3 voltage angle; however, commonly they are modeled

- Here the PSG has a single boundary transformer and a single bus (i.e., Bus 3)



Phase Shift Groups Dialog



- PSGs are only calculated and shown in the **Run Mode**.
- To view all the PSGs in a case select **Tools, Connections, Find Phase Shift Groups** to display the Phase Shift Groups Dialog.
 - The below example is for a recent WECC case, with the bus numbers sequentially renumbered to obscure the actual system components

Phase Shift Groups

Phase Shift Groups Count: 613 Check for Likely Invalid Groups In Update Update Phase Shift Groups Update Time (Sec.) 0.004

Total Transformers Count: 623 Only Check Multiple of 30 Degree Shifts Set All Group Phase Shifts to Zero (Except Not Likely Invalid)

Total Buses in Groups : 667 Likely Invalid Count: 2 Setup Phase Shifts Groups Using Transformer Vector Groups

Find Bus Number in Group Bus Number Close

Find Group with Bus Number Help

Find Group with Boundary Bus Number

Records Set Columns Options

ID Number ▲	Transformer Count	Bus Count	Phase Shift (Degrees)	High Side Nominal kV	Highest Nominal kV	Transformer ID First	Minimum Bus Number	Maximum Bus Number	Is Three-Winder Group	Likely Invalid	Vector Group	# of Generators	Gen MW	# of Loads	Load MW	# of Switched Shunts	Shunt Mvar (switched)
1	1	1	-30	34.50	0.69	526 TO 573 CK	573	573	No	NO		1	0.00	0	0.00	0	0.00
2	1	1	30	34.50	0.69	527 TO 526 CK	527	527	No	NO		1	0.00	0	0.00	0	0.00
3	3	1	-30	34.50	0.69	543 TO 528 CK	528	528	No	NO		1	0.00	0	0.00	0	0.00
4	4	1	-30	34.50	0.69	543 TO 542 CK	542	542	No	NO		1	0.00	0	0.00	0	0.00
5	5	1	-30	34.50	0.69	546 TO 550 CK	550	550	No	NO		1	0.00	0	0.00	0	0.00
6	6	1	30	34.50	0.69	547 TO 546 CK	547	547	No	NO		1	0.00	0	0.00	0	0.00
7	7	1	30	34.50	0.69	552 TO 549 CK	552	552	No	NO		1	0.00	0	0.00	0	0.00
8	8	1	30	34.50	0.69	553 TO 549 CK	553	553	No	NO		1	0.00	0	0.00	0	0.00
9	9	1	-30	34.50	0.69	555 TO 556 CK	556	556	No	NO		1	0.00	0	0.00	0	0.00
10	10	1	-30	34.50	0.69	555 TO 590 CK	590	590	No	NO		1	0.00	0	0.00	0	0.00
11	11	1	-30	34.50	0.69	564 TO 565 CK	565	565	No	NO		1	10.20	0	0.00	0	0.00
12	12	1	-30	34.50	0.69	566 TO 524 CK	524	524	No	NO		1	49.19	0	0.00	0	0.00
13	13	1	-30	34.50	0.69	589 TO 529 CK	529	529	No	NO		1	50.81	0	0.00	0	0.00
14	14	1	-30	34.50	13.80	794 TO 795 CK	794	794	Yes	NO	VNan0d0	0	0.00	0	0.00	1	0.00

Switched Shunts and SVCs



- Switched capacitors and sometimes reactors are widely used at both the transmission and distribution levels to supply or (for reactors) absorb discrete amounts of reactive power.
- Static var compensators (SVCs) are also used to supply continuously varying amounts of reactive power.
- In the power flow SVCs are sometimes represented as PV buses with zero real power.



Switched Shunt Control



- The status of switched shunts can be handled in an outer loop algorithm, similar to what is done for LTCs and phase shifters.
 - Because they are discrete they need to regulate a value to a voltage range
- Switches shunts often have multiple levels that need to be simulated.
- Switched shunt control also interacts with the LTC and PV control.
- The power flow modeling needs to take into account the control time delays associated with the various devices.

Switched Shunt System Design



- Because switched shunts tend to have a local impact, there needs to be a coordinated design in their implementation at the transmission level.
 - Shunt capacitors used to raise the voltage, shunt reactors used to lower the voltage; used with LTCs and gens
- Often in the transmission system they are switched manually by a system operator.
- The size and number of banks depends
 - Change in the system voltages caused by bank switching
 - The availability of different sizes
 - Cost for the associated switchgear and protection system

Switched Shunt Sizing



- A goal with switched shunt sizing is to avoid human irritation caused by excessive changes in lighting.
- IEEE Std 1453-2015 gives guidance on the percentage of voltage changes as a function of time; Table 3 of the standard suggests keeping the voltage changes below about 3%.
- We determine analytic methods to calculate this percentage later in the semester.

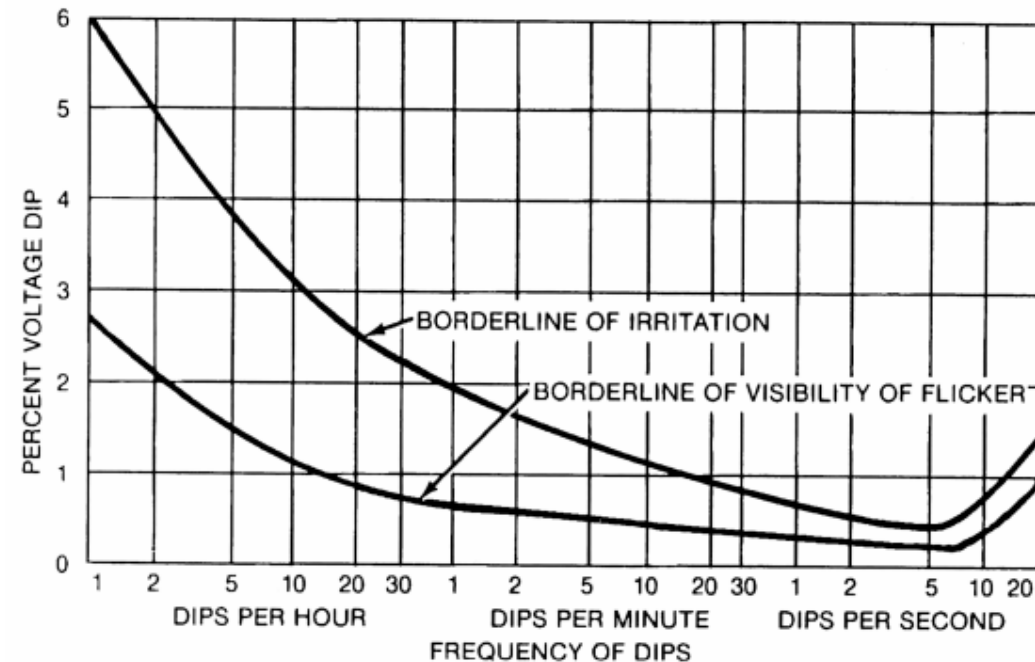


Image from IEEE Std. 1453-2015, "IEEE Recommended Practice for Measurement and Limits of Voltage Fluctuations and Associated Light Flicker on AC Power Systems"

Dynamic Reactive Capability



- Switched shunts are often used to maintain adequate dynamic reactive power from generators and SVCs.
- FERC Order 827 (from June 2016, titled “Reactive Power Requirements for Non-Synchronous Generation”) states that the power factor of generators should be between 0.95 leading to 0.95 lagging.
 - Hence the absolute value of the Mvar output of the machines should be no more than 31% of the MW output
 - Often a value substantially better for reactive reserves
- Switched shunts are used to keep the generator power factor within this range.

Area Interchange Control



- The purpose of area interchange control is to regulate or control the interchange of real power between specified areas of the network.
- Under area interchange control, the mutually exclusive subnetworks, the so-called areas, that make up a power system need to be explicitly represented.
- These areas may be particular subnetworks of a power grid or may represent various interconnected systems.
- The specified net power out of each area is controlled by the generators within the area.
- A power flow may have many more areas than balancing authority areas.

Area Interchange Control

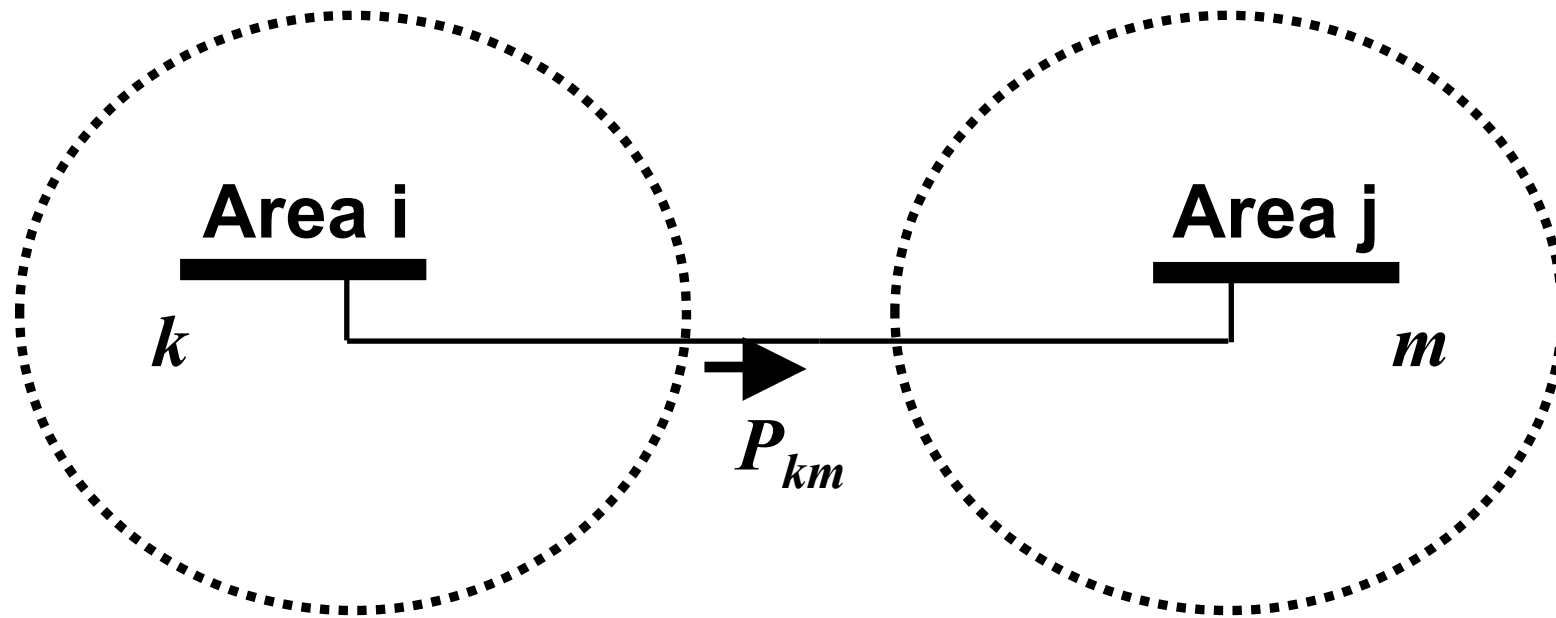


- The net power interchange for an area is the algebraic sum of all its tie line real power flows.
- We denote the real power flow across the tie line from bus k to bus m by P_{km}
- We use the convention that $P_{km} > 0$ if power leaves node k and $P_{km} \leq 0$ otherwise.
- Thus the net area interchange S_i of area i is positive (negative) if area i exports (imports).
- Consider the two areas i and j that are directly connected by the single tie line (k, m) with the node k in area i and the node m in area j .

Net Power Interchange



- Then, for the complex power interchange S_i , we have a sum in which P_{km} appears with a positive sign; for the area j power interchange it appears with a negative sign.



Area i exports P_{km} and Area j imports P_{km}

Net Power Interchange



- Since each tie line flow appears twice in the net interchange equations, it follows that if the power system as a distinct areas, then

$$\sum_{i=1}^a S_i = 0$$

- Consequently, the specification of S_i for a collection of $(a-1)$ areas determines the system interchange; we must leave the interchange for one area unspecified.
 - This is usually (but not always) the area with the system slack bus

Modeling Area Interchange



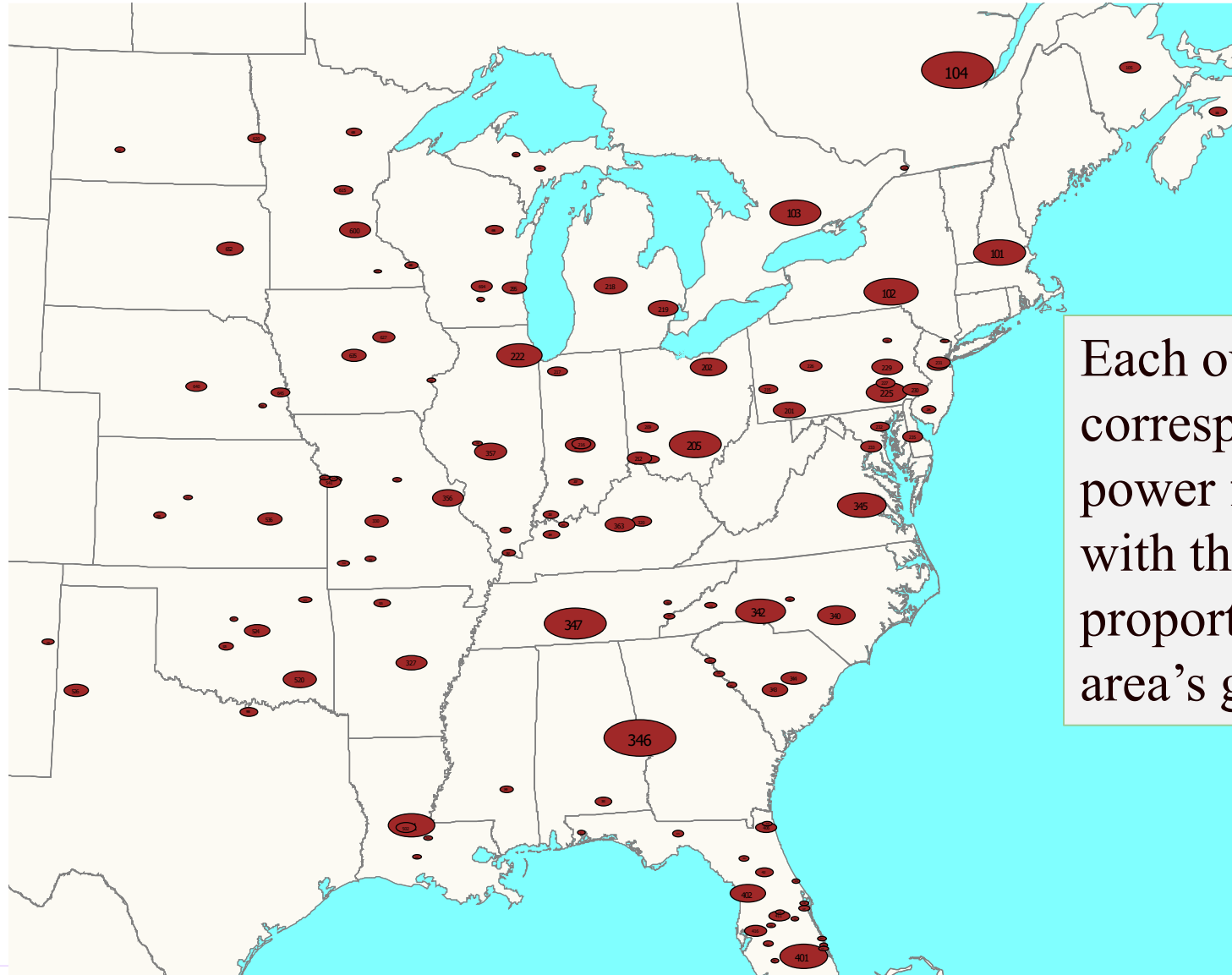
- Area interchange is usually modeled using an outer loop control.
- The net generation imbalance for an area can be handled using several different approaches.
 - Specify a single area slack bus, and the entire generation change is picked up by this bus; this may work if the interchange difference is small
 - Pick up the change at a set of generators in the area using constant participation factors; each generator gets a share
 - Use some sort of economic dispatch algorithm, so how generation is picked up depends on an assumed cost curve
 - Min/max limits need to be enforced

Including Impact on Losses



- A change in the generation dispatch can also change the system losses. These incremental impacts need to be included in an area interchange algorithm.
- We'll discuss the details of these calculations later in the course when we consider sensitivity analysis.

Example Large System Areas



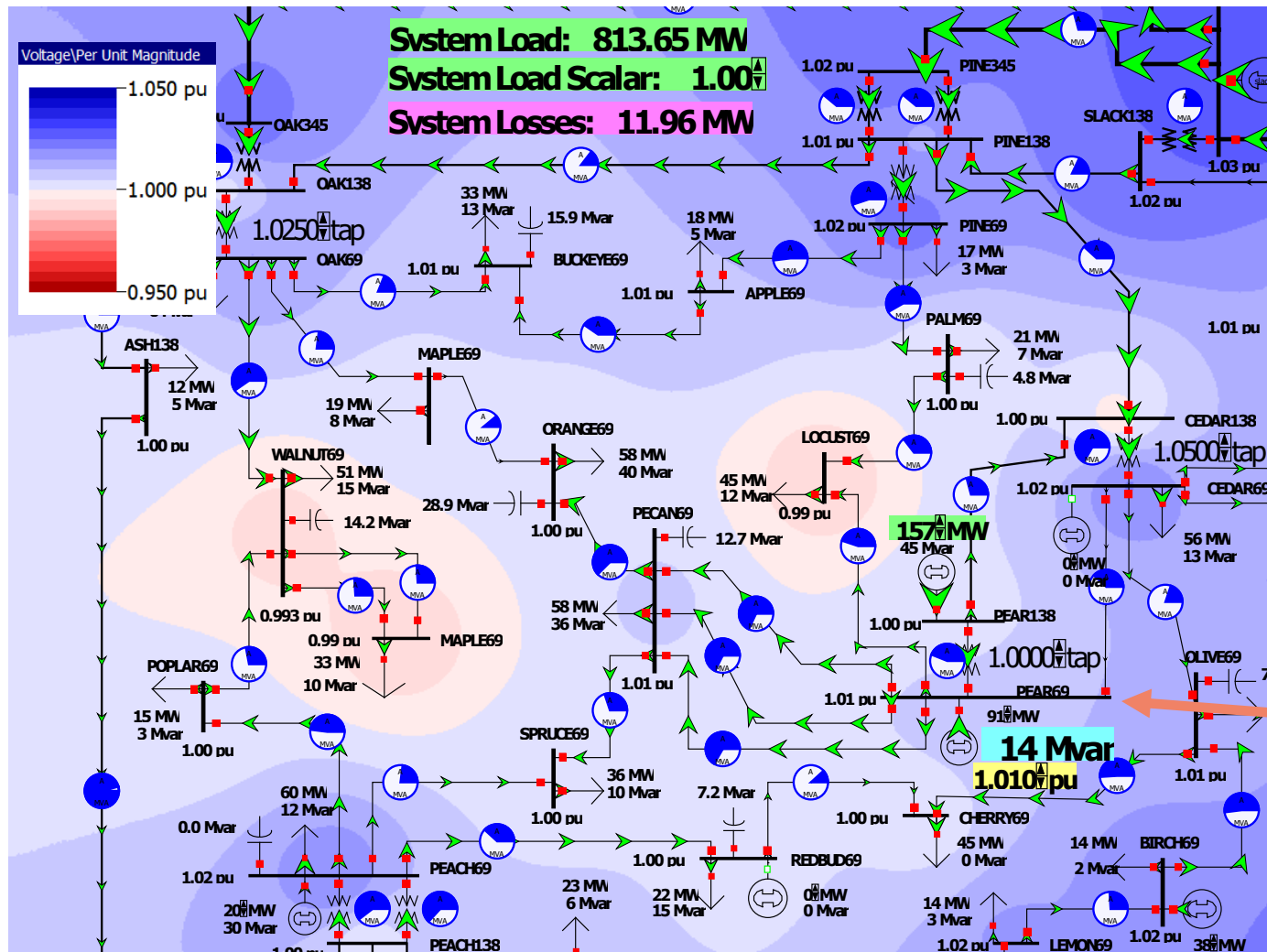
Each oval corresponds to a power flow area with the size proportional to the area's generation.

Generator Volt/Reactive Control



- Simplest situation is a single generator at a bus regulating its own terminal.
 - Either PV, modeled as a voltage magnitude constraint, or as a PQ with reactive power fixed at a limit value. If PQ the reactive power limits can vary with the generator MW output
- Next simplest is multiple generators at a bus. Obviously, they need to be regulating the bus to the same voltage magnitude
 - From a power flow solution perspective, it is similar to a single generator, with limits being the total of the individual units
 - Options for allocation of vars among generators; this can affect the transient stability results

Generator Voltage Control



This example uses the case **PSC_37Bus** with a voltage contour. Try varying the voltage setpoint for the generator at PEAR69.

Generator Remote Bus Voltage Control



- Next complication is generators at a single bus regulating a remote bus; usually this is the high side of their generator step-up (GSU) transformer.
 - When multiple generators regulate a single point their exciters need to have a dual input
 - This can be implemented in the power flow for the generators at bus j regulating the voltage at bus k by changing the bus j voltage constraint equation to be

$$|V_k| - V_{k,set} = 0$$

(however, this does create a zero on the diagonal of the Jacobian)

- Helps with power system voltage stability

Reactive Power Sharing Options



Options

Power Flow Solution

Common Options Advanced Options Island-Based AGC DC Options General Storage

Dynamically add/remove slack buses as topology is changed
 Evaluate Power Flow Solution For Each Island

Define Post Power Flow Solution Actions

Power Flow (Inner) Loop Options

Disable Power Flow Optimal Multiplier
 Initialize from Flat Start Values

Minimum Per Unit Voltage for

Constant Power Loads 0.000
Constant Current Loads 0.000

Control (Middle) Loop Options

Disable Treating Continuous SSs as PV Buses
 Disable Balancing of Parallel LTC Taps
 Model Phase Shifters as Discrete Controls
 Disable Transformer Tap Control if Tap Sens. is the Wrong Sign (Normally Check This)
Min. Sensitivity for LTC Control 0.0500

Pre-Processing

Disable Angle Smoothing

Post-Processing

Disable Angle Rotation Processing

Sharing of generator vars across groups of buses during remote regulation

Allocate across buses using the user-specified remote regulation percentages
 Allocate so all generators are at same relative point in their [min .. max] var range
 Allocate across buses using the SUM OF user-specified remote regulation percentages

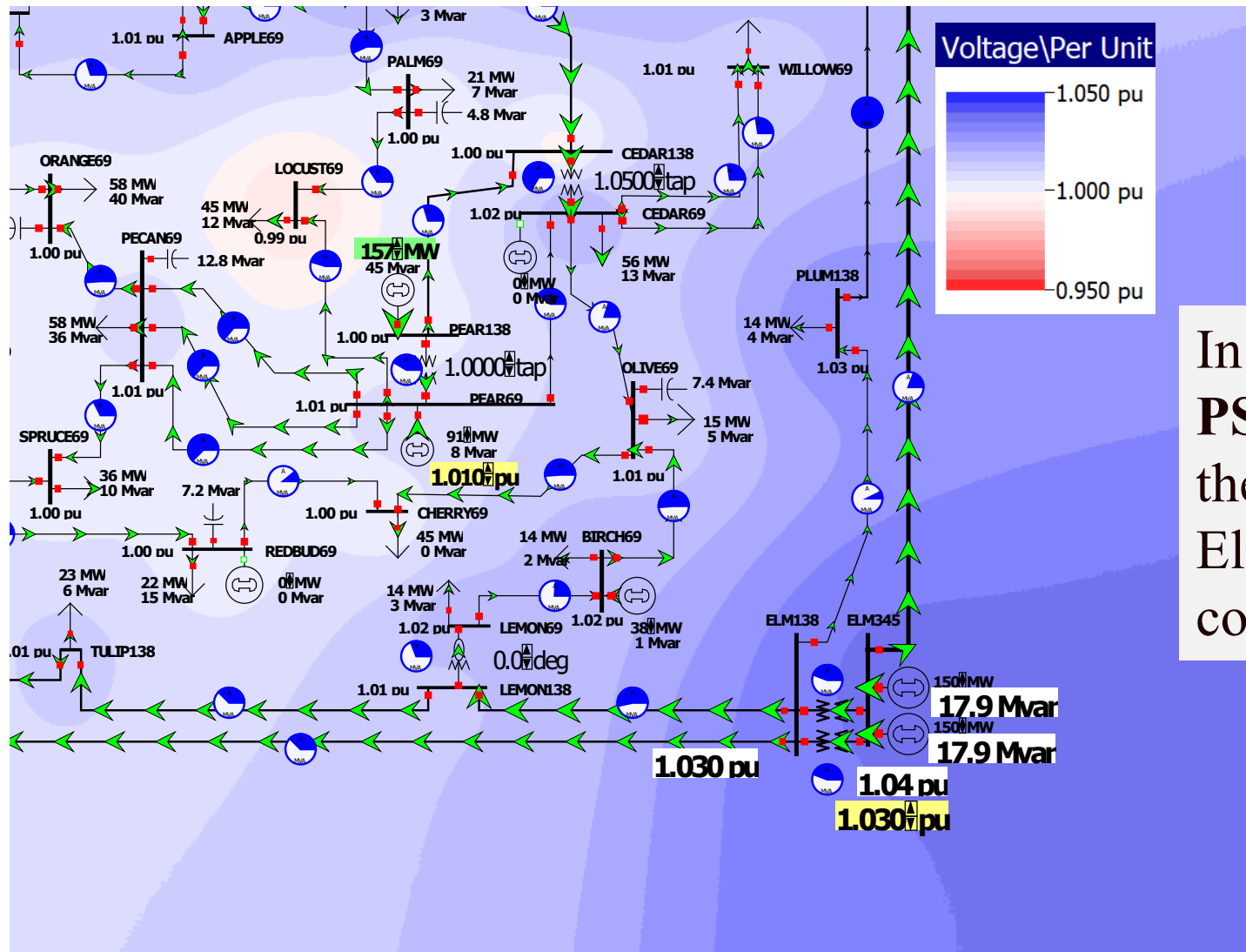
ZBR Threshold 0.000200

Options for Areas on Economic Dispatch

Include Loss Penalty Factors in ED
 Enforce Convex Cost Curves in ED

Different software packages use different approaches for allocating the reactive power; PowerWorld has several options.

Reactive Power Sharing



In this example, case **PSC_37Bus_Varsharing**, the two generators at Elm345 are jointly controlling Elms138.

Generator Remote Bus Voltage Control



- The next complication is to have the generators at multiple buses doing coordinated voltage control.
 - Controlled bus may or may not be one of the terminal buses
- There must be an a priori decision about how much reactive power is supplied by each bus; example allocations are a fixed percentage or placing all generators at the same place in their regulation range.
- Implemented by designating one bus as the master; this bus models the voltage constraint.
- All other buses are treated as PQ, with the equation including a percent of the total reactive power output of all the controlling bus generators.

Power Flow Topology Processing



- Commercial power flow software must have algorithms to determine the number of asynchronous, interconnected systems in the model.
 - These separate systems are known as Islands
 - In large system models such as the Eastern Interconnect it is common to have multiple islands in the base case (one recent EI model had nine islands)
 - Islands can also form unexpectedly as a result of contingencies
 - Power can be transferred between islands using dc lines
 - Each island must have a slack bus

Power Flow Topology Processing



- Anytime a status change occurs the power flow must perform topology processing to determine whether there are either 1) new islands or 2) islands have merged.
- Determination is needed to determine whether the island is “viable.” That is, could it truly function as an independent system, or should the buses just be marked as dead.
 - A quite common occurrence is when a single load or generator is isolated; in the case of a load it can be immediately killed; generators are more tricky

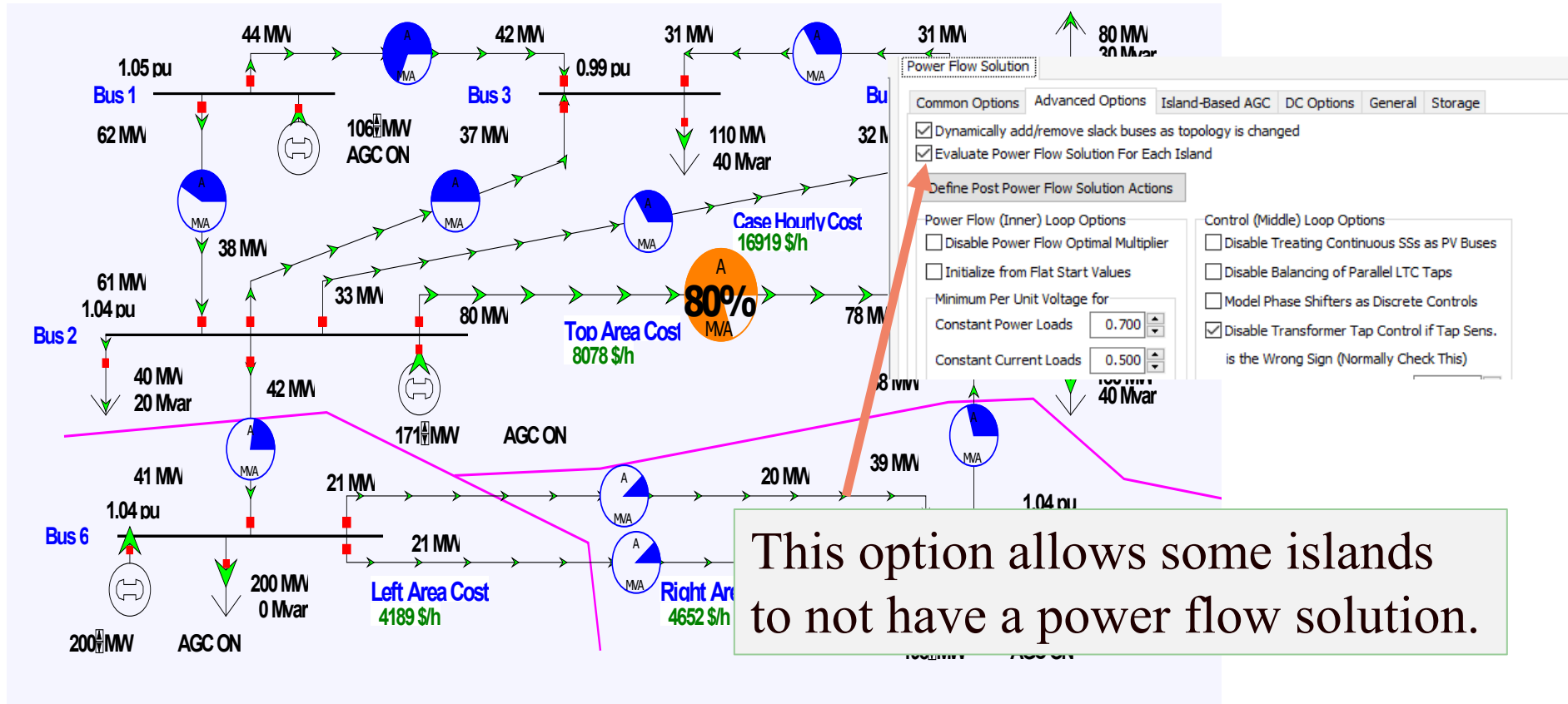
Topology Processing Algorithm



- Since topology processing is performed often, it must be quick (order $n \ln(n)$)!
- Simple, yet quick topology processing algorithm is as follows:
 - Set all buses as being in their own island (equal to bus number)
 - Set ChangeInIslandStatus true
 - While ChangeInIslandStatus Do
 - Go through all the in-service lines, setting the islands for each of the buses to be the smaller island number; if the island numbers are different set ChangeInIslandStatus true
 - Determine which islands are viable, assigning a slack bus as necessary

This algorithm does depend on the depth of the system.

Example of Island Formation



This option allows some islands to not have a power flow solution.

Splitting large systems requires a careful consideration of the flow on the island tie-lines as they are opened.

Bus Branch versus Node Breaker



- Due to a variety of issues during the 1970's and 1980's the real-time operations and planning stages of power systems adopted different modeling approaches.

Real-Time Operations

Use detailed node/breaker model
EMS system as a set of integrated applications and processes
Real-time operating system
Real-time databases

Planning

Use simplified bus/branch model
PC approach
Use of files
Stand-alone applications

Entire data sets and software tools developed around these two distinct power system models.

Google View of a 345 kV Substation



Substation Configurations



- Several different substation breaker/disconnect configurations are common:
- Single bus: simple but a fault anywhere requires taking out the entire substation; also doing breaker or disconnect maintenance requires taking out the associated line.

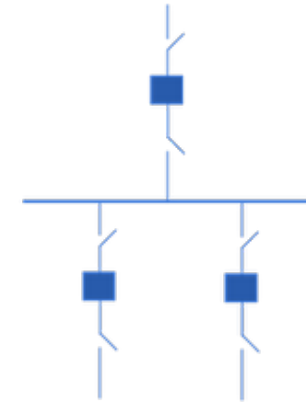


Fig B: Single Bus

Substation Configurations, cont.



- Main and Transfer Bus:
Now the breakers can be taken out for maintenance without taking out a line, but protection is more difficult, and a fault on one line will take out at least two.
- Double Bus Breaker:
Now each line is fully protected when a breaker is out, so high reliability, but more costly.

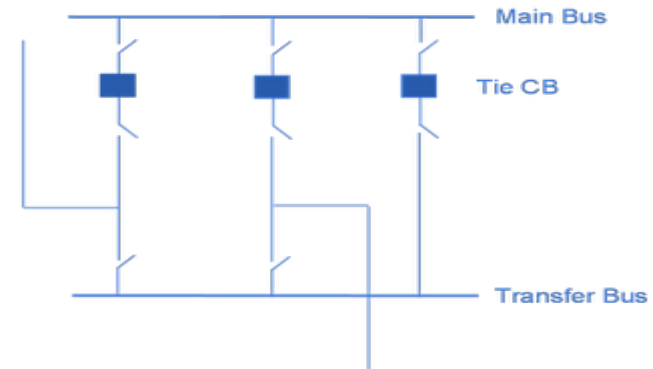


Fig C: Main and Transfer Bus

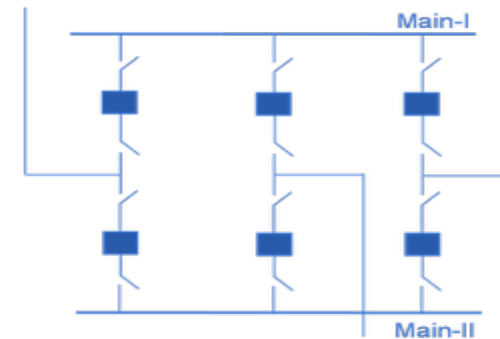


Fig D: Double Bus Double Breaker

Ring Bus, Breaker and Half



- As the name implies with a ring bus the breakers form a ring; number of breakers is same as number of devices; any breaker can be removed for maintenance.
- The breaker and half has two buses and uses three breakers for two devices; both breakers and buses can be removed for maintenance.

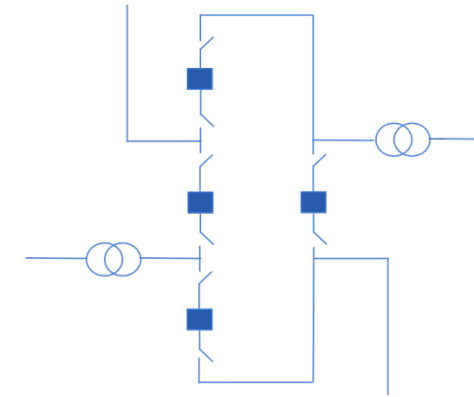


Fig F: Ring Bus

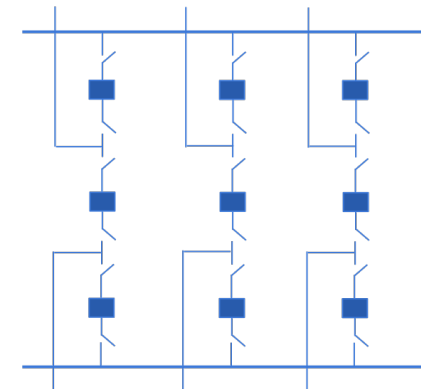


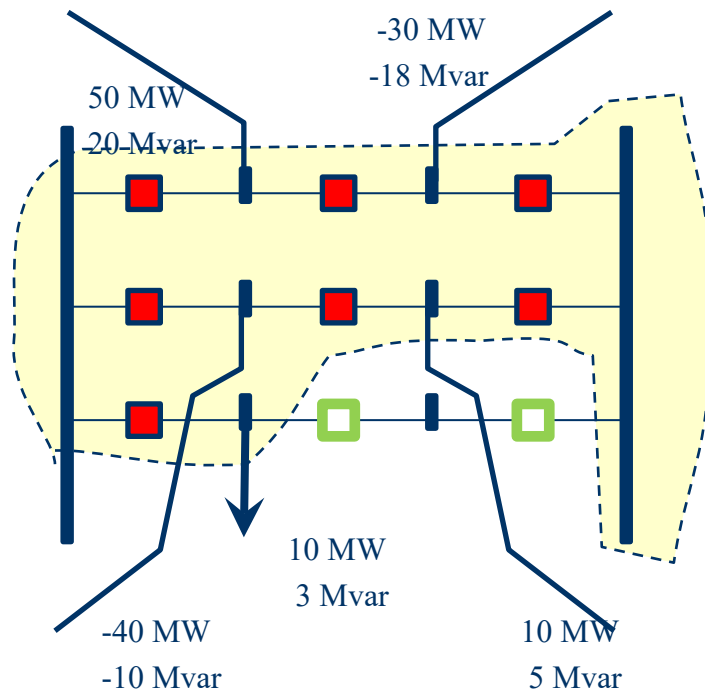
Fig G: Breaker and Half

EMS and Planning Models



- EMS Model

- Used for real-time operations
- Called full topology model
- Has node-breaker detail



- Planning Model

- Used for off-line analysis
- Called consolidated model by PowerWorld
- Has bus/branch detail

