ECEN 615
Methods of Electric Power Systems Analysis

Lecture 7: Advanced Power Flow

Prof. Tom Overbye

Dept. of Electrical and Computer Engineering

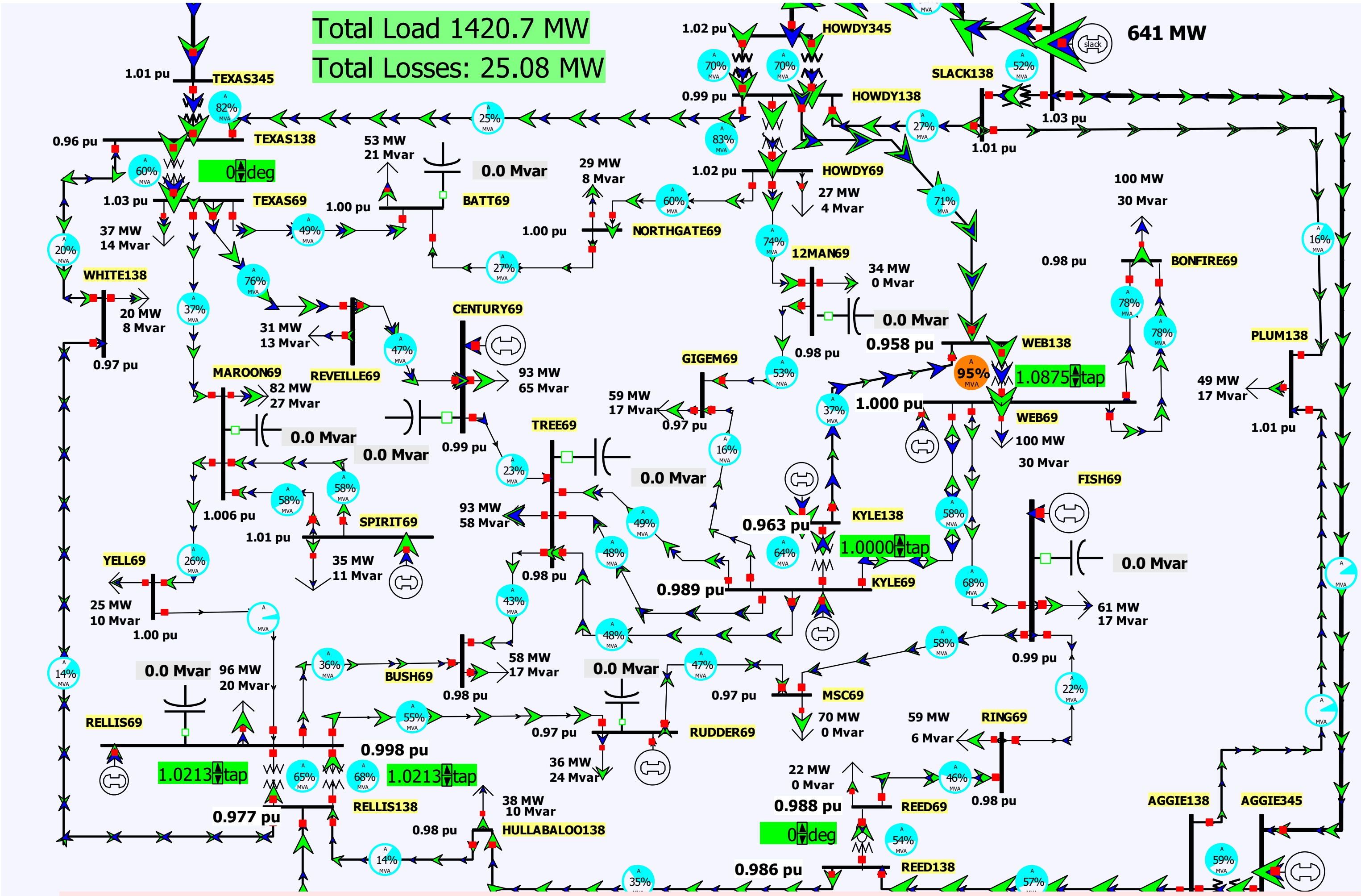
Texas A&M University

overbye@tamu.edu

Announcements

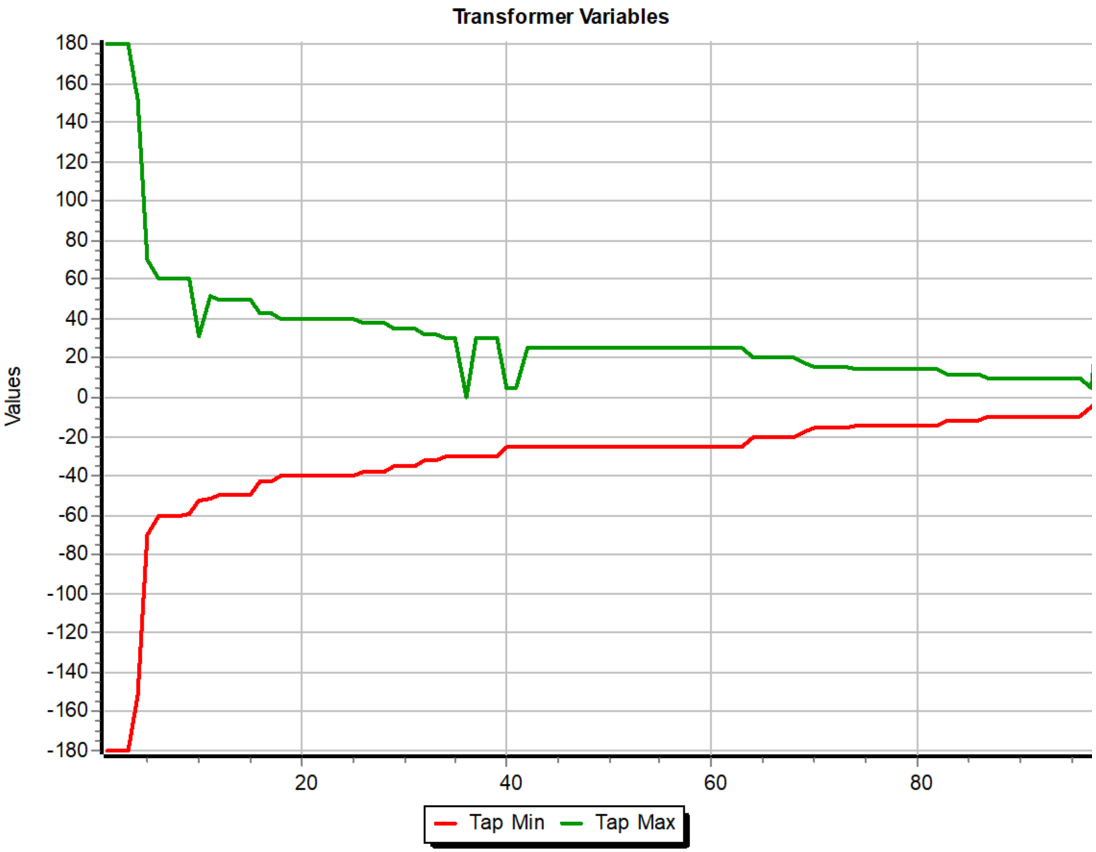
- Read Chapter 6 from the book
  - They formulate the power flow using the polar form for the Y_{bus} elements
- Homework 2 is due on Thursday September 26

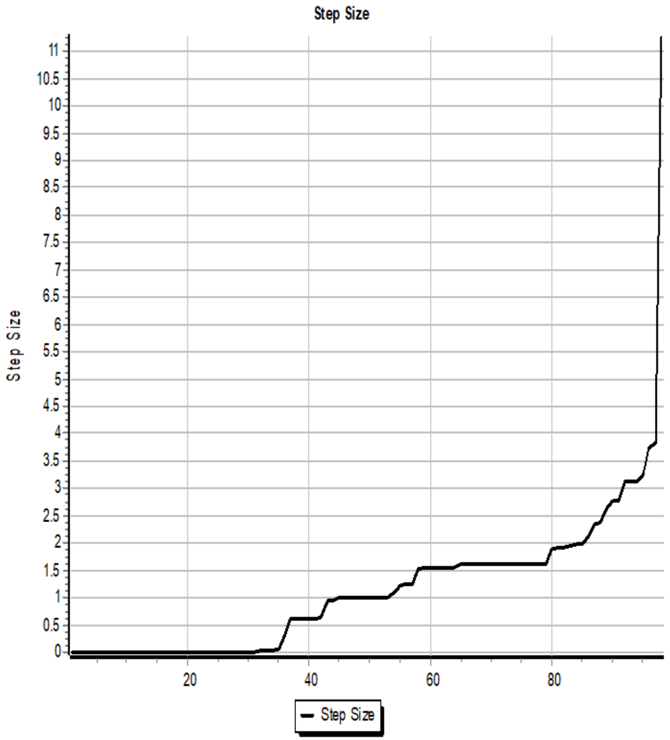
Aggieland37 With Phase Shifters



PowerWorld Case: **Aggieland37_PhaseShifter**

Large Case Phase Shifter Limits and Step Size





Impedance Correction Tables

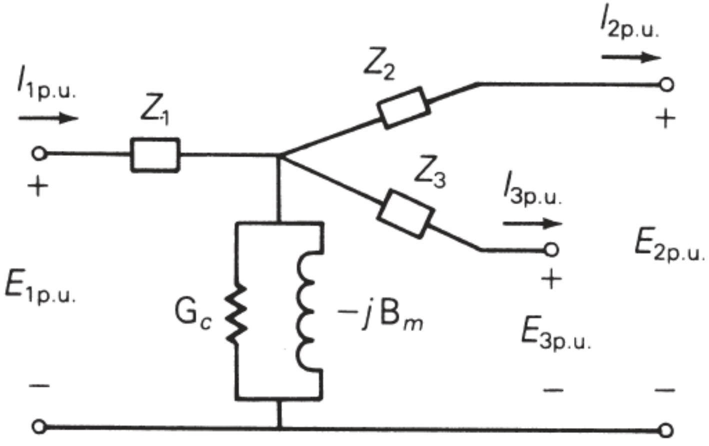
- With taps the impedance of the transformer changes; sometimes the changes are relatively minor and sometimes they are dramatic
  - A unity turns ratio phase shifter is a good example with essentially no impedance when the phase shift is zero
  - Often modeled with piecewise linear function with impedance correction varying with tap ratio or phase shift
  - Next lines give several examples, with format being (phase shift or tap ratio, impedance correction)
    - (-60,1), (0,0.01), (60,1)
    - (-25,2.43),(0,1),(25,2.43)
    - (0.941,0.5), (1.04,1), (1.15,2.45)
    - (0.937,1.64), (1,1), (1.1, 1.427)

Three-Winding Transformers

- Three-winding transformers are very common, with the third winding called the tertiary
  - The tertiary is often a delta winding
- Three-winding transformers have various benefits
  - Providing station service
  - Place for a capacitor connection
  - Reduces third-harmonics
  - Allows for three different transmission level voltages
  - Better handling of fault current

Three-Winding Transformers

- Usually modeled in the power flow with a star equivalent; the internal "star" bus does not really exist
- Star bus is often given a voltage of 1.0 or 999 kV



Per-unit equivalent circuit—practical transformer

Impedances calculated using the wye-delta transform can result in negative resistance (about 900 out of 97,000 in EI model)

The winding impedances are measured between the windings with one winding shorted and the other open; for example Z_{12} is measured from 1 with winding 2 shorted, 3 open

Image from *Power System Analysis and Design*, by Glover, Overbye, and Sarma 6th Edition

Three-Winding Transformer Example

EXAMPLE 3.9

Three-winding single-phase transformer: per-unit impedances

The ratings of a single-phase three-winding transformer are

winding 1: 300 MVA, 13.8 kV
winding 2: 300 MVA, 199.2 kV
winding 3: 50 MVA, 19.92 kV

The leakage reactances, from short-circuit tests, are

$X_{12} = 0.10$ per unit on a 300-MVA, 13.8-kV base
$X_{13} = 0.16$ per unit on a 50-MVA, 13.8-kV base
$X_{23} = 0.14$ per unit on a 50-MVA, 199.2-kV base

Winding resistances and exciting current are neglected. Calculate the impedances of the per-unit equivalent circuit using a base of 300 MVA and 13.8 kV for terminal 1.

SOLUTION

$S_{base} = 300$ MVA is the same for all three terminals. Also, the specified voltage base for terminal 1 is $V_{base1} = 13.8$ kV. The base voltages for terminals 2 and 3 are then $V_{base2} = 199.2$ kV and $V_{base3} = 19.92$ kV, which are the rated voltages of these windings. From the data given, $X_{12} = 0.10$ per unit was measured from terminal 1 using the same base values as those specified for the circuit. However, $X_{13} = 0.16$ and $X_{23} = 0.14$ per unit on a 50-MVA base are first converted to the 300-MVA circuit base.

(*Continued*)

$Z_{12} = Z_1 + Z_2$

$Z_{13} = Z_1 + Z_3$

$Z_{23} = Z_2 + Z_3$

Hence

$Z_1 = 0.5(Z_{12}+Z_{13}-Z_{23})$

$Z_2 = 0.5(Z_{12}+Z_{23}-Z_{13})$

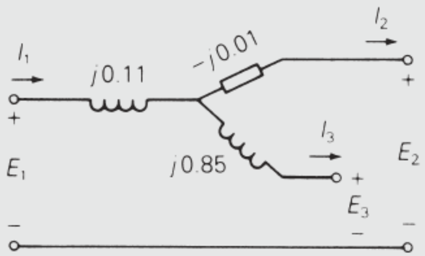
$Z_3 = 0.5(Z_{13}+Z_{23}-Z_{12})$

Image from *Power System Analysis and Design*, by Glover, Overbye, and Sarma 6th Edition

Three-Winding Transformer Example, cont.

FIGURE 3.21

Circuit for Example 3.9



$$X_{13} = (0.16)\left(\frac{300}{50}\right) = 0.96 \quad \text{per unit}$$

$$X_{23} = (0.14)\left(\frac{300}{50}\right) = 0.84 \quad \text{per unit}$$

Then, from (3.6.8) through (3.6.10),

$$X_1 = \tfrac{1}{2}(0.10 + 0.96 - 0.84) = 0.11 \quad \text{per unit}$$

$$X_2 = \tfrac{1}{2}(0.10 + 0.84 - 0.96) = -0.01 \quad \text{per unit}$$

$$X_3 = \tfrac{1}{2}(0.84 + 0.96 - 0.10) = 0.85 \quad \text{per unit}$$

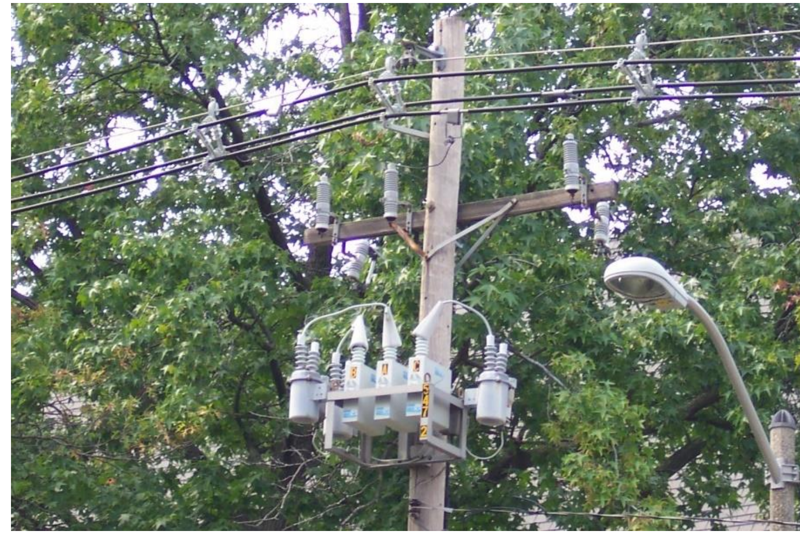
The per-unit equivalent circuit of this three-winding transformer is shown in Figure 3.21. Note that X_2 is negative. This illustrates the fact that X_1, X_2, and X_3 are *not* leakage reactances, but instead are equivalent reactances derived from the leakage reactances. Leakage reactances are always positive.

Note also that the node where the three equivalent circuit reactances are connected does not correspond to any physical location within the transformer. Rather, it is simply part of the equivalent circuit representation.

Image from *Power System Analysis and Design*, by Glover, Overbye, and Sarma 6th Edition

When Transformers go Bad

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

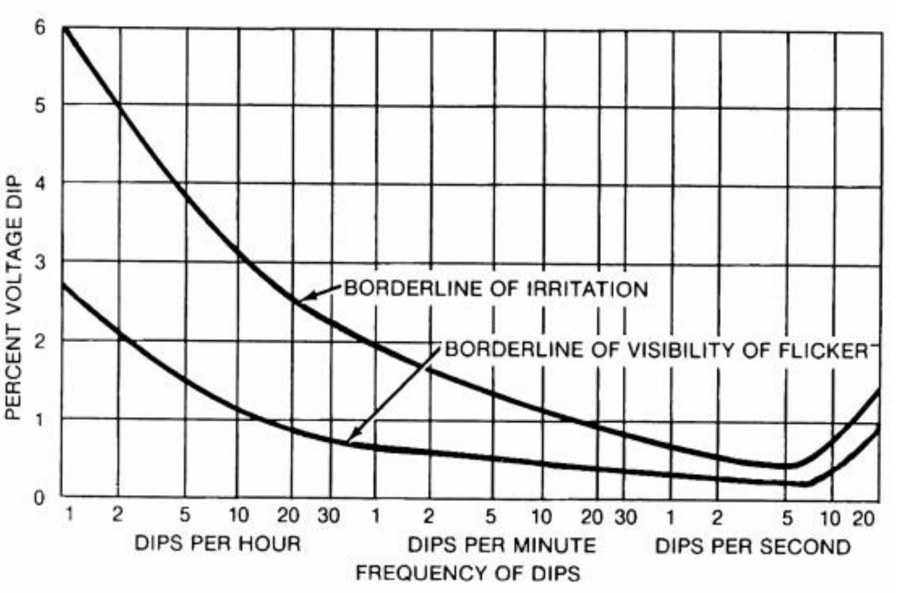
- The status of switched shunts can be handled in an outer loop algorithm, similar to what is done for LTCs and phase shifters
  - Because they are discrete they need to regulate a value to a voltage range
- Switches shunts often have multiple levels that need to be simulated
- Switched shunt control 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

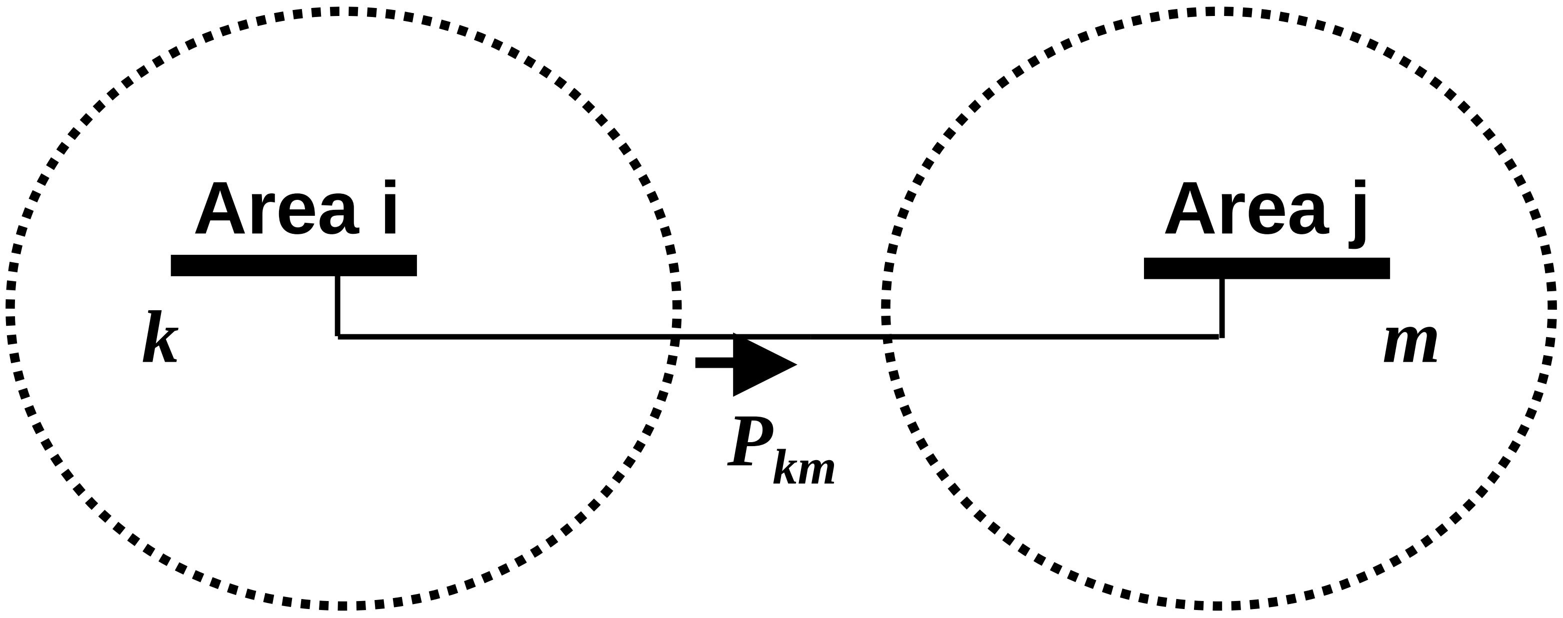
- The purpose of area interchange control is to regulate or control the interchange of real power between specified areas of the network
- Under area interchange control, the mutually exclusive subnetworks, the so-called areas, that make up a power system need to be explicitly represented
- These areas 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

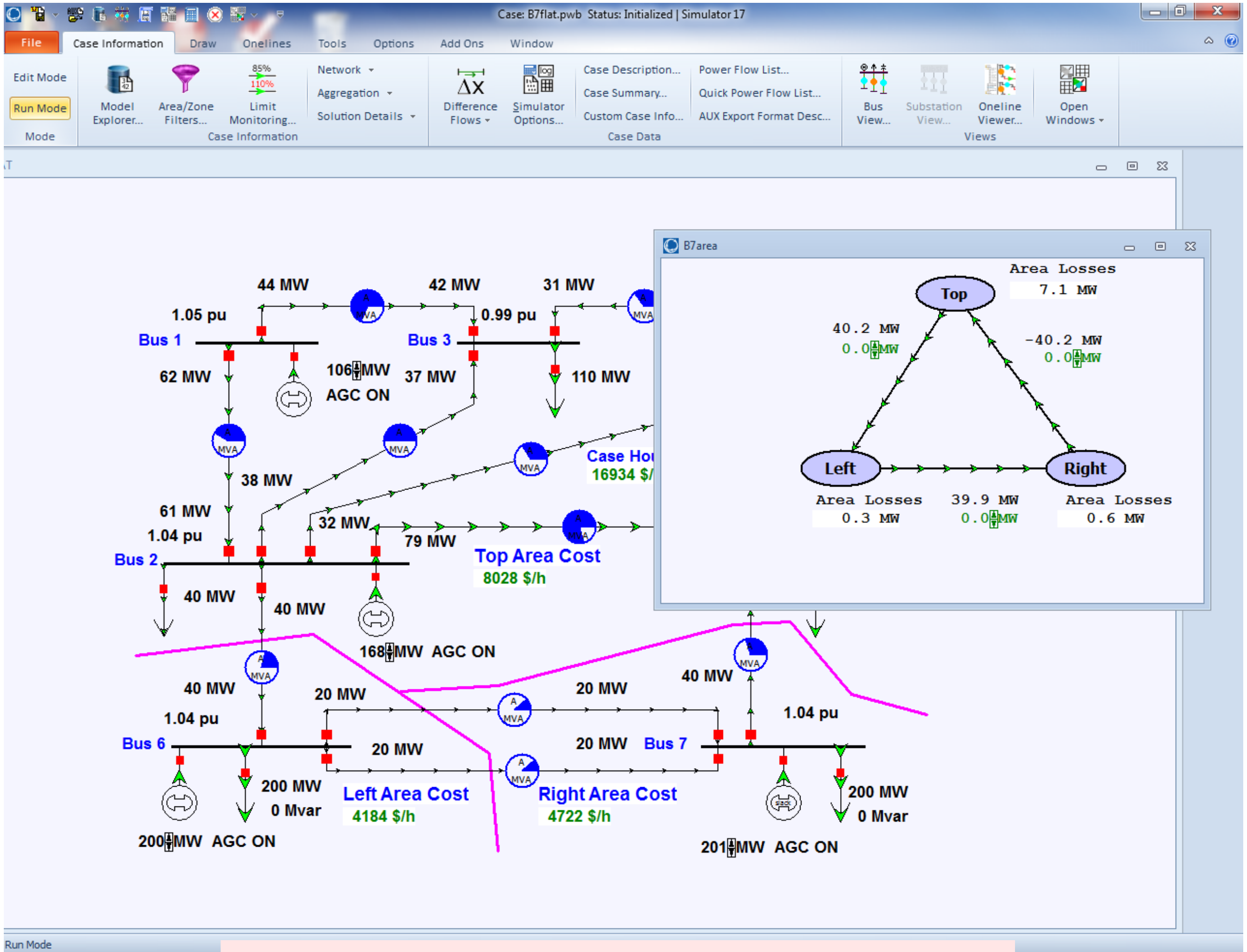
Modeling Area Interchange

- Area interchange is usually modeled using an outer loop control
- The net generation imbalance for an area can be handled using several different approach
  - 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

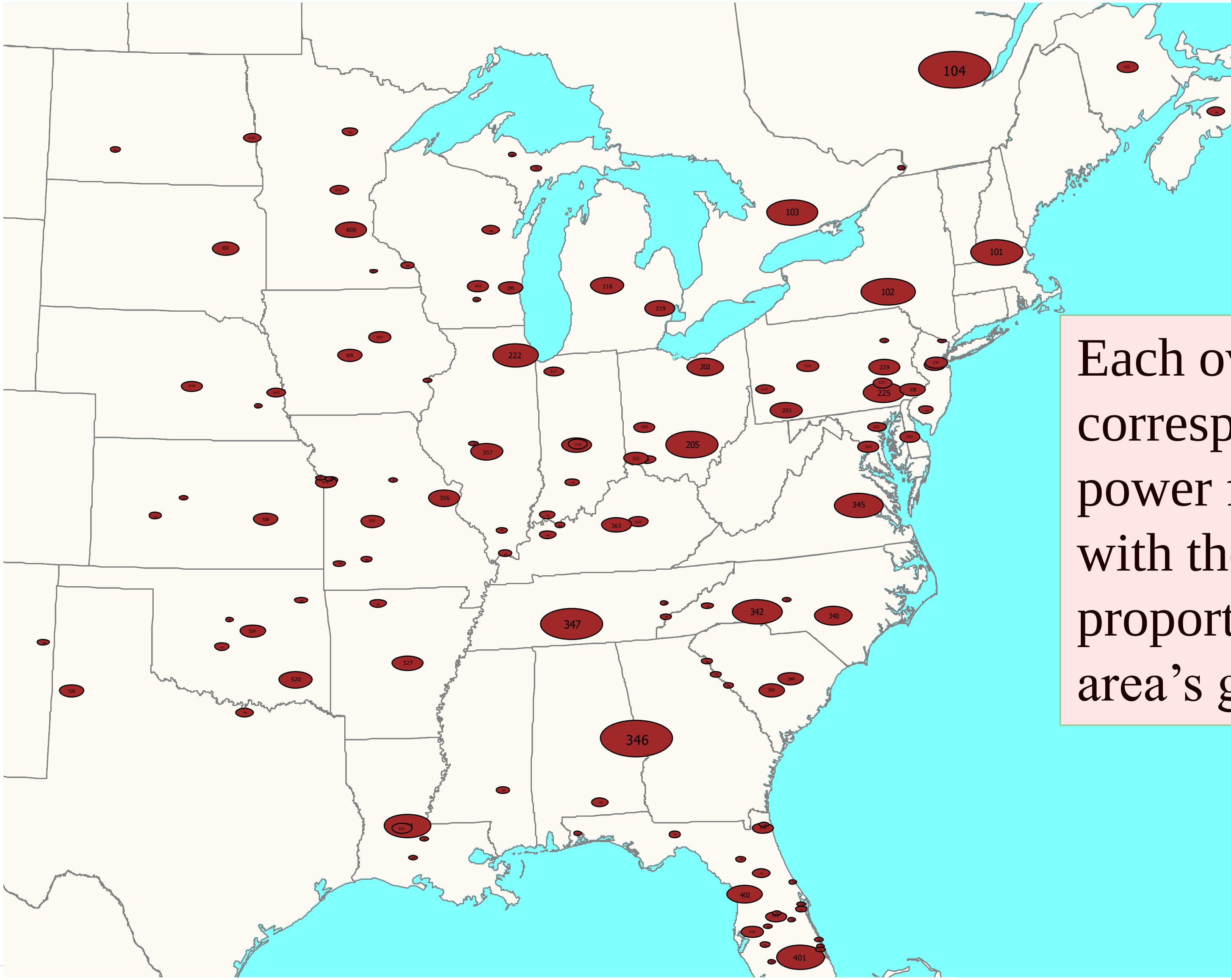
- A change in the generation dispatch can also change the system losses. These incremental impacts need to be included in an area interchange algorithm
- We'll discuss the details of these calculations later in the course when we consider sensitivity analysis

Area Interchange Example: Seven Bus, Three Area System



PowerWorld Case: **B7Flat**

Example Large System Areas

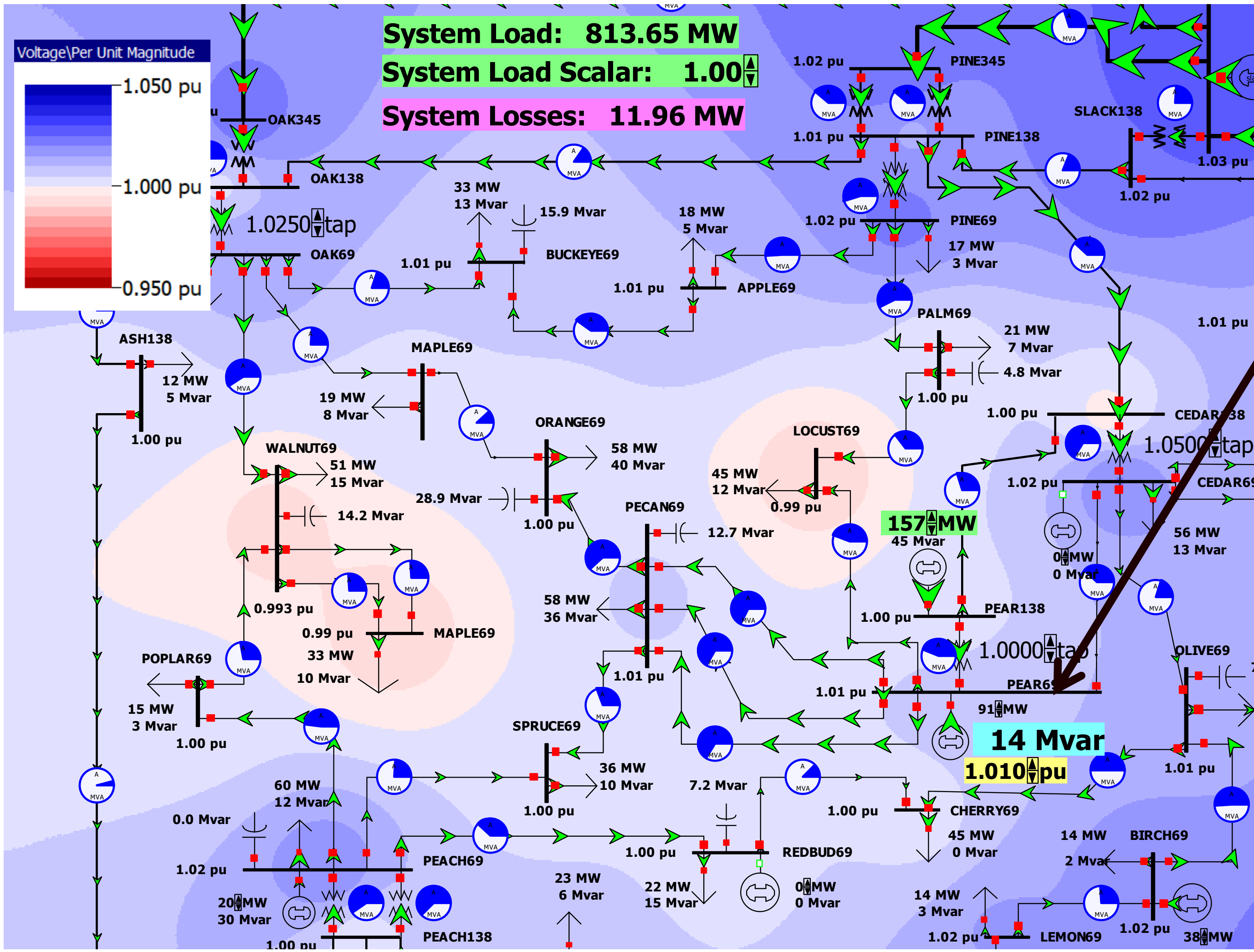


Each oval corresponds to a power flow area with the size proportional to the area's generation

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

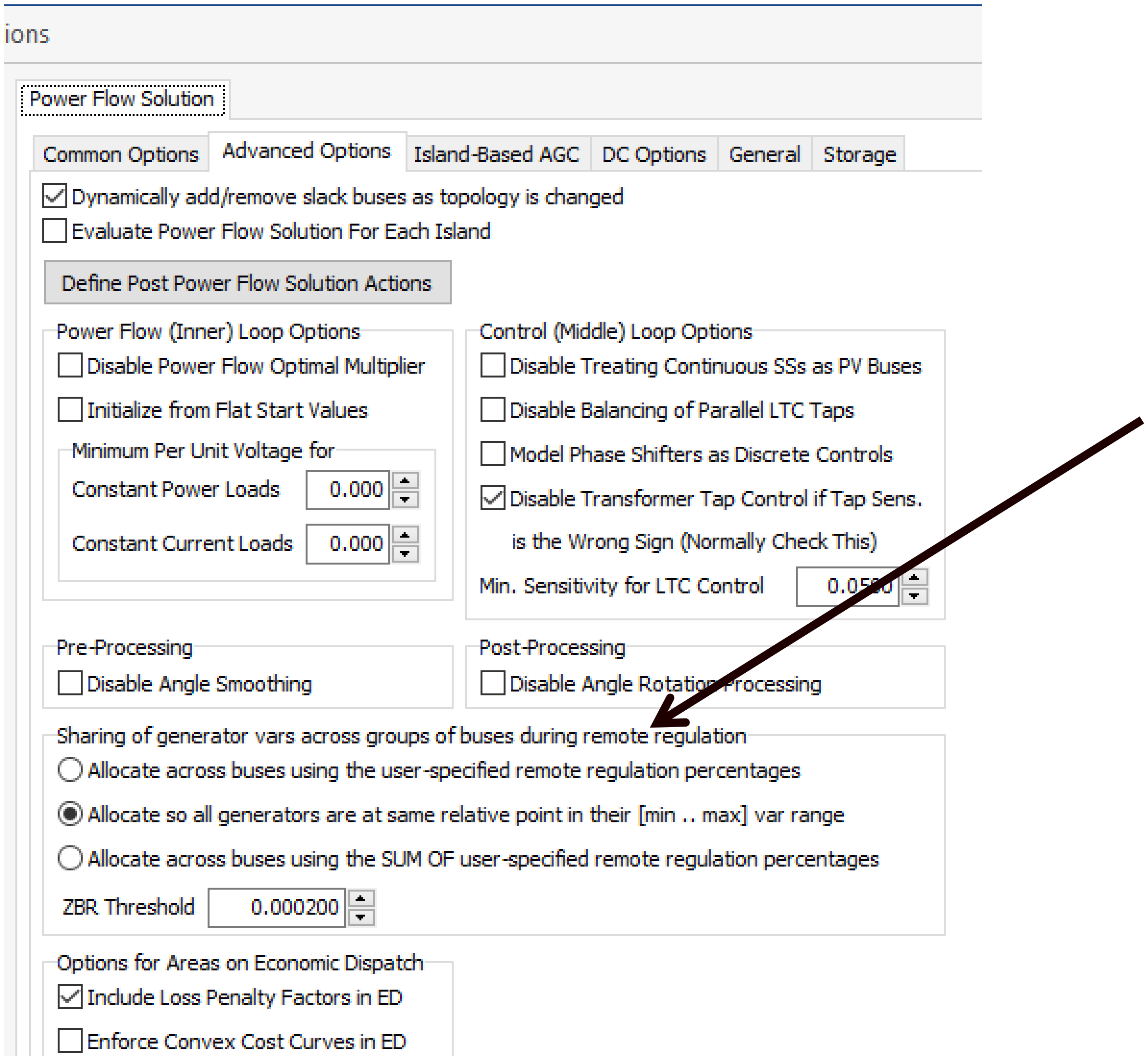
Generator Remote Bus Voltage Control

- 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

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

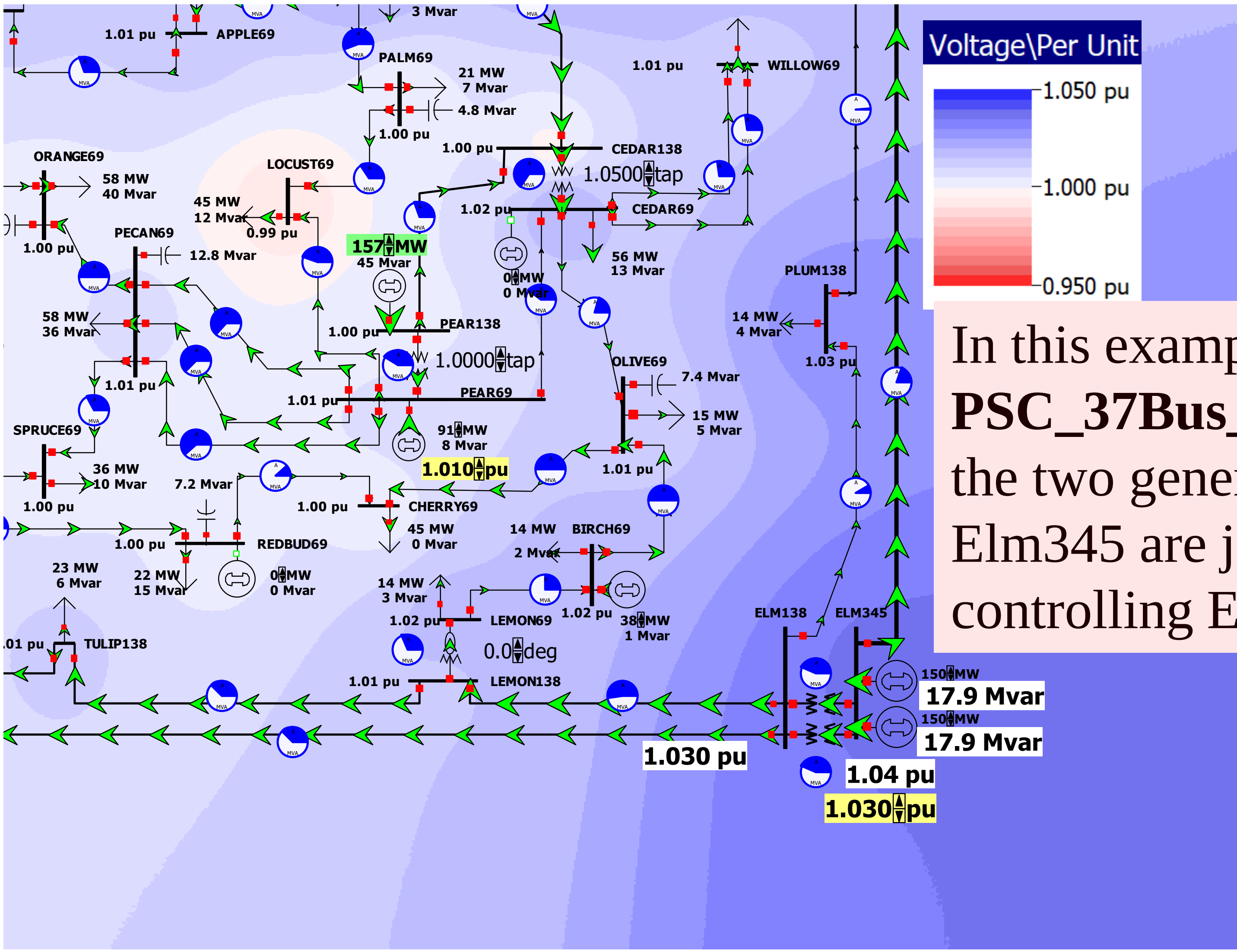
    (however, this does create a zero on the diagonal of the Jacobian)
  - Helps with power system voltage stability

Reactive Power Sharing Options



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

Reactive Power Sharing

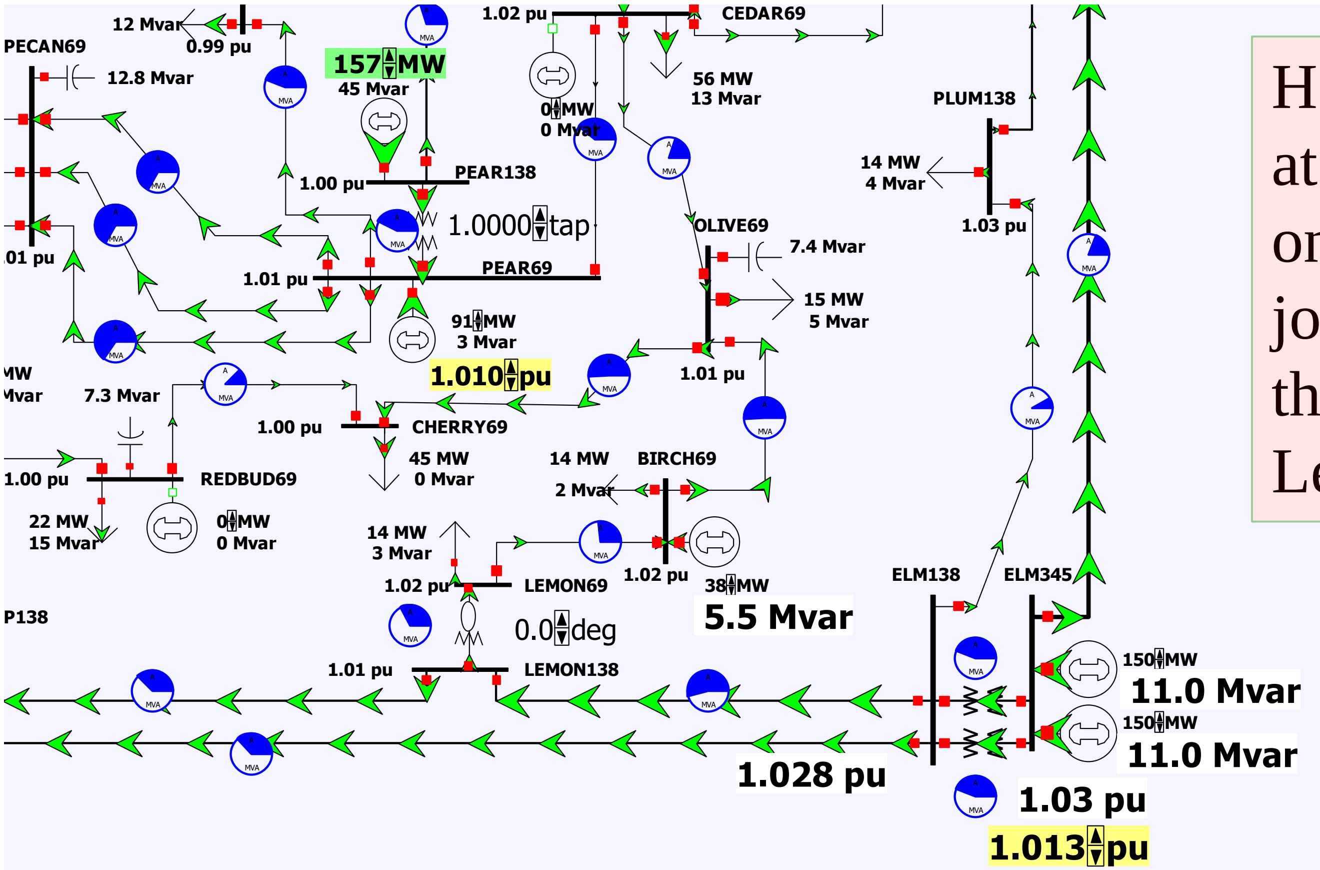


In this example, case **PSC_37Bus_Varsharing**, the two generators at Elm345 are jointly controlling Elms138

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

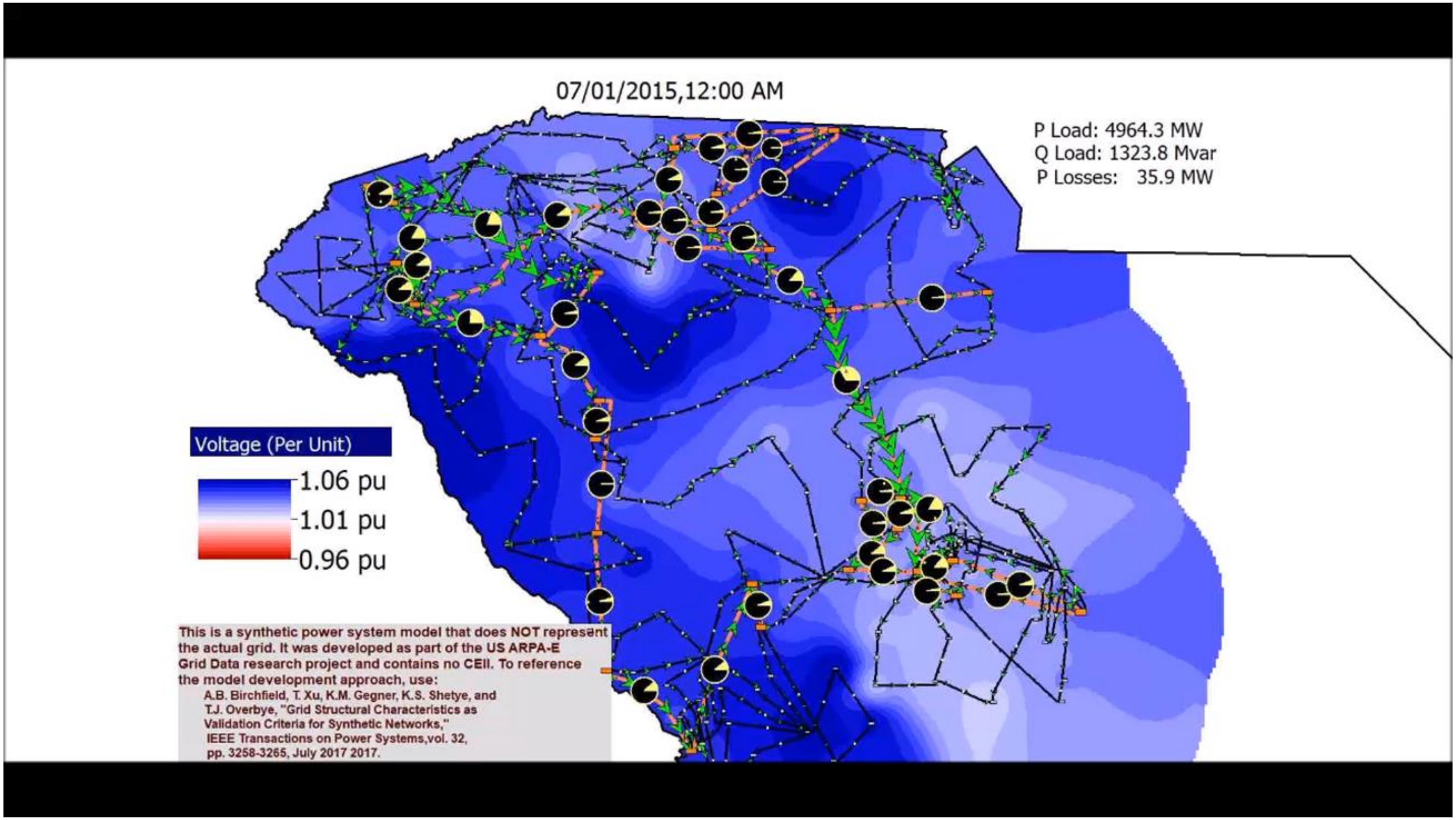
Remote and Coordinated Var Control Example



Here the generators at Elm345 and the one at Birch69 are jointly controlling the voltage at the Lemon138 bus.

Case is **PSC_37Bus_Varsharing_MultipleBuses**

Example of Hourly Voltage Variation Over Time



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

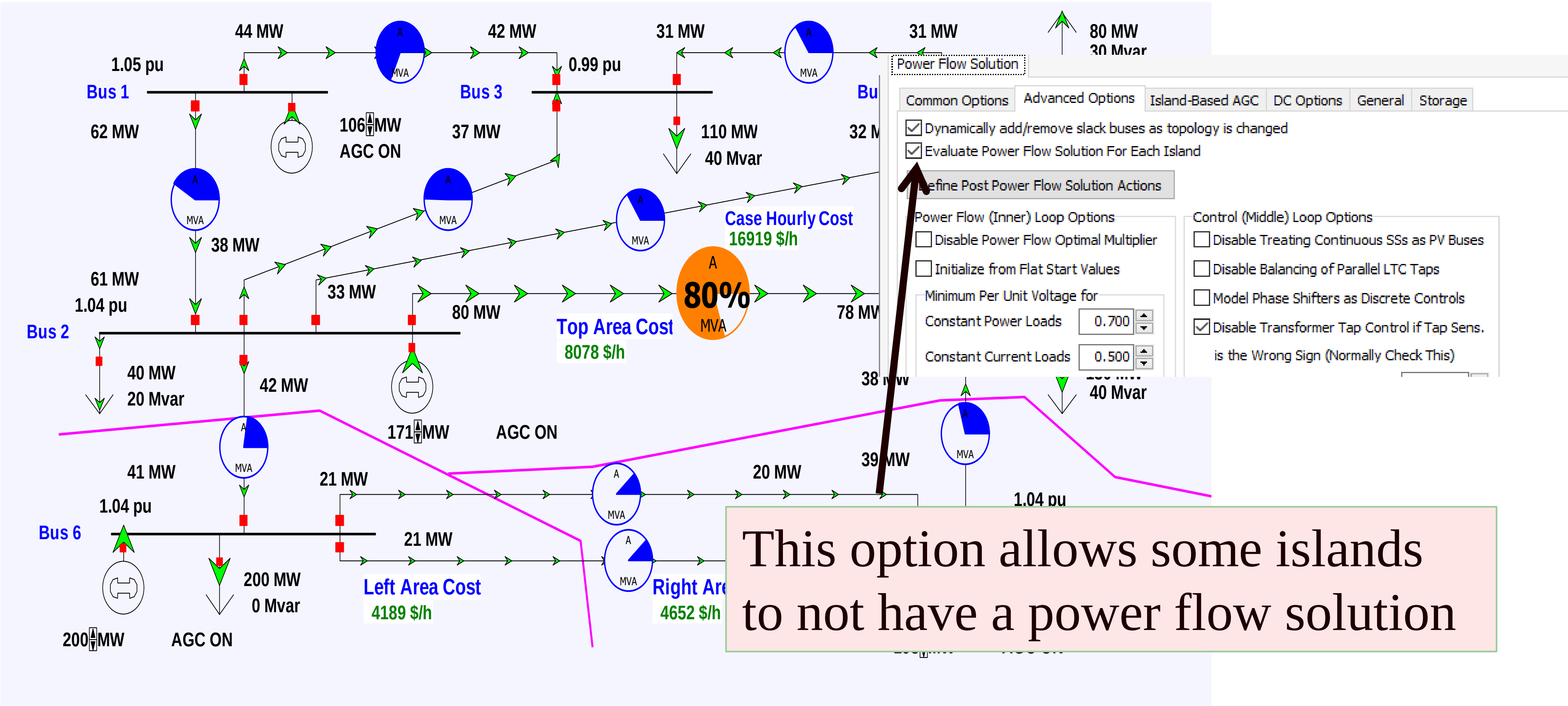
- Anytime a status change occurs the power flow must perform topology processing to determine whether there are either 1) new islands or 2) islands have merged
- Determination is needed to determine whether the island is "viable." That is, could it truly function as an independent system, or should the 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 algoritm
  - 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

Example of Using a Disconnect to Break Load Current