ECEN 615
Methods of Electric Power Systems Analysis

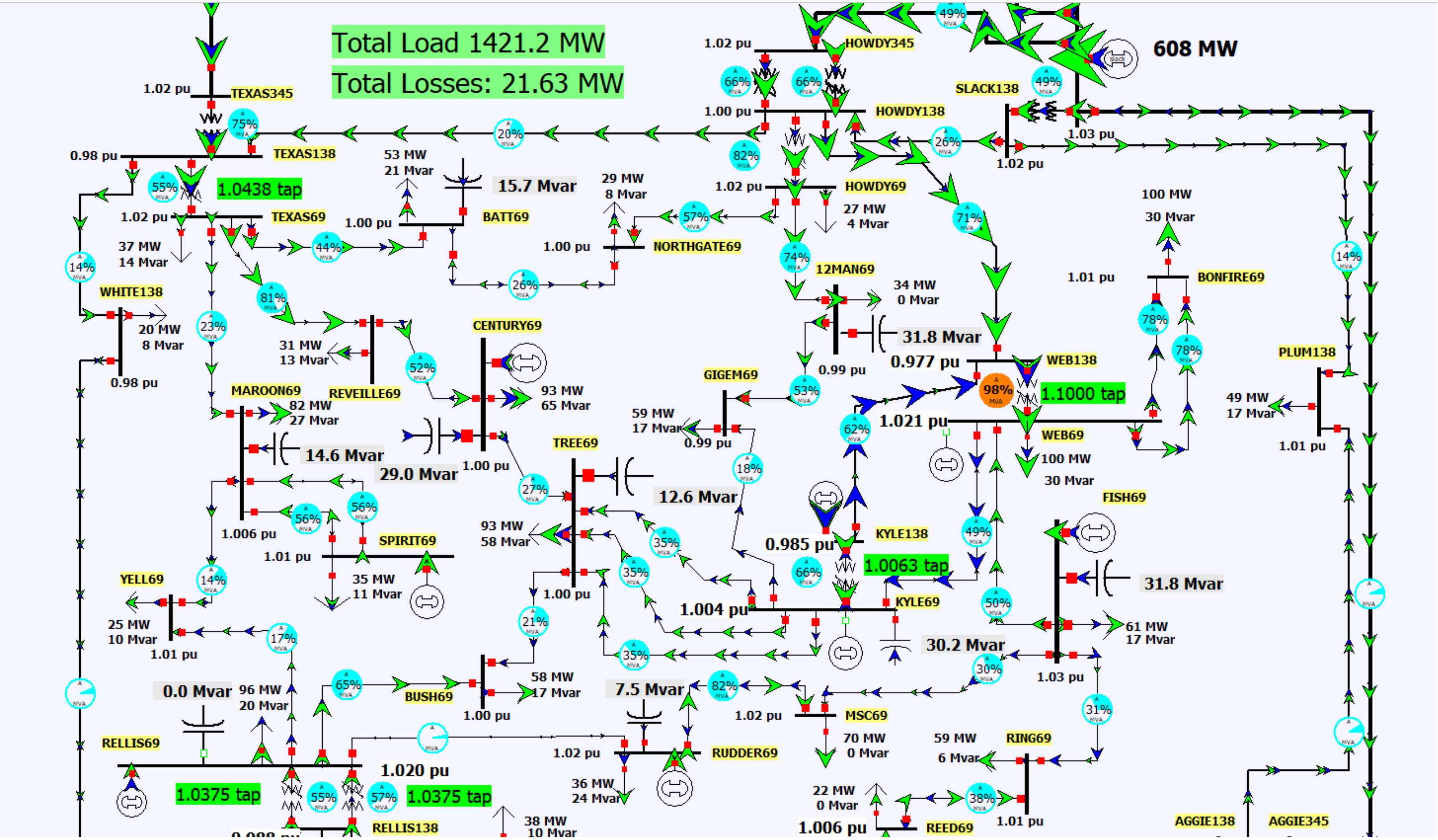
Lecture 8: Advanced Power Flow

Prof. Tom Overbye
Dept. of Electrical and Computer Engineering
Texas A&M University
overbye@tamu.edu

Announcements

- Read Chapter 6
- Homework 2 is due on Sept 27

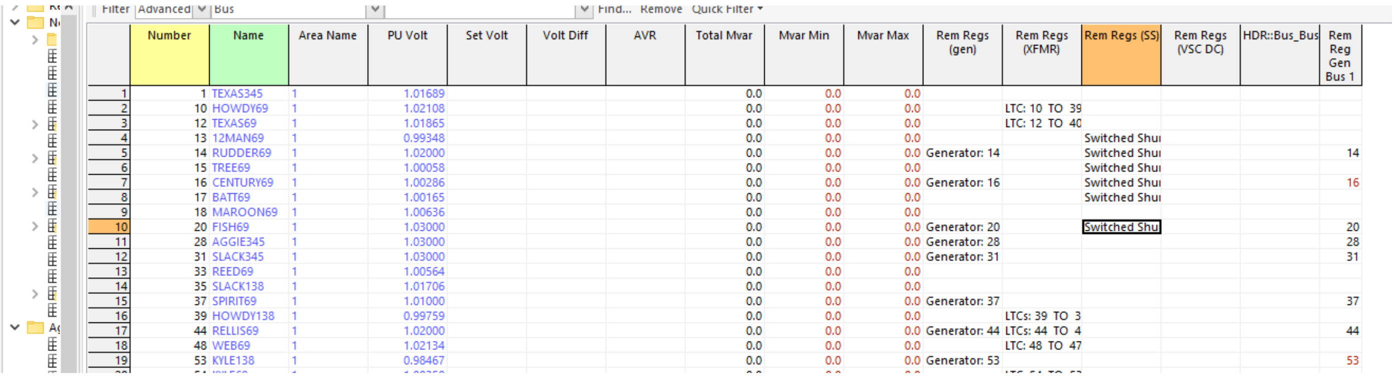
LTC Tap Coordination - Automatic



PowerWorld Case: Aggieland37_LTC_Auto

Coordinated Reactive Control

- A number of different devices may be doing automatic reactive power control. They must be considered in some control priority
  - One example would be 1) generator reactive power, 2) switched shunts, 3) LTCs
- You can see the active controls in PowerWorld with **Case Information, Solution Details, Remotely Regulated Buses**



	Number	Name	Area Name	PU Volt	Set Volt	Volt Diff	AVR	Total Mvar	Mvar Min	Mvar Max	Rem Regs (gen)	Rem Regs (XFMR)	Rem Regs (SS)	Rem Regs (VSC DC)	HDR::Bus_Bus	Rem Reg Gen Bus 1
1	1	TEXAS345	1	1.01689				0.0	0.0	0.0						
2	10	HOWDY69	1	1.02108				0.0	0.0	0.0		LTC: 10 TO 39				
3	12	TEXAS69	1	1.01865				0.0	0.0	0.0		LTC: 12 TO 40				
4	13	12MAN69	1	0.99348				0.0	0.0	0.0			Switched Shu			
5	14	RUDDER69	1	1.02000				0.0	0.0	0.0	Generator: 14		Switched Shu			14
6	15	TREE69	1	1.00058				0.0	0.0	0.0			Switched Shu			
7	16	CENTURY69	1	1.00286				0.0	0.0	0.0	Generator: 16		Switched Shu			16
8	17	BATT69	1	1.00165				0.0	0.0	0.0			Switched Shu			
9	18	MAROON69	1	1.00636				0.0	0.0	0.0						
10	20	FISH69	1	1.03000				0.0	0.0	0.0	Generator: 20		Switched Shu			20
11	28	AGGIE345	1	1.03000				0.0	0.0	0.0	Generator: 28					28
12	31	SLACK345	1	1.03000				0.0	0.0	0.0	Generator: 31					31
13	33	REED69	1	1.00564				0.0	0.0	0.0						
14	35	SLACK138	1	1.01706				0.0	0.0	0.0						
15	37	SPIRIT69	1	1.01000				0.0	0.0	0.0	Generator: 37					37
16	39	HOWDY138	1	0.99759				0.0	0.0	0.0		LTCs: 39 TO 3				
17	44	RELLIS69	1	1.02000				0.0	0.0	0.0	Generator: 44	LTCs: 44 TO 4				44
18	48	WEB69	1	1.02134				0.0	0.0	0.0		LTC: 48 TO 47				
19	53	KYLE138	1	0.98467				0.0	0.0	0.0	Generator: 53					53

Coordinated Reactive Control

- The challenge with implementing tap control in the power flow is it is quite common for at least some of the taps to reach their limits
  - Keeping in mind a large case may have thousands of LTCs!
- If this control was directly included in the power flow equations then every time a limit was encountered the Jacobian would change
  - Also taps are discrete variables, so voltages must be a range
- Doing an outer loop control can more directly include the limit impacts; often time sensitivity values are used
- We’ll return to this once we discuss sparse matrices and sensitivity calculations

Phase-Shifting Transformers

- Phase shifters are transformers in which the phase angle across the transformer can be varied in order to control real power flow
  - Sometimes they are called phase angle regulars (PAR)
  - Quadrature booster (evidently British though I've never heard this term)
- They are constructed by include a delta-connected winding that introduces a 90° phase shift that is added to the output voltage

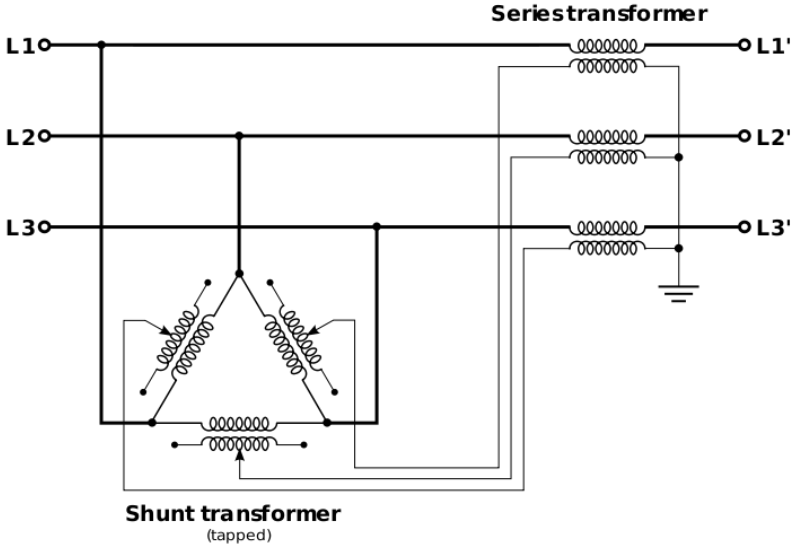


Image: http://en.wikipedia.org/wiki/Quadrature_booster

Phase-Shifter Model

- We develop the mathematical model of a phase shifting transformer as a first step toward our study of its simulation
- Let buses *k* and *m* be the terminals of the phase–shifting transformer, then define the phase shift angle as Φ_{km}
- The latter differs from an off–nominal turns ratio LTC transformer in that its tap ratio is a complex quantity, i.e., a complex number, $t_{km}\angle\Phi_{km}$
- The phase shift angle is a discrete value, with one degree a typical increment

Phase-Shifter Model

- For a phase shifter located on the branch (*k*, *m*), the admittance matrix representation is obtained analogously to that for the LTC

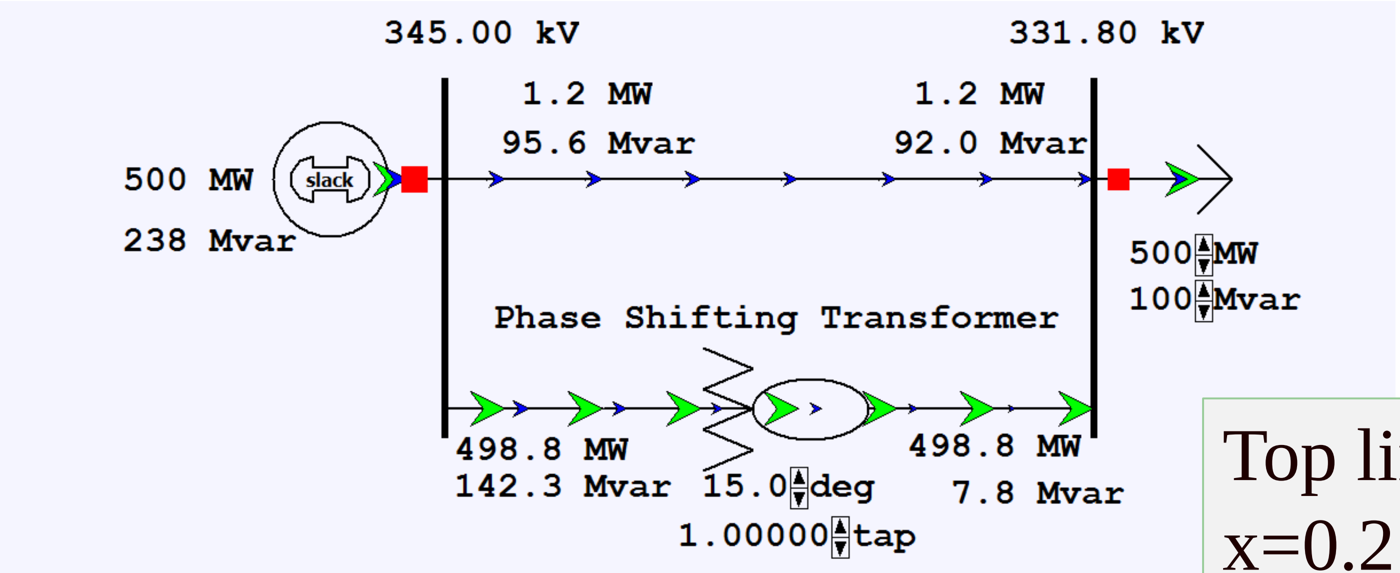
$$\begin{bmatrix} \bar{I}_k \\ \bar{I}_m \end{bmatrix} = \begin{bmatrix} \dfrac{\bar{y}_{km}}{t^2} & -\dfrac{\bar{y}_{km}}{te^{j\phi_{km}}} \\ -\dfrac{\bar{y}_{km}}{te^{-j\phi_{km}}} & \bar{y}_{km} \end{bmatrix} \begin{bmatrix} \bar{E}_k \\ \bar{E}_m \end{bmatrix}$$

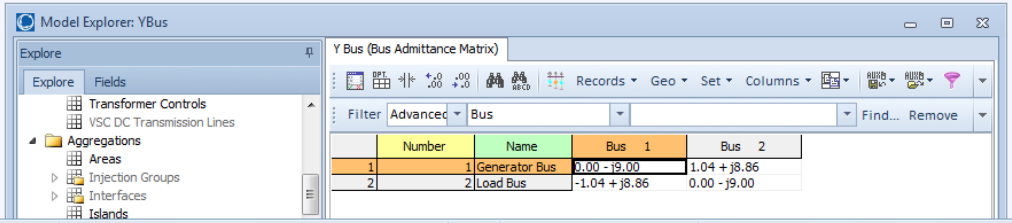
- Note, if there is a phase shift then $\mathbf{Y}_{\text{bus}}$ is no longer symmetric!! In a large case there are almost always some phase shifters. Y-Δ transformers also introduce a phase shift that is often not modeled

Integrated Phase-Shifter Control

- Phase shifters are usually used to control the real power flow on a device
- Similar to LTCs, phase-shifter control can either be directly integrated into the power flow equations (adding an equation for the real power flow equality constraint, and a variable for the phase shifter value), or they can be handled in with an outer loop approach
- As was the case with LTCs, limit enforcement often makes the outer loop approach preferred
- Coordinated control is needed when there are multiple, close by phase shifters

Two Bus Phase Shifter Example





	Number	Name	Bus 1	Bus 2
1	1	Generator Bus	0.00 - j9.00	1.04 + j8.86
2	2	Load Bus	-1.04 + j8.86	0.00 - j9.00

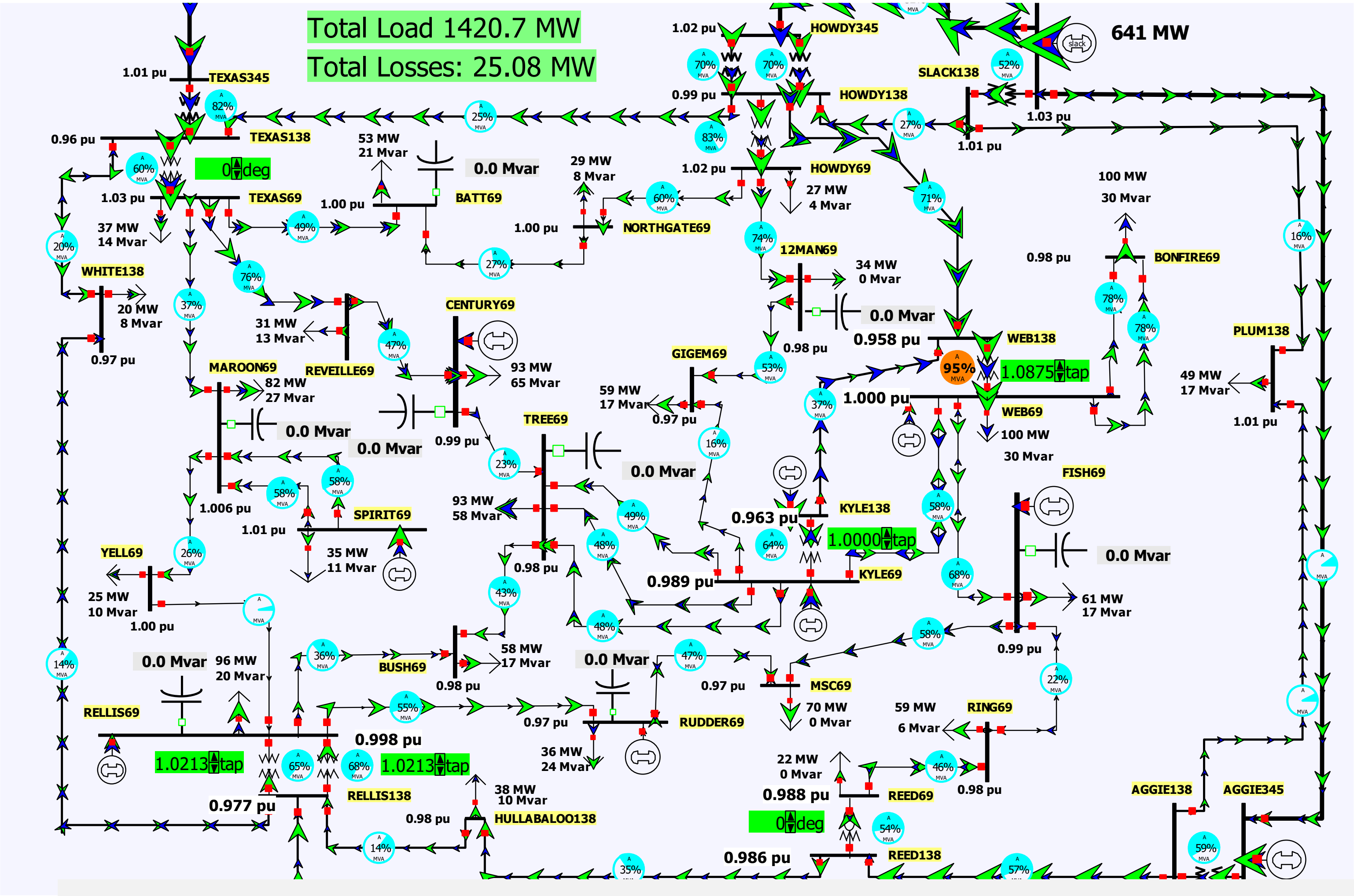
Top line has x=0.2 pu, while the phase shifter has x=0.25 pu.

$$\mathbf{Y}_{12} = -\frac{1}{j0.2} - \frac{1}{j0.25}\left(\cos\left(-15°\right) + j\sin\left(-15°\right)\right) = j5 + (j4)(0.966 - j0.259)$$

$$\mathbf{Y}_{12} = 1.036 + j8.864$$

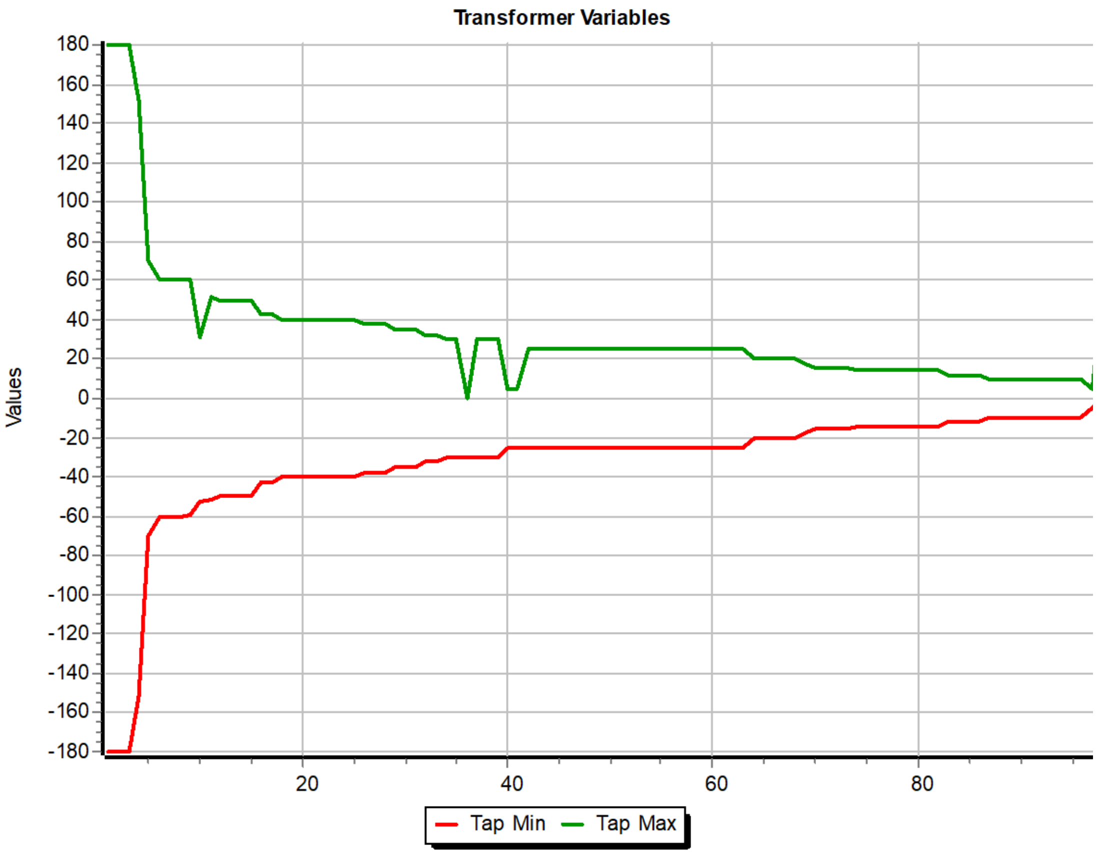
PowerWorld Case: B2PhaseShifter

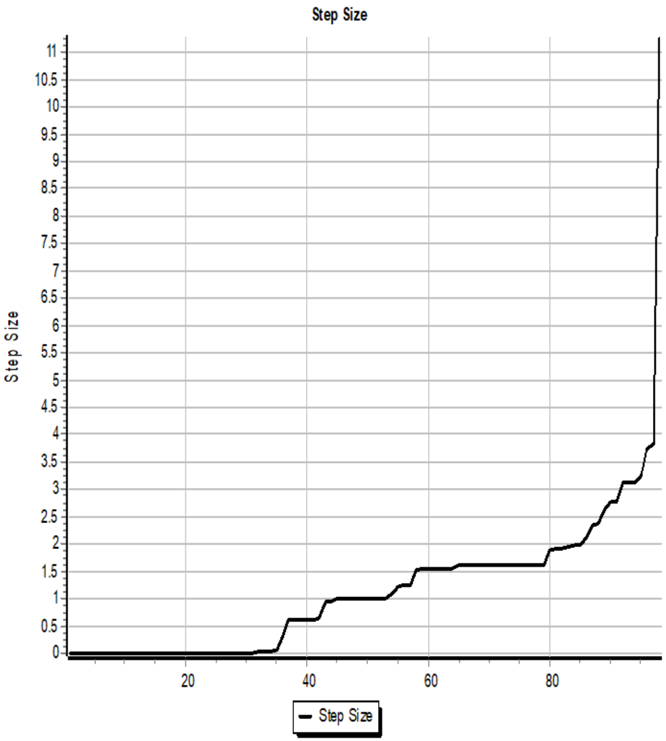
Aggieland37 With Phase Shifters



PowerWorld Case: Aggieland37_PhaseShifter

Large Case Phase Shifter Limits and Step Size



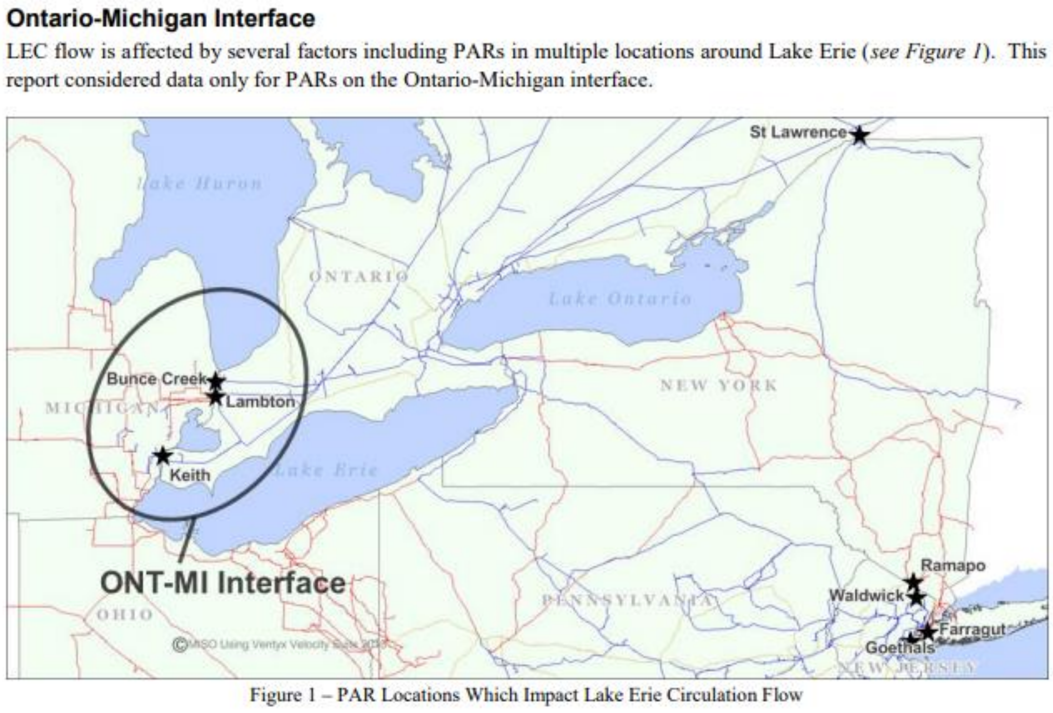


Impedance Correction Tables

- 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)

Example of Phase Shifters in Practice

- The below report mentions issues associated with the Ontario-Michigan PARs



Ontario-Michigan Interface

LEC flow is affected by several factors including PARs in multiple locations around Lake Erie (*see Figure 1*). This report considered data only for PARs on the Ontario-Michigan interface.

Figure 1 – PAR Locations Which Impact Lake Erie Circulation Flow

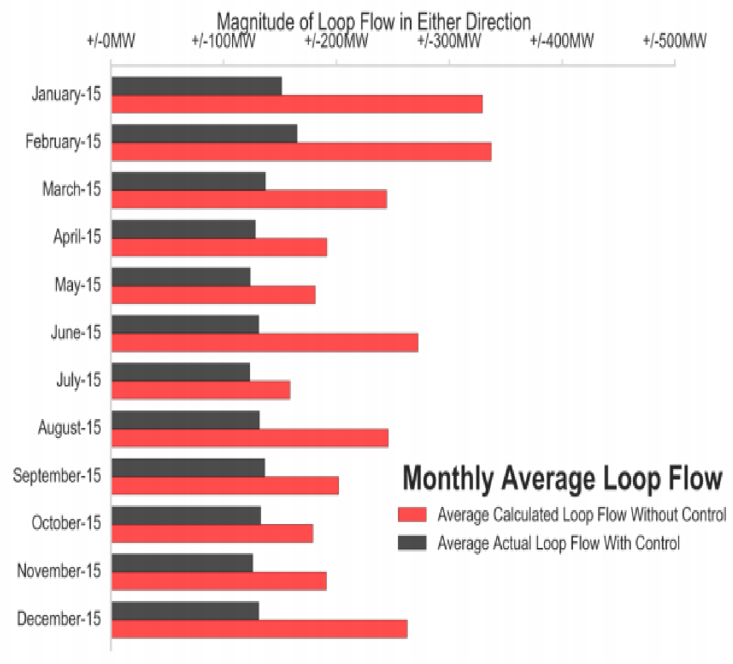


Figure 6 - Monthly Average Loop Flow

https://www.nyiso.com/public/webdocs/markets_operations/committees/bic_miwg/meeting_materials/2017-02-28/2016%20Ontario-Michigan%20Interface%20PAR%20Evaluation%20Final%20Report.pdf

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

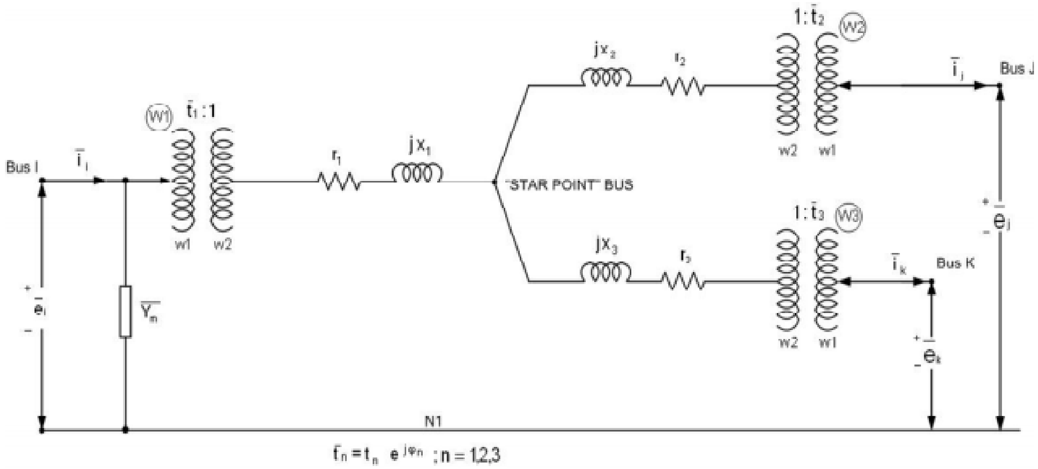


Figure 1 - PSS®E Three-Winding Transformer Model

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

Image Source and Reference
https://w3.usa.siemens.com/datapool/us/SmartGrid/docs/pti/2010July/PDFS/Modeling%20of%20Three%20Winding%20Voltage%20Regulating%20Transformers.pdf

Three-Winding Transformer Example, cont.

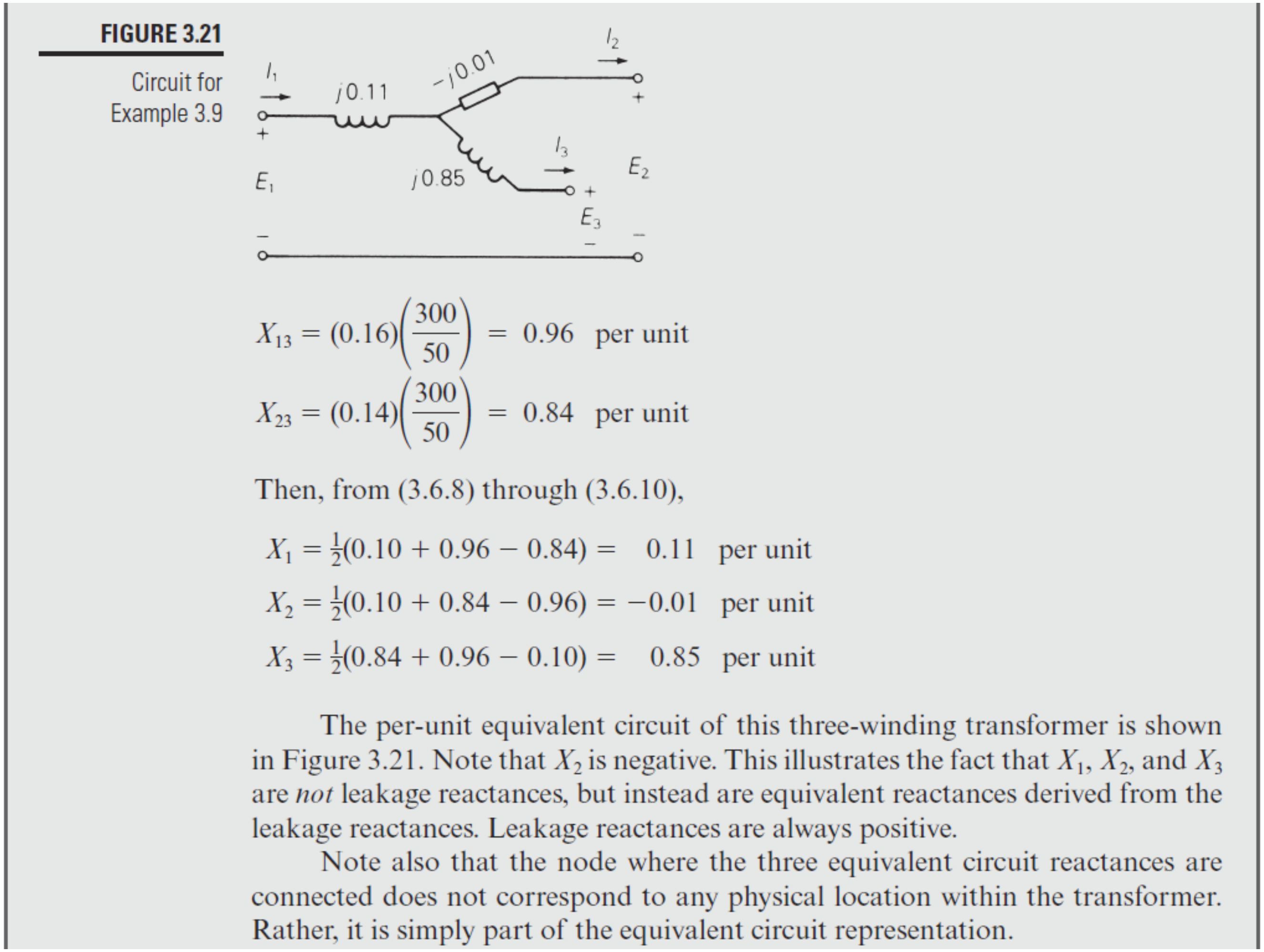


FIGURE 3.21

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),

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

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

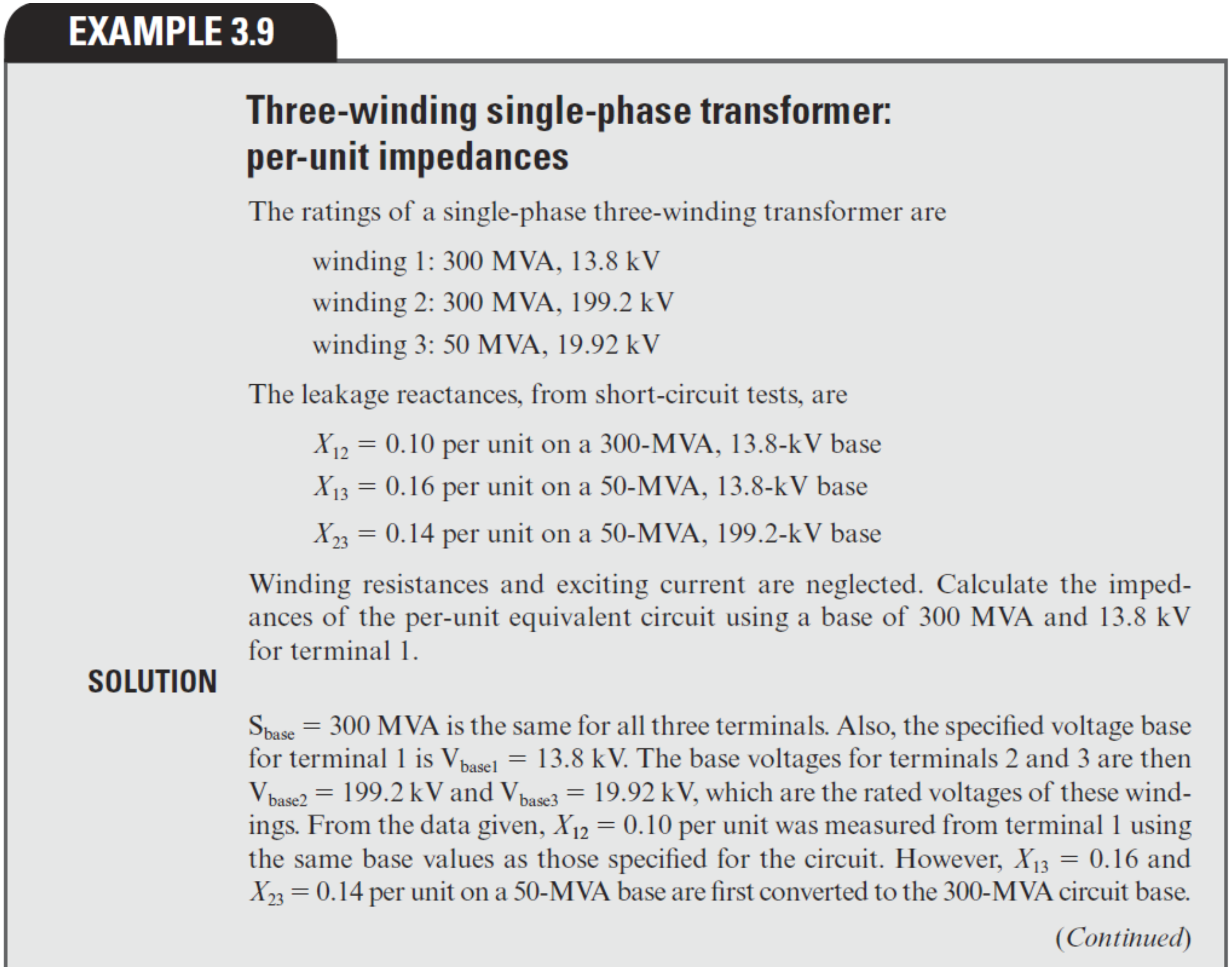
$$X_3 = \tfrac{1}{2}(0.84 + 0.96 - 0.10) = 0.85 \quad \text{per unit}$$

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

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.

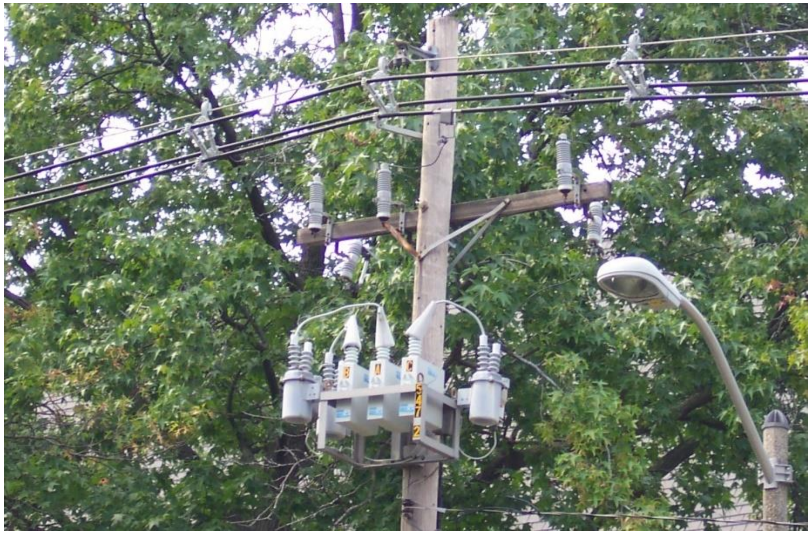
SOLUTION

$S_{base} = 300$ 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)

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

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

Area Interchange Control

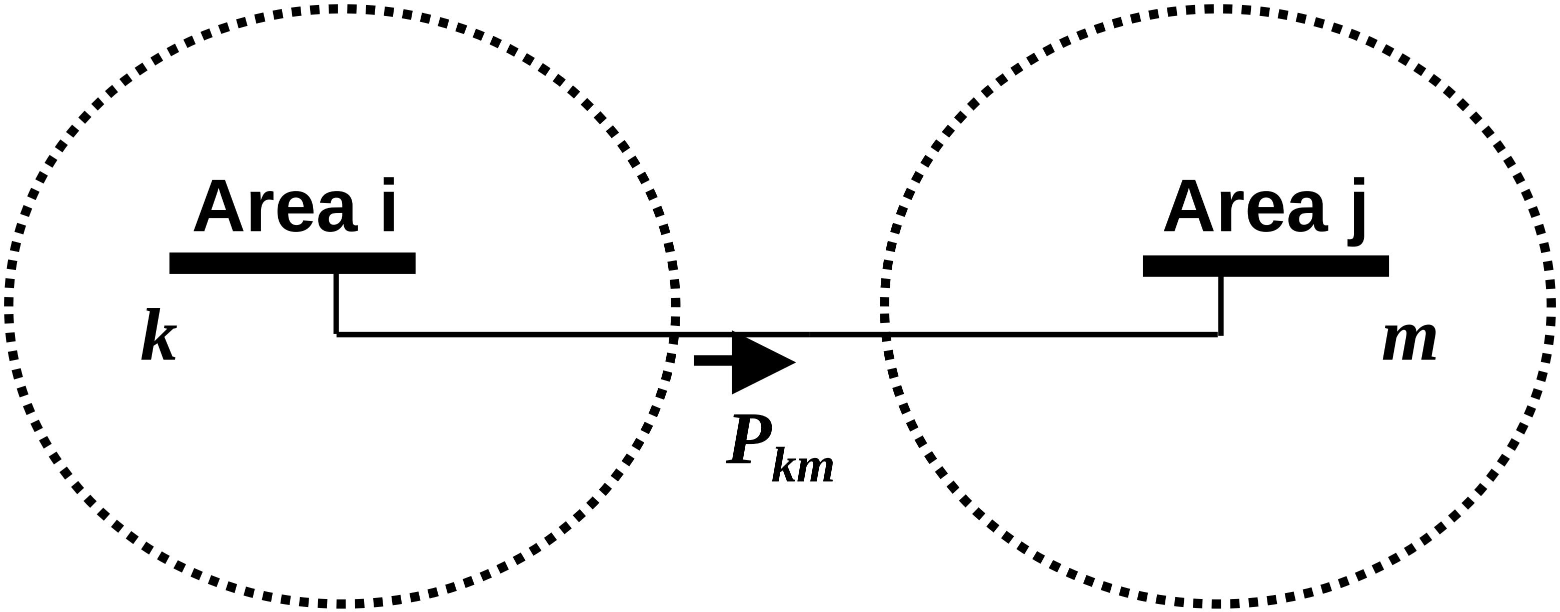
- The purpose of area interchange control is to regulate or control the interchange of real power between specified areas of the network
- Under area interchange control, the mutually exclusive subnetworks, the so-called areas, that make up a power system need to be explicitly represented
- These areas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

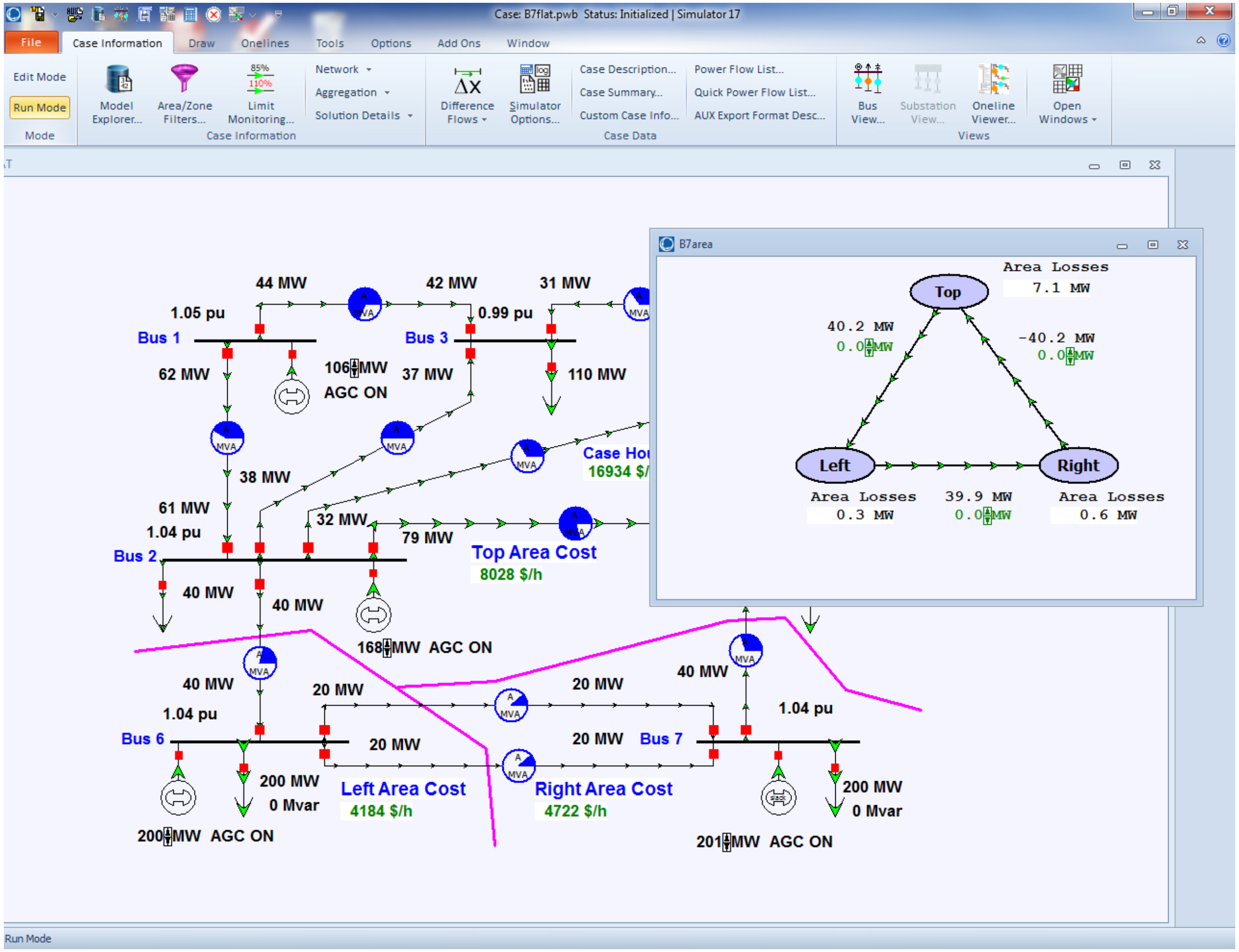
Modeling Area Interchange

- 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

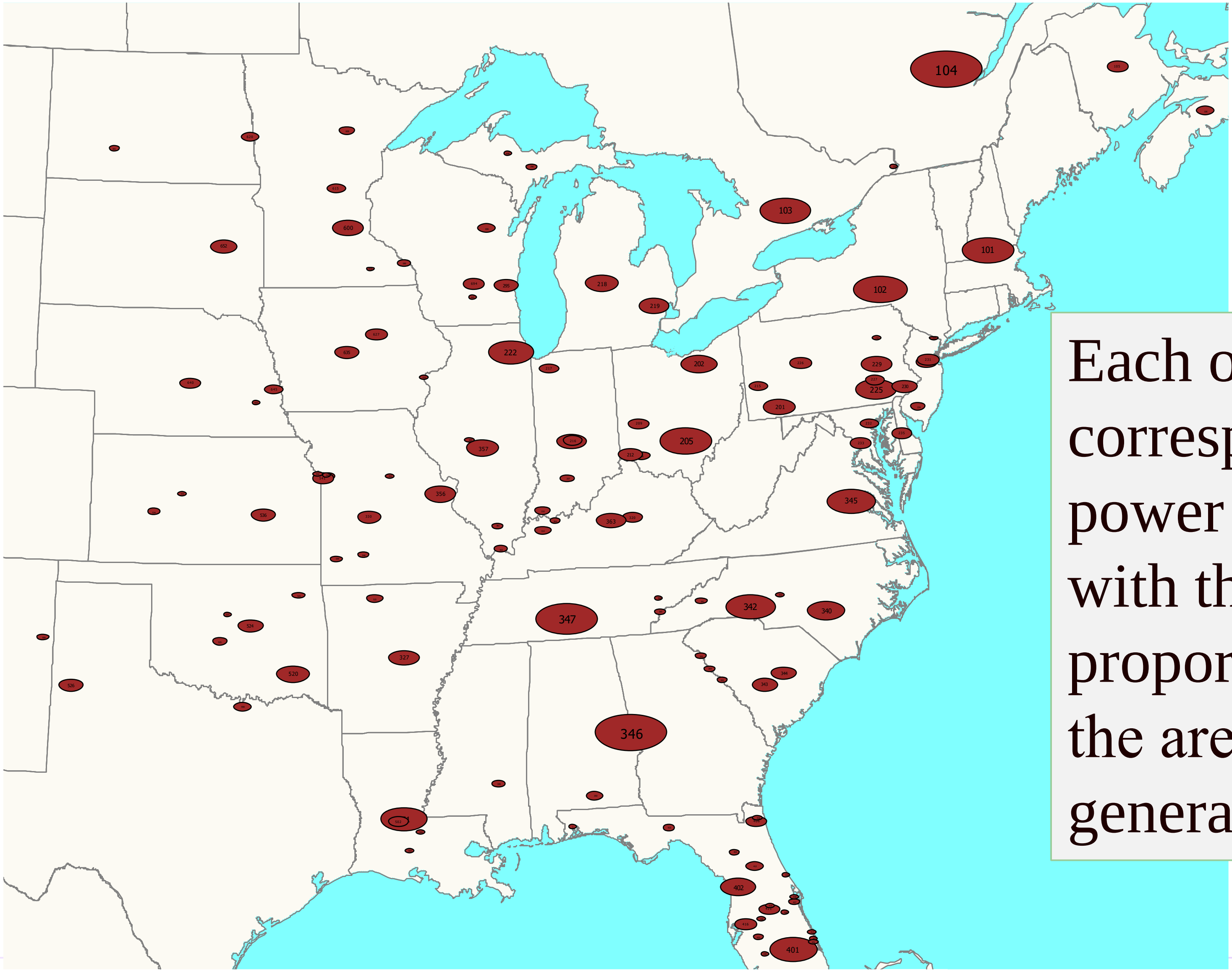
- A change in the generation dispatch can also change the system losses. These incremental impacts need to be included in an area interchange algorithm
- We'll discuss the details of these calculations later in the course when we consider sensitivity analysis

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