ECEN 615
Methods of Electric Power Systems Analysis

Lecture 6: Power Operations, Power Flow

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

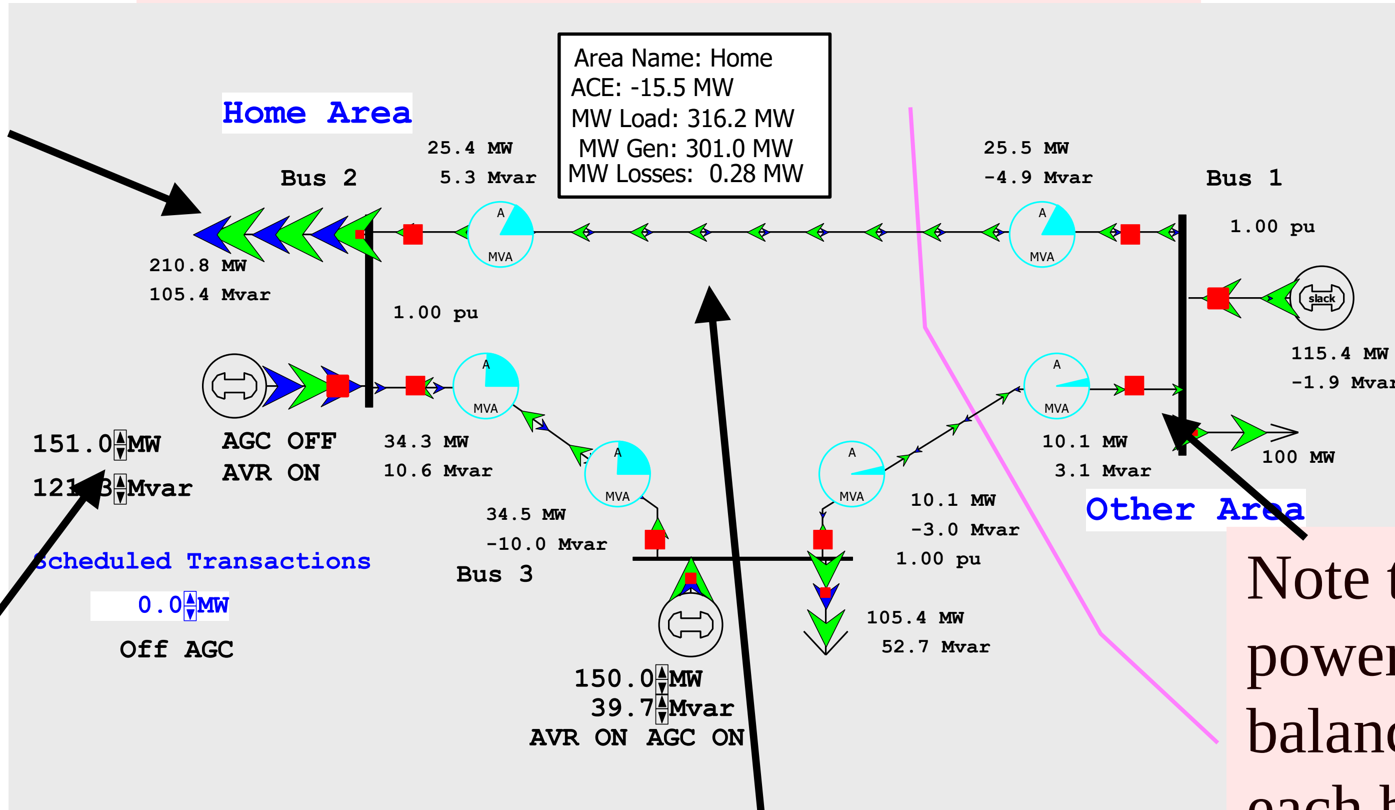
Announcements

- Read Chapter 6 from the book
  - The book formulates the power flow using the polar form for the Y_{bus} elements
- Homework 2 is due on Thursday September 17

Three Bus PowerWorld Simulator Case

PowerWorld Case Name: **B3Slow**

Load with green arrows indicating amount of MW flow



Used to control output of generator

Note the power balance at each bus

Direction of green arrow is used to indicate direction of real power (MW) flow; the blue arrows show the reactive power

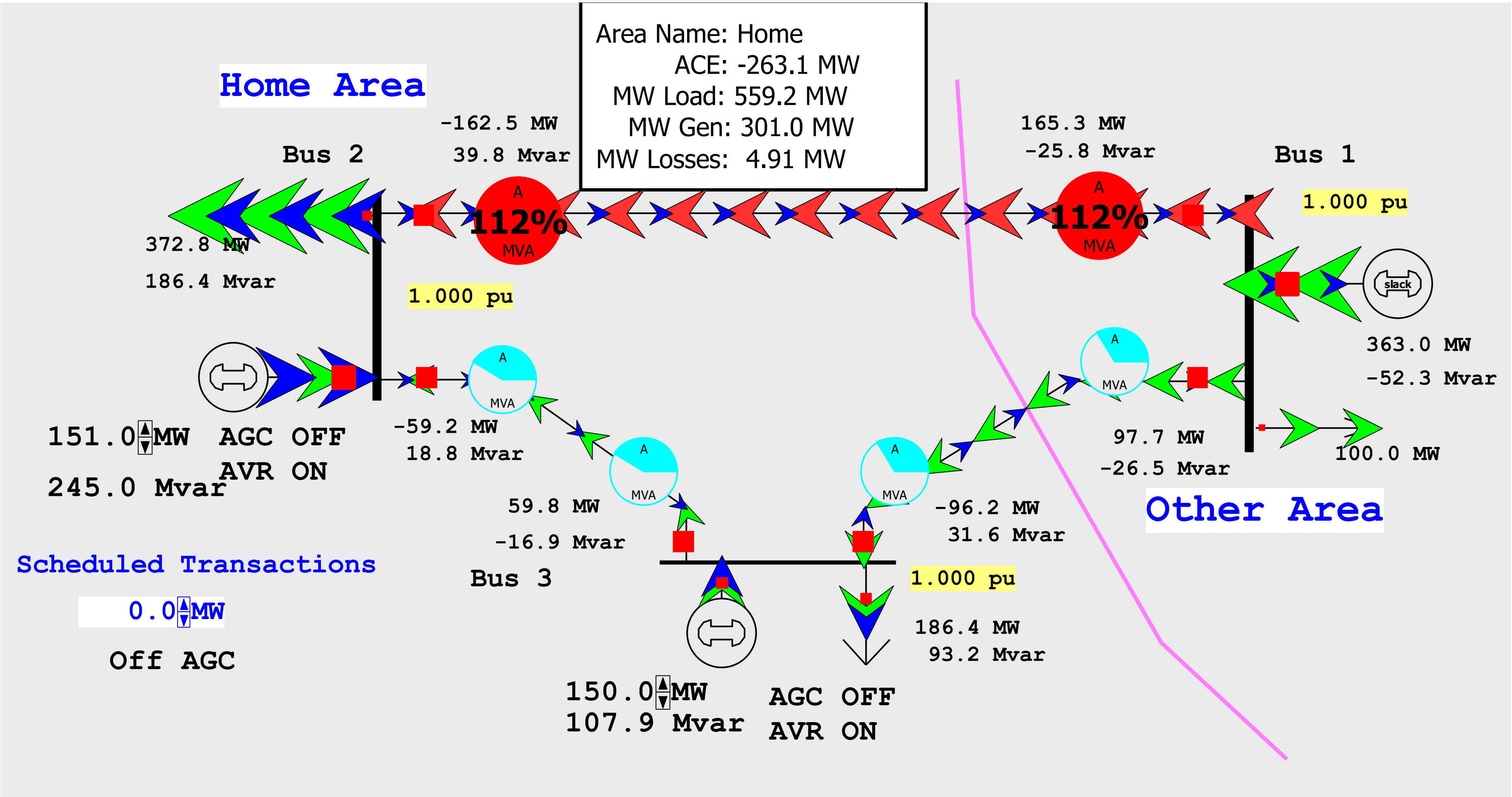
Basic Power Control

- Opening a circuit breaker causes the power flow to instantaneously (nearly) change.
- No other way to directly control power flow in a transmission line.
- By changing generation we can indirectly change this flow.
- Power flow in transmission line is limited by heating considerations
- Losses ($I^2 R$) can heat up the line, causing it to sag.

Transmission Line Limits

- Power flow in transmission line is limited by heating considerations.
- Losses ($I^2 R$) can heat up the line, causing it to sag.
- Each line has a limit; many utilities use winter/summer limits.

Overloaded Transmission Line

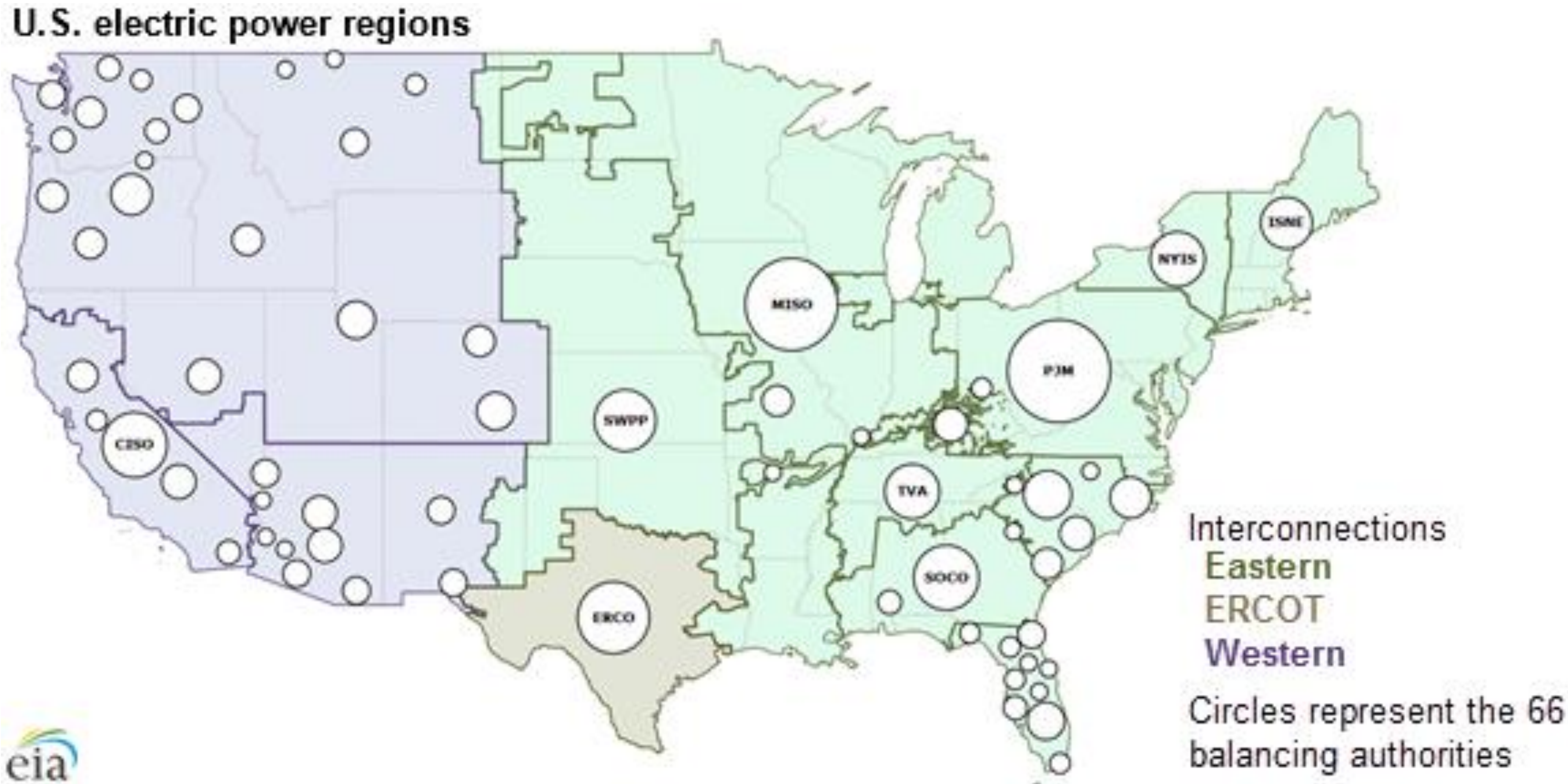


Interconnected Operation Balancing Authority (BA) Areas

- North American Eastern and Western grids are divided into balancing authority areas (BA)
  - Often just called an area
- Transmission lines that join two areas are known as tie-lines.
- The net power out of an area is the sum of the flow on its tie-lines.
- The flow out of an area is equal to

  total gen - total load - total losses = tie-flow

US Balancing Authorities



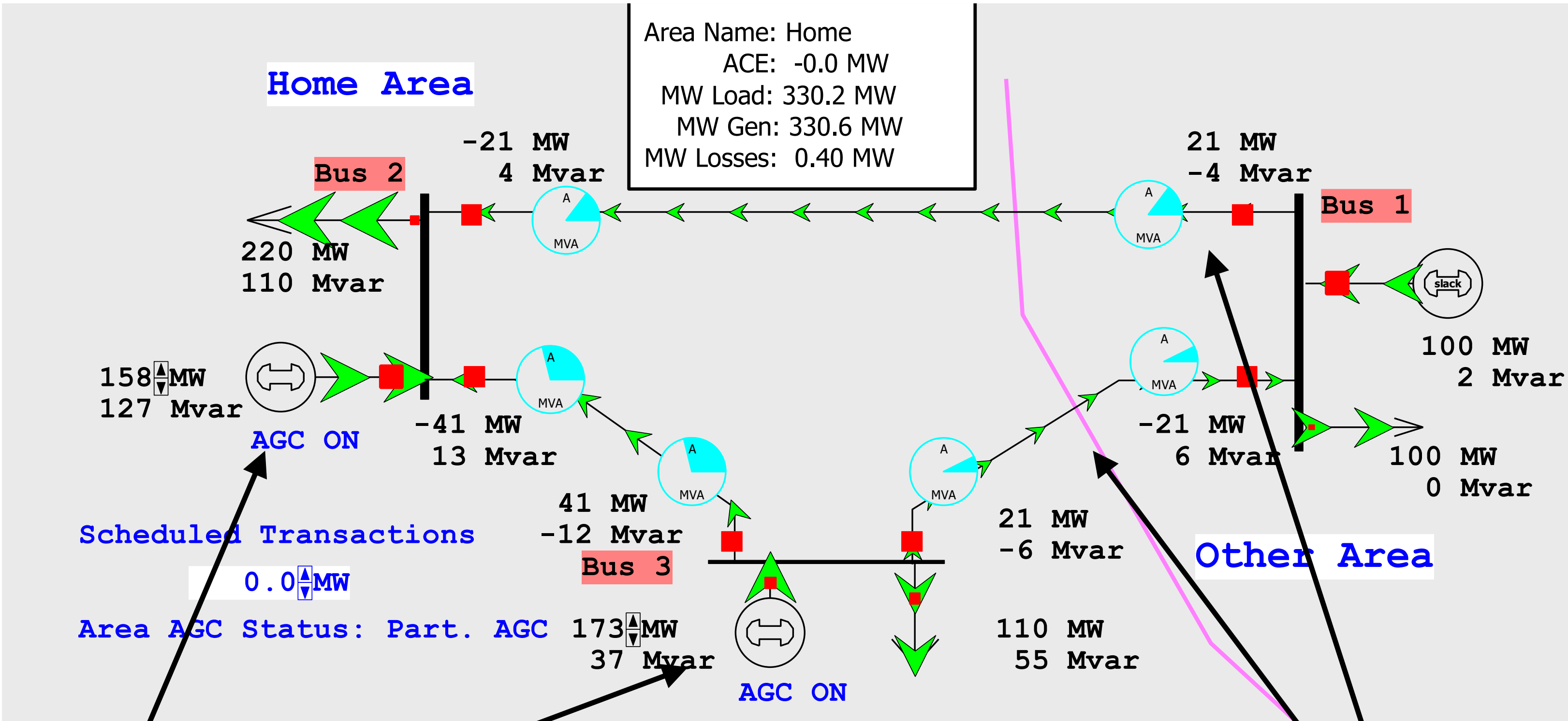
Area Control Error (ACE)

- The area control error is the difference between the actual flow out of an area, and the scheduled flow
  - ACE also includes a frequency component that we will probably consider later in the semester
- Ideally the ACE should always be zero
- Because the load is constantly changing, each utility (or ISO) must constantly change its generation to "chase" the ACE
- ACE was originally computed by utilities; increasingly it is computed by larger organizations such as ISOs

Automatic Generation Control

- Most utilities (ISOs) use automatic generation control (AGC) to automatically change their generation to keep their ACE close to zero.
- Usually the control center calculates ACE based upon tie-line flows; then the AGC module sends control signals out to the generators every couple seconds.

Three Bus Case on AGC



Generation is automatically changed to match change in load

Net tie flow is close to zero

Generator Costs

- There are many fixed and variable costs associated with power system operation
- The major variable cost is associated with generation.
- Cost to generate a MWh can vary widely
- For some types of units (such as hydro and nuclear) it is difficult to quantify
- More others such as wind and solar the marginal cost of energy is essentially zero (actually negative for wind!)
- For thermal units it is straightforward to determine
- Many markets have moved from cost-based to price-based generator costs

Economic Dispatch

- Economic dispatch (ED) determines the least cost dispatch of generation for an area.
- For a lossless system, the ED occurs when all the generators have equal marginal costs.

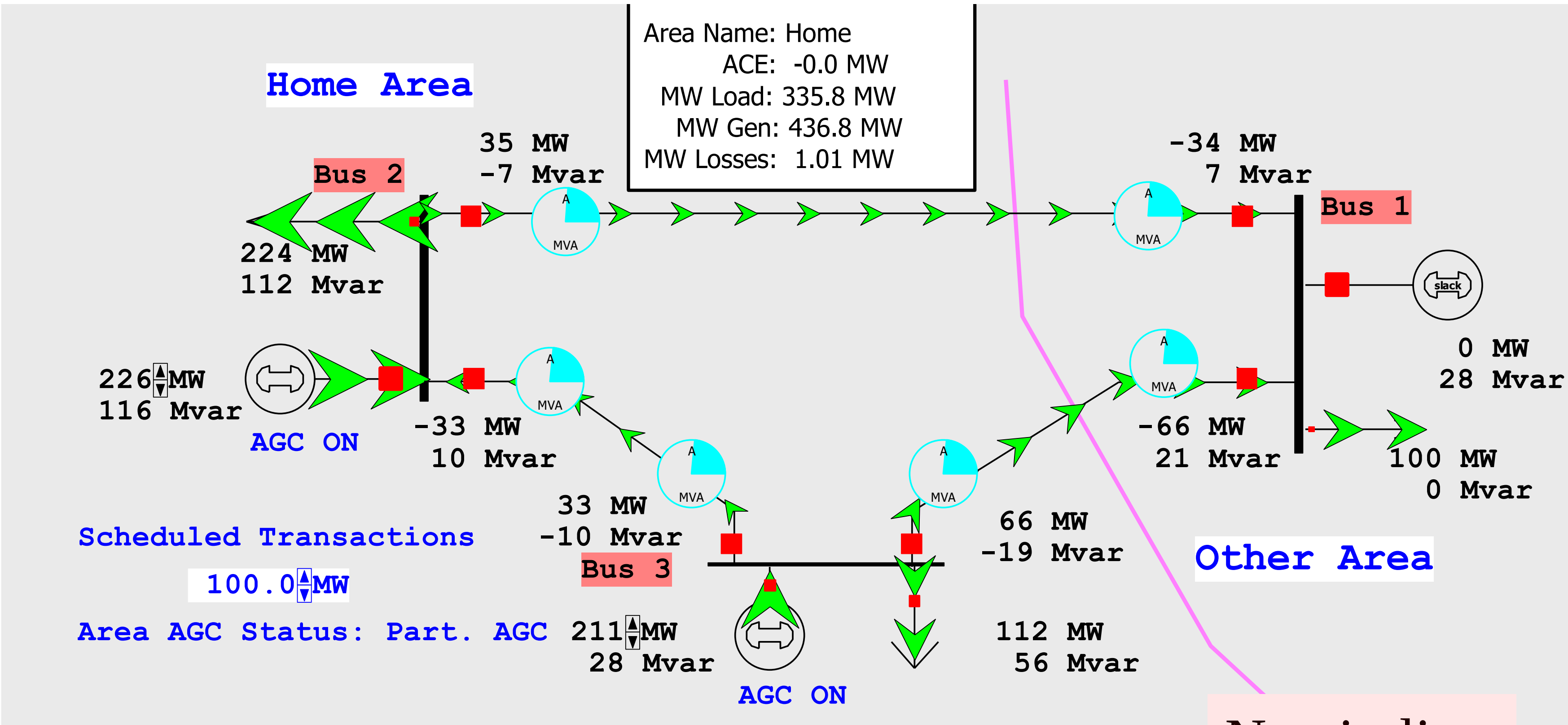
$$IC_1(P_{G,1}) = IC_2(P_{G,2}) = \ldots = IC_m(P_{G,m})$$

Power Transactions

- Power transactions are contracts between areas to do power transactions.
- Contracts can be for any amount of time at any price for any amount of power.
- Scheduled power transactions are implemented by modifying the area ACE:

$$ACE = P_{actual,tie\text{-}flow} - P_{sched}$$

100 MW Transaction



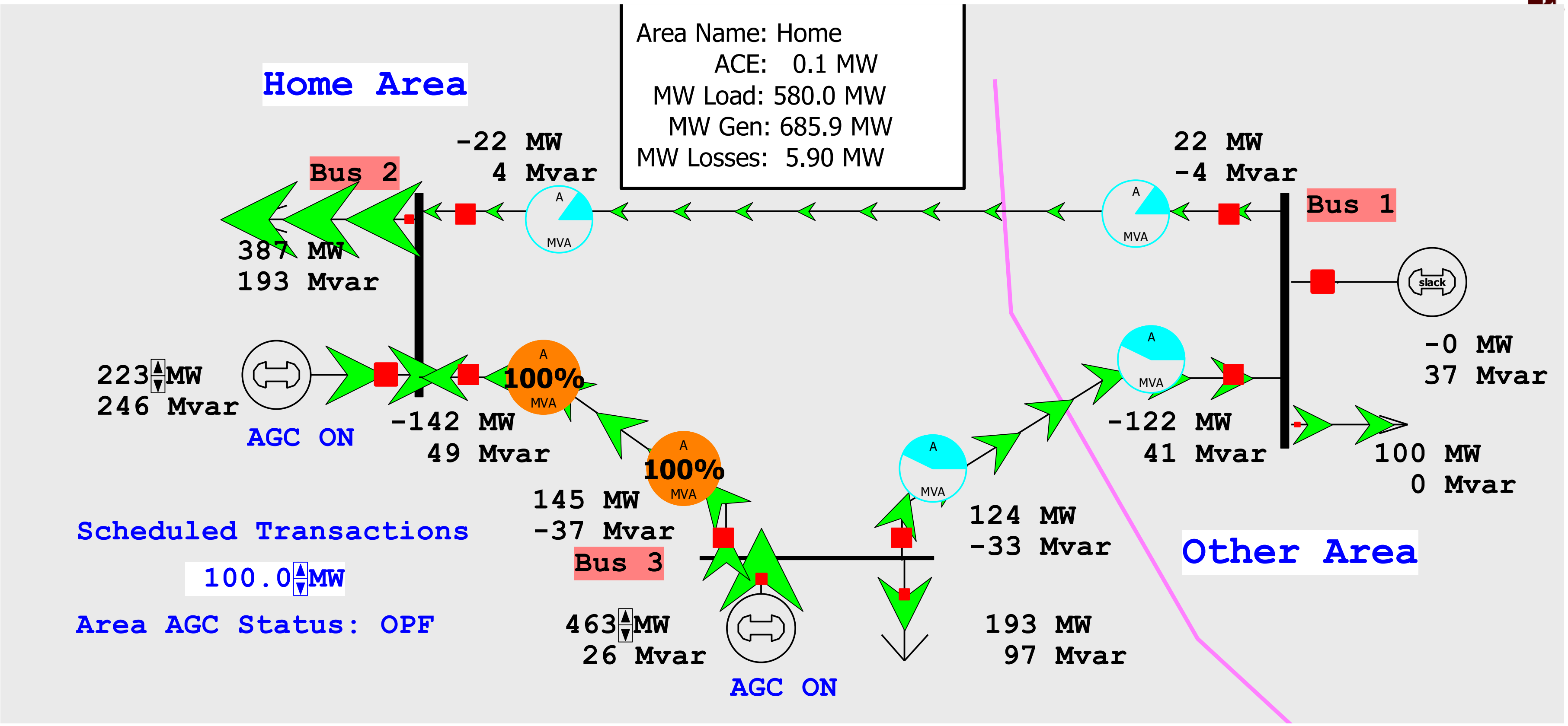
Scheduled 100 MW transaction from the Home Area to the Other Area

Net tie-line flow is now 100 MW

Security Constrained ED

- Transmission constraints often limit system economic operation.
- Such limits required a constrained dispatch in order to maintain system security.
- In the three bus case the generation at bus 3 must be constrained to avoid overloading the line from bus 2 to bus 3.

Security Constrained Dispatch



Dispatch is no longer optimal due to need to keep the line from bus 2 to bus 3 from overloading

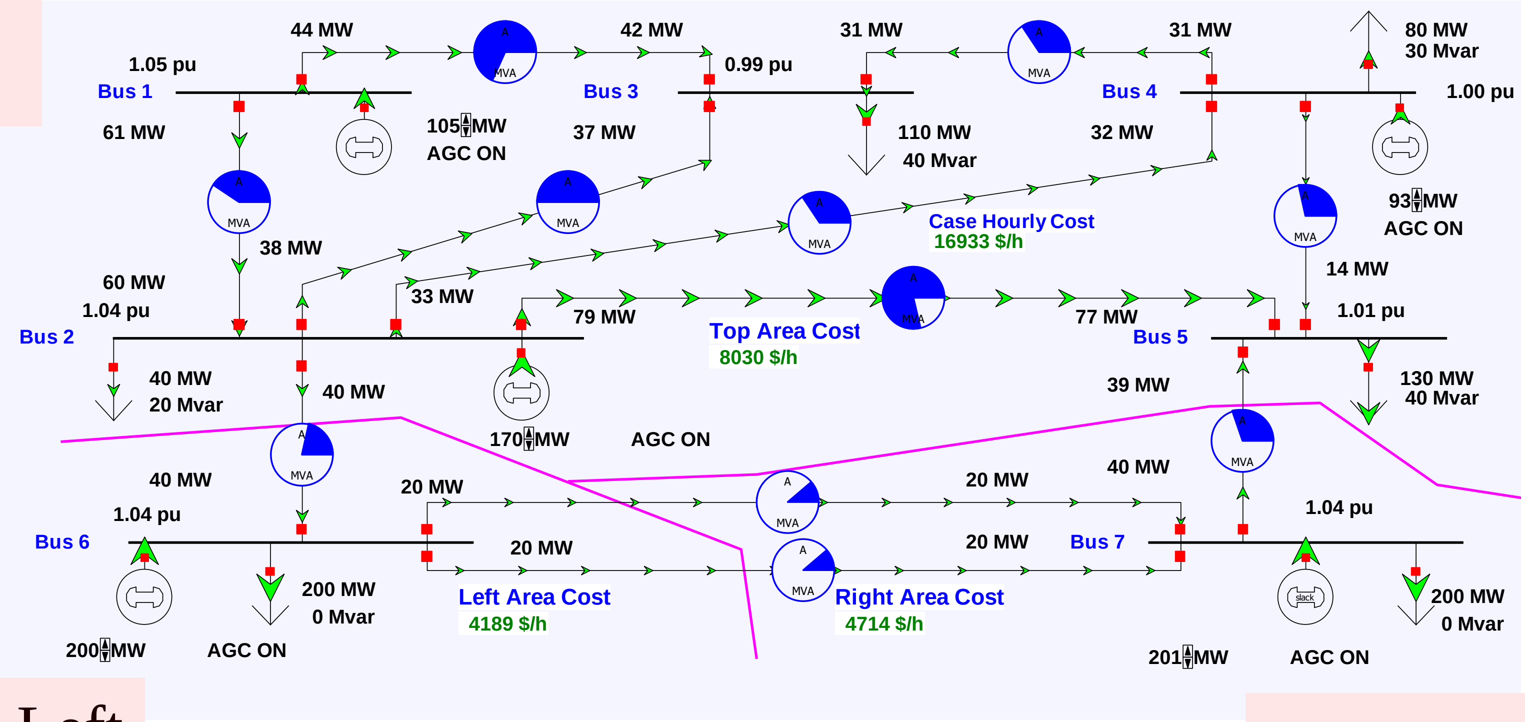
Multi-Area Operation

- If areas have direct interconnections then they may directly transact, up to the capacity of their tie-lines.
- Actual power flows through the entire network according to the impedance of the transmission lines.
- Flow through other areas is known as "parallel path" or "loop flow."

Seven Bus Case: One-line

Area Top has five buses

System has three areas



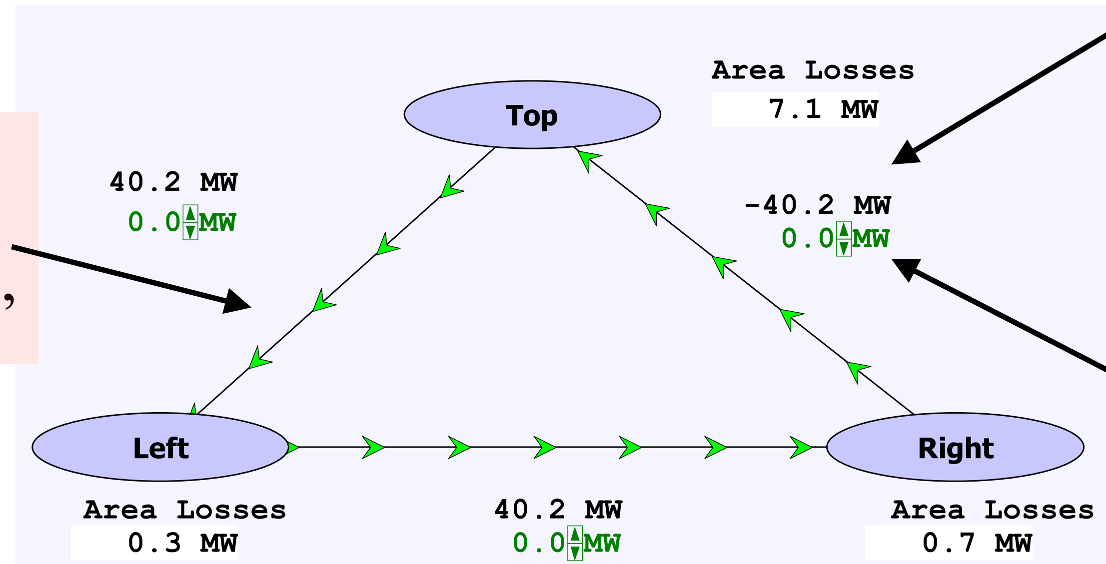
Area Left has one bus

Area Right has one bus

PowerWorld Case: **B7Flat**

Seven Bus Case: Area View

System has 40 MW of "Loop Flow"

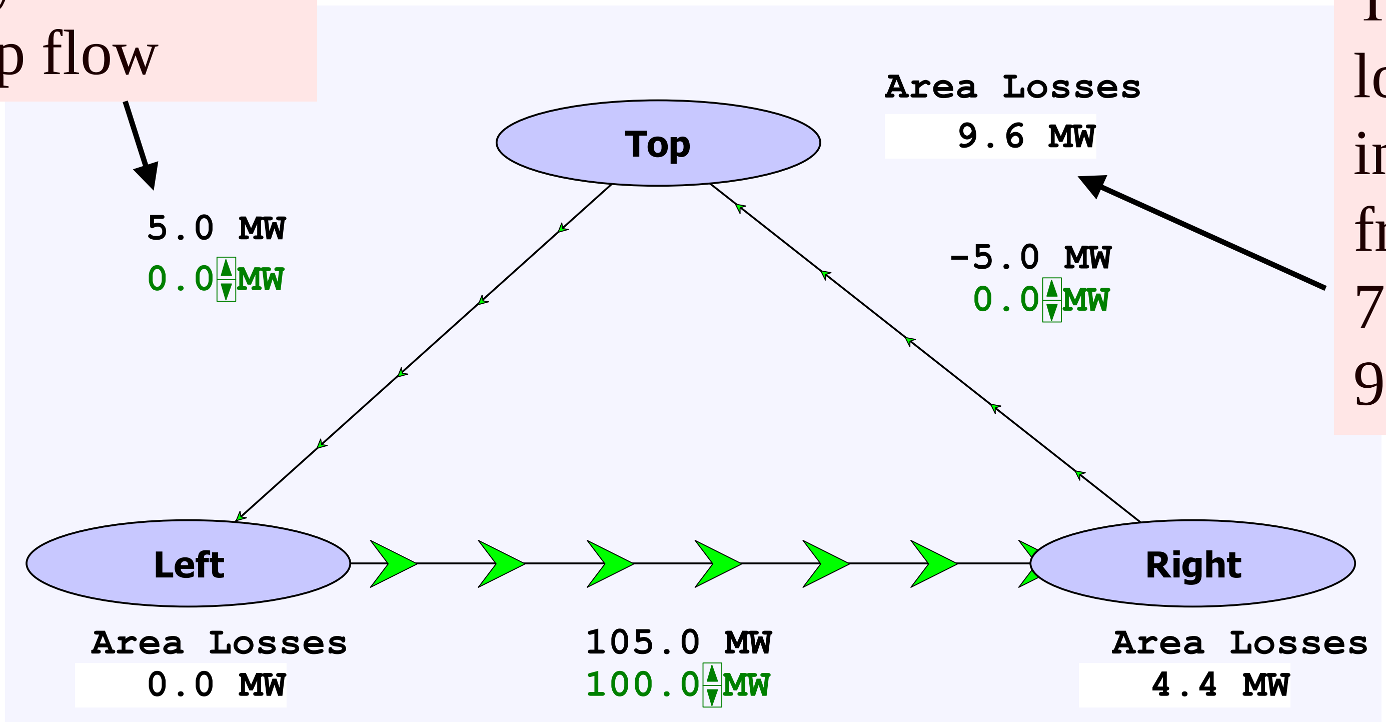


Actual flow between areas

Scheduled flow

Seven Bus - Loop Flow?

Transaction has actually decreased the loop flow



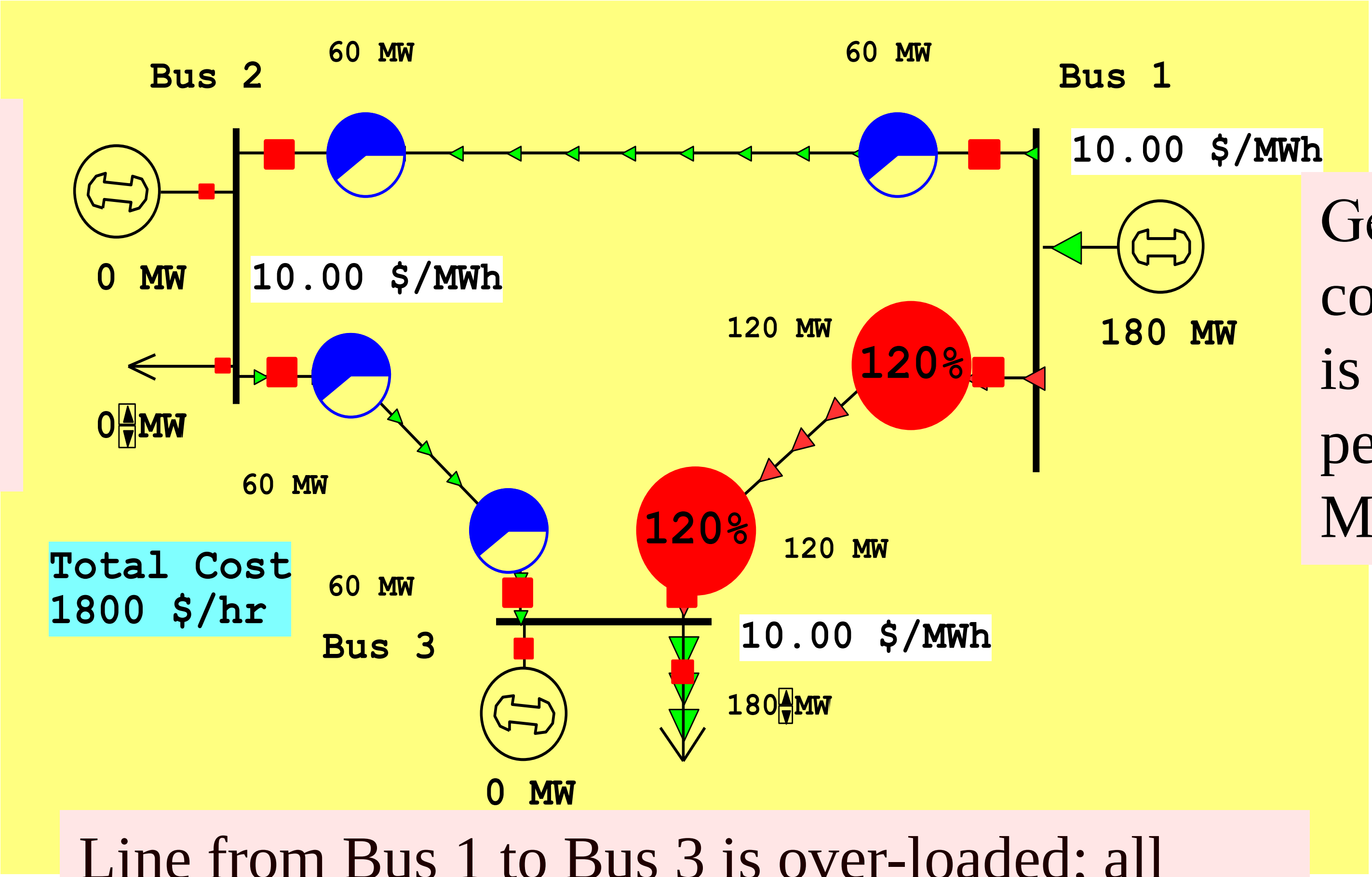
Note that Top's losses have increased from 7.1 MW to 9.6 MW

100 MW Transaction between Left and Right

Pricing Electricity

- Cost to supply electricity to bus is called the locational marginal price (LMP)
- Presently some electric markets post LMPs on the web
- In an ideal electricity market with no transmission limitations the LMPs are equal
- Transmission constraints can segment a market, resulting in differing LMP
- Determination of LMPs requires the solution on an Optimal Power Flow (OPF), which will be covered later in the semester

Three Bus LMPs – Constraints Ignored



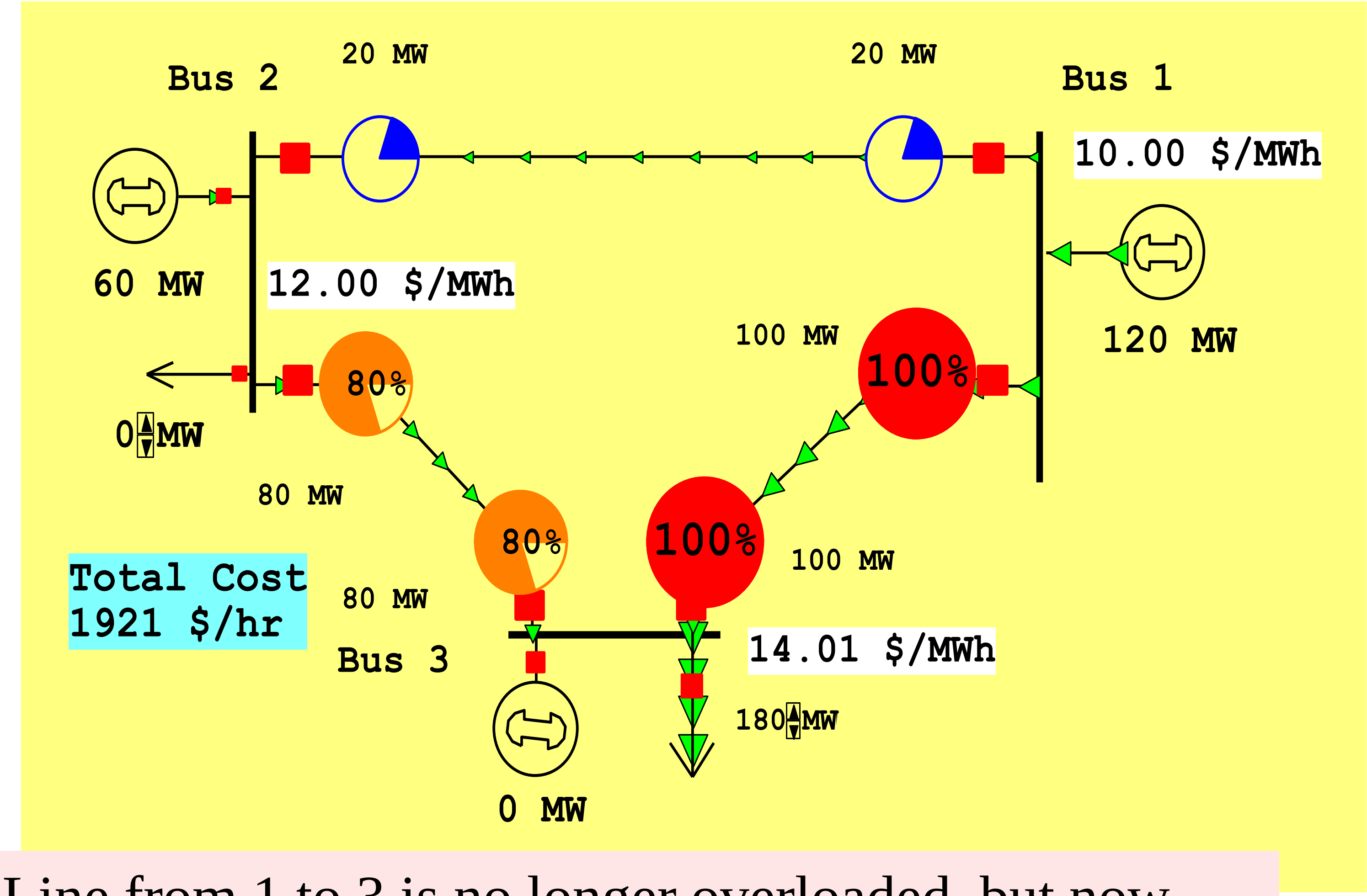
Gen 2's cost is $12 per MWh

Gen 1's cost is $10 per MWh

Line from Bus 1 to Bus 3 is over-loaded; all buses have same marginal cost

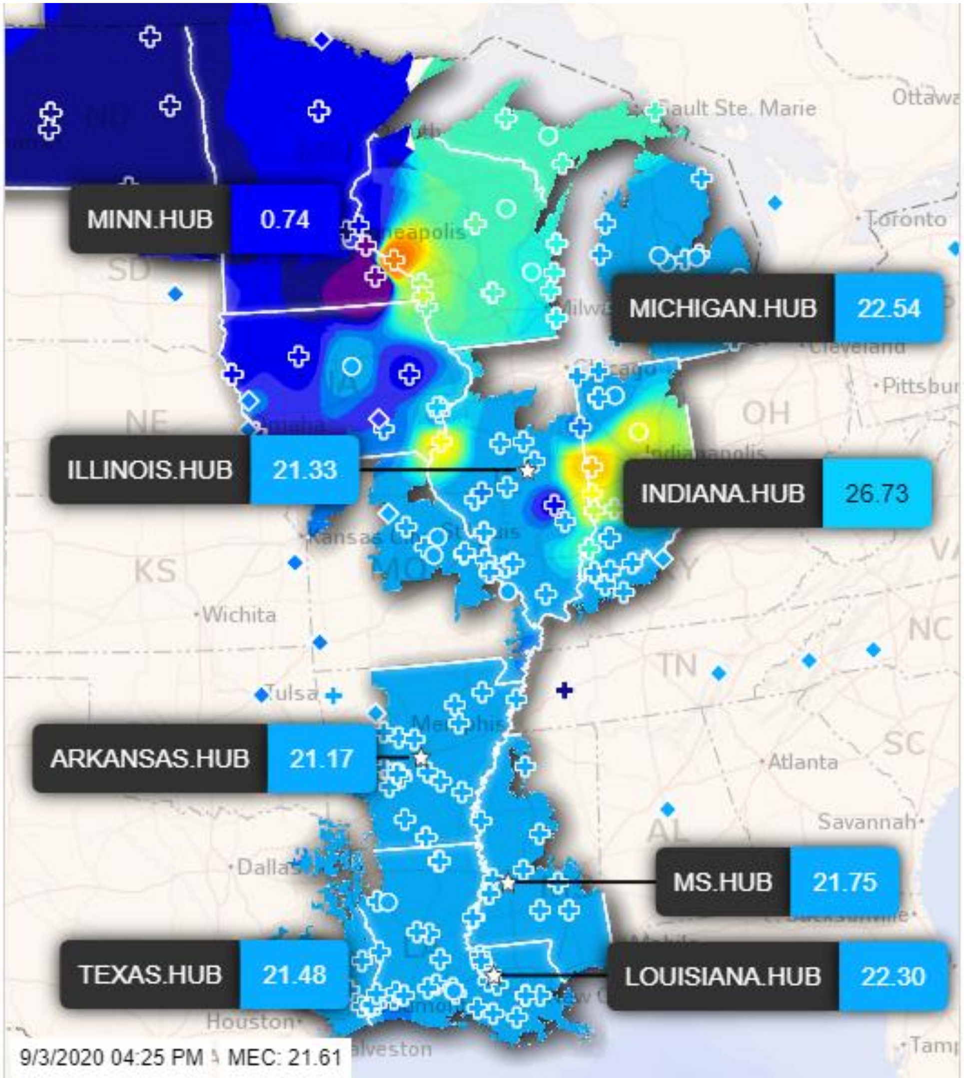
PowerWorld Case: **B3LP**

Three Bus LMPs – Constraint Unforced



Line from 1 to 3 is no longer overloaded, but now the marginal cost of electricity at bus 3 is $14 / MWh

MISO LMPs on 9/3/2020, 4:30 PM



Five minute LMPs are posted online for the MISO footprint

Source: https://www.misoenergy.org/markets-and-operations/real-time--market-data/real-time-displays/

Advanced Power Flow

- Next slides cover some more advanced power flow topics that need to be considered in many commercial power flow studies
- An important consideration in the power flow is the assumed time scale of the response, and the assumed model of operator actions
  - Planning power flow studies usually assume automatic modeling of operator actions and a longer time frame of response (controls have time to reach steady-state)
    - For example, who is actually doing the volt/var control
  - In real-time applications operator actions are usually not automated and controls may be more limited in time

Quasi-Newton Power Flow Methods

- First we consider some modified versions of the Newton power flow (NPF)
- Since most of the computation in the NPF is associated with building and factoring the Jacobian matrix, **J**, the focus is on trying to reduce this computation
- In a pure NPF **J** is build and factored each iteration
- Over the years pretty much every variation of the NPF has been tried; here we just touch on the most common
- Whether a method is effective can be application dependent
  - For example, in contingency analysis we are usually just resolving a solved case with an often small perturbation

Quasi-Newton Power Flow Methods

- The simplest modification of the NPF results when **J** is kept constant for a number of iterations, say k iterations
  - Sometimes known as the Dishonest Newton
- The approach balances increased speed per iteration, with potentially more iterations to perform
- There is also an increased possibility for divergence
- Since the mismatch equations are not modified, if it converges it should converge to the same solution as the NPF
- These methods are not commonly used, except in very short duration, sequential power flows with small mismatches

Dishonest N-R Example

$$x^{(v+1)} = x^{(v)} - \left[\frac{1}{2x^{(0)}}\right]((x^{(v)})^2 - 2)$$

Guess $x^{(0)} = 1$. Iteratively solving we get

v	$x^{(v)}$(honest)	$x^{(v)}$(dishonest)
0	1	1
1	1.5	1.5
2	1.41667	1.375
3	1.41422	1.429
4	1.41422	1.408

We pay a price in increased iterations, but with decreased computation per iteration; that price is too high in this example

Decoupled Power Flow

- Rather than not updating the Jacobian, the decoupled power flow takes advantage of characteristics of the power grid in order to decouple the real and reactive power balance equations
  - There is a strong coupling between real power and voltage angle, and reactive power and voltage magnitude
  - There is a much weaker coupling between real power and voltage angle, and reactive power and voltage angle
- Key reference is B. Stott, "Decoupled Newton Load Flow," *IEEE Trans. Power. App and Syst.*, Sept/Oct. 1972, pp. 1955-1959

Decoupled Power Flow Formulation

General form of the power flow problem

$$-\begin{bmatrix} \dfrac{\partial \mathbf{P}}{\partial \boldsymbol{\theta}}^{(v)} & \dfrac{\partial \mathbf{P}}{\partial |\mathbf{V}|}^{(v)} \\ \dfrac{\partial \mathbf{Q}}{\partial \boldsymbol{\theta}}^{(v)} & \dfrac{\partial \mathbf{Q}}{\partial |\mathbf{V}|}^{(v)} \end{bmatrix} \begin{bmatrix} \Delta \boldsymbol{\theta}^{(v)} \\ \Delta |\mathbf{V}|^{(v)} \end{bmatrix} = \begin{bmatrix} \Delta \mathbf{P}(\mathbf{x}^{(v)}) \\ \Delta \mathbf{Q}(\mathbf{x}^{(v)}) \end{bmatrix} = \mathbf{f}(\mathbf{x}^{(v)})$$

where

$$\Delta \mathbf{P}(\mathbf{x}^{(v)}) = \begin{bmatrix} P_2(\mathbf{x}^{(v)}) + P_{D2} - P_{G2} \\ \vdots \\ P_n(\mathbf{x}^{(v)}) + P_{Dn} - P_{Gn} \end{bmatrix}$$

Decoupling Approximation

Usually the off-diagonal matrices, $\dfrac{\partial \mathbf{P}}{\partial |\mathbf{V}|}^{(v)}$ and $\dfrac{\partial \mathbf{Q}}{\partial \boldsymbol{\theta}}^{(v)}$

are small. Therefore we approximate them as zero:

$$-\begin{bmatrix} \dfrac{\partial \mathbf{P}}{\partial \boldsymbol{\theta}}^{(v)} & \mathbf{0} \\ \mathbf{0} & \dfrac{\partial \mathbf{Q}}{\partial |\mathbf{V}|}^{(v)} \end{bmatrix} \begin{bmatrix} \Delta\boldsymbol{\theta}^{(v)} \\ \Delta|\mathbf{V}|^{(v)} \end{bmatrix} = \begin{bmatrix} \Delta\mathbf{P}(\mathbf{x}^{(v)}) \\ \Delta\mathbf{Q}(\mathbf{x}^{(v)}) \end{bmatrix} = \mathbf{f}(\mathbf{x}^{(v)})$$

Then the problem can be decoupled

$$\Delta\boldsymbol{\theta}^{(v)} = -\left[\dfrac{\partial \mathbf{P}}{\partial \boldsymbol{\theta}}^{(v)}\right]^{-1} \Delta\mathbf{P}(\mathbf{x}^{(v)}) \quad \Delta|\mathbf{V}|^{(v)} = -\left[\dfrac{\partial \mathbf{Q}}{\partial |\mathbf{V}|}^{(v)}\right]^{-1} \Delta\mathbf{Q}(\mathbf{x}^{(v)})$$

Off-diagonal Jacobian Terms

Justification for Jacobian approximations:

1. Usually r << x, therefore $\left|G_{ij}\right| << \left|B_{ij}\right|$
2. Usually θ_{ij} is small so $\sin\theta_{ij} \approx 0$

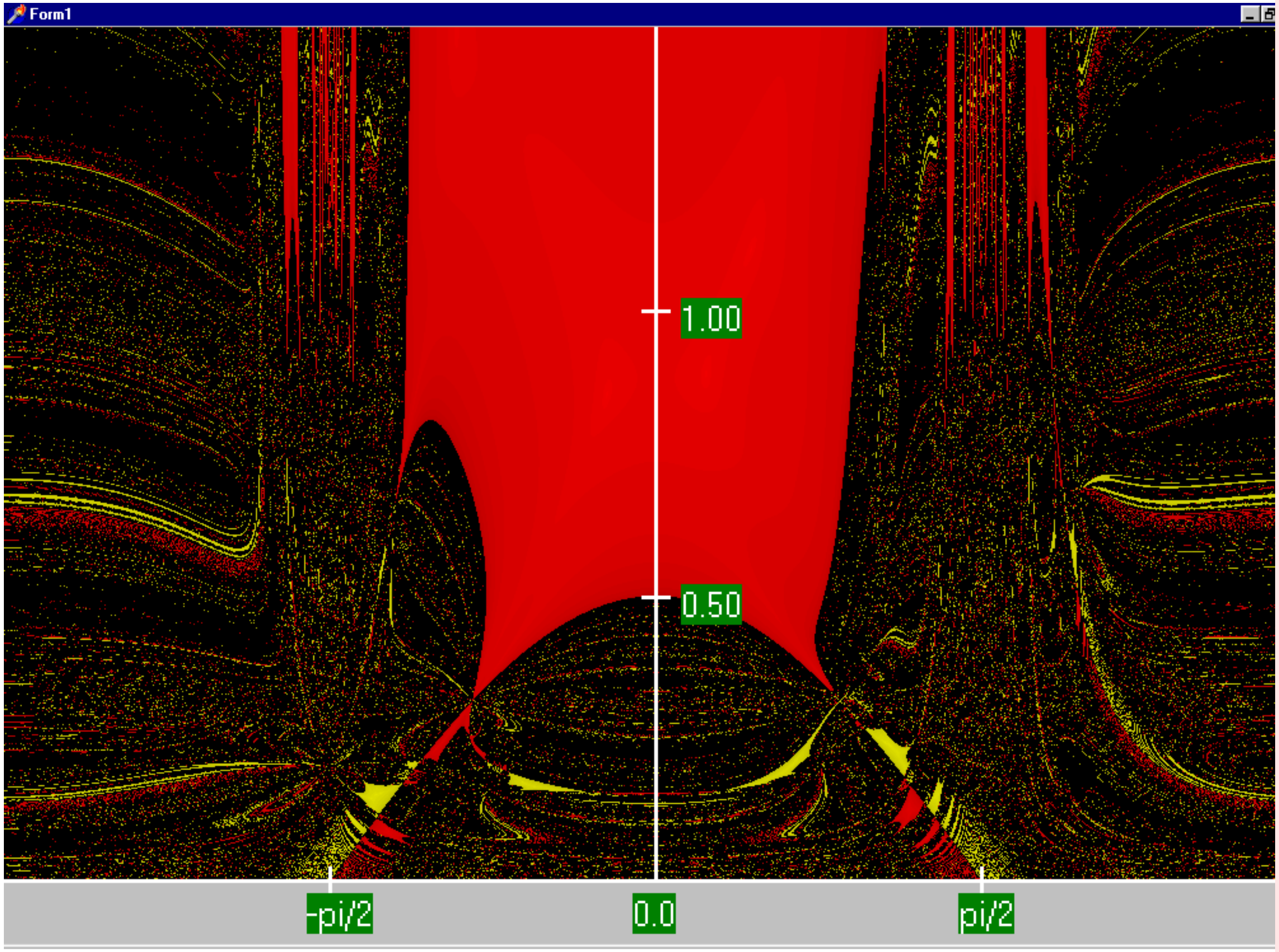
Therefore

$$\frac{\partial \mathbf{P}_i}{\partial \left|\mathbf{V}_j\right|} = \left|V_i\right|\left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}\right) \approx 0$$

$$\frac{\partial \mathbf{Q}_i}{\partial \boldsymbol{\theta}_j} = -\left|V_i\right|\left|V_j\right|\left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}\right) \approx 0$$

By assuming ½ the elements are zero, we only have to do ½ the computations

Decoupled N-R Region of Convergence



The high solution ROC is actually larger than with the standard NPF. Obviously this is not a good a way to get the low solution

Fast Decoupled Power Flow

- By continuing with our Jacobian approximations we can actually obtain a reasonable approximation that is independent of the voltage magnitudes/angles.
- This means the Jacobian need only be built/inverted once per power flow solution
- This approach is known as the fast decoupled power flow (FDPF)

Fast Decoupled Power Flow, cont.

- FDPF uses the same mismatch equations as standard power flow (just scaled) so it should have same solution
- The FDPF is widely used, though usually only when we only need an approximate solution
- Key fast decoupled power flow reference is B. Stott, O. Alsac, "Fast Decoupled Load Flow," *IEEE Trans. Power App. and Syst.*, May 1974, pp. 859-869
- Modified versions also exist, such as D. Jajicic and A. Bose, "A Modification to the Fast Decoupled Power Flow for Networks with High R/X Ratios, "*IEEE Transactions on Power Sys.*, May 1988, pp. 743-746

FDPF Approximations

The FDPF makes the following approximations:

1. $\left|G_{ij}\right| = 0$
2. $\left|V_i\right| \quad = \quad 1$
3. $\sin\theta_{ij} = 0 \qquad \cos\theta_{ij} = 1$

To see the impact on the real power equations recall

$$P_i \;=\; \sum_{k=1}^{n} V_i V_k (G_{ik}\cos\theta_{ik} + B_{ik}\sin\theta_{ik}) = P_{Gi} - P_{Di}$$

Which can also be written as

$$\frac{P_i}{V_i} \;=\; \sum_{k=1}^{n} V_k (G_{ik}\cos\theta_{ik} + B_{ik}\sin\theta_{ik}) = \frac{P_{Gi} - P_{Di}}{V_i}$$

FDPF Approximations

- With the approximations for the diagonal term we get

$$\frac{\partial \mathrm{P_i}}{\partial \theta_i} \approx \sum_{\substack{k=1 \\ k \neq i}}^{n} B_{ik} = -B_{ii}$$

The for the off-diagonal terms (k $\neq$ i) with **G=0** and **V=1**

$$\frac{\partial P_i}{\partial \theta_k} = -B_{ik} \cos \theta_{ik} \approx -B_{ik}$$

- Hence the Jacobian for the real equations can be approximated as –**B**

FPDF Approximations

- For the reactive power equations we also scale by V_i

$$\mathrm{Q_i} = \sum_{k=1}^{n} |V_i||V_k|(G_{ik} \sin\theta_{ik} - B_{ik} \cos\theta_{ik}) = Q_{Gi} - Q_{Di}$$

$$\frac{\mathrm{Q_i}}{V_i} = \sum_{k=1}^{n} V_k (G_{ik} \sin\theta_{ik} - B_{ik} \cos\theta_{ik}) = \frac{Q_{Gi} - Q_{Di}}{V_i}$$

- For the Jacobian off-diagonals we get

$$\frac{\partial Q_i}{\partial V_k} = -B_{ik} \cos\theta_{ik} \approx -B_{ik}$$

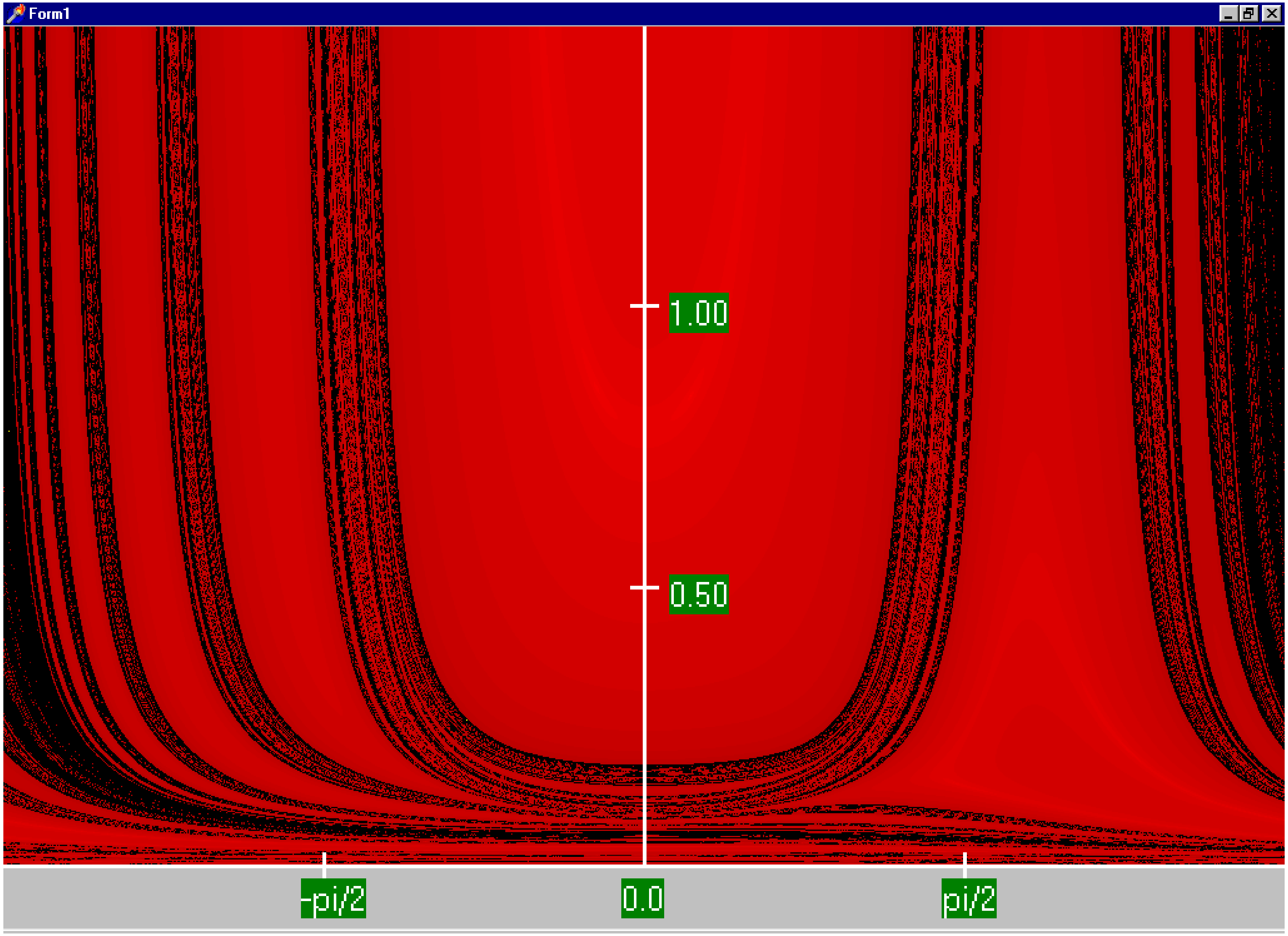
FDPF Approximations

- And for the reactive power Jacobian diagonal we get

$$\frac{\partial Q_{\mathrm{i}}}{\partial V_i} \approx -2B_{ii} - \sum_{\substack{k=1 \\ k\neq i}}^{n} B_{ik} = -B_{ii}$$

- As derived the real and reactive equations have a constant Jacobian equal to –**B**
  - Usually modifications are made to omit from the real power matrix elements that affect reactive flow (like shunts) and from the reactive power matrix elements that affect real power flow, like phase shifters
  - We’ll call the real power matrix **B**’ and the reactive **B**”

FDPF Region of Convergence



FDPF Cautions

- The FDPF works well as long as the previous approximations hold for the entire system
- With the movement towards modeling larger systems, with more of the lower voltage portions of the system represented (for which r/x ratios are higher) it is quite common for the FDPF to get stuck because small portions of the system are ill-behaved
- The FDPF is commonly used to provide an initial guess of the solution or for contingency analysis

DC Power Flow

- The "DC" power flow makes the most severe approximations:
  - completely ignore reactive power, assume all the voltages are always 1.0 per unit, ignore line conductance
- This makes the power flow a linear set of equations, which can be solved directly

$$\boldsymbol{\theta} = -\mathbf{B}^{-1}\,\mathbf{P}$$

P sign convention is generation is positive

- The term dc power flow actually dates from the time of the old network analyzers (going back into the 1930's)
- Not to be confused with the inclusion of HVDC lines in the standard NPF

DC Power Flow References

- I don’t think a classic dc power flow paper exists; a nice formulation is given in our book *Power Generation and Control* book by Wood, Wollenberg and Sheble
- The August 2009 paper in IEEE Transactions on Power Systems, “DC Power Flow Revisited” (by Stott, Jardim and Alsac) provides good coverage
- T. J. Overbye, X. Cheng, and Y. Sun, “A comparison of the AC and DC power flow models for LMP Calculations,” in *Proc. 37th Hawaii Int. Conf. System Sciences*, 2004, compares the accuracy of the approach

DC Power Flow Example

EXAMPLE 6.17

Determine the dc power flow solution for the five bus from Example 6.9.

SOLUTION With bus 1 as the system slack, the **B** matrix and **P** vector for this system are

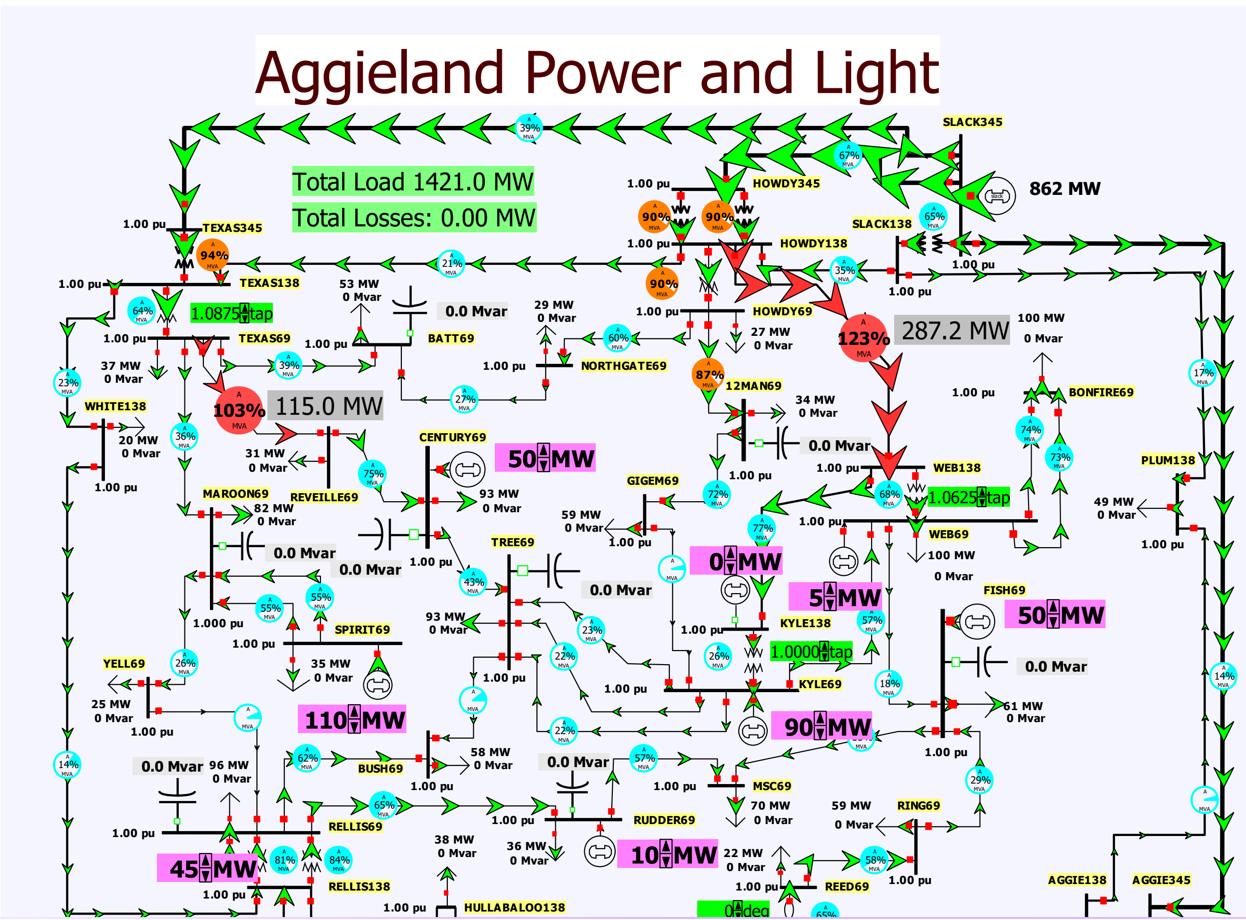
$$\mathbf{B} = \begin{bmatrix} -30 & 0 & 10 & 20 \\ 0 & -100 & 100 & 0 \\ 10 & 100 & -150 & 40 \\ 20 & 0 & 40 & -110 \end{bmatrix} \quad \mathbf{P} = \begin{bmatrix} -8.0 \\ 4.4 \\ 0 \\ 0 \end{bmatrix}$$

$$\boldsymbol{\delta} = -\mathbf{B}^{-1}\mathbf{P} = \begin{bmatrix} -0.3263 \\ 0.0091 \\ -0.0349 \\ -0.0720 \end{bmatrix} \text{radians} = \begin{bmatrix} -18.70 \\ 0.5214 \\ -2.000 \\ -4.125 \end{bmatrix} \text{degrees}$$

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

DC Power Flow in PowerWorld

- PowerWorld allows for easy switching between the dc and ac power flows (case **Aggieland37**)



To use the dc approach in PowerWorld select **Tools, Solve, DC Power Flow**

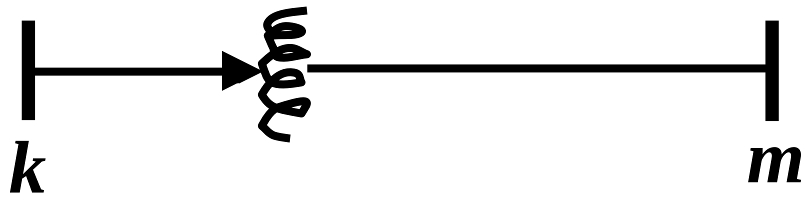
Notice there are no losses

Modeling Transformers with Off-Nominal Taps and Phase Shifts

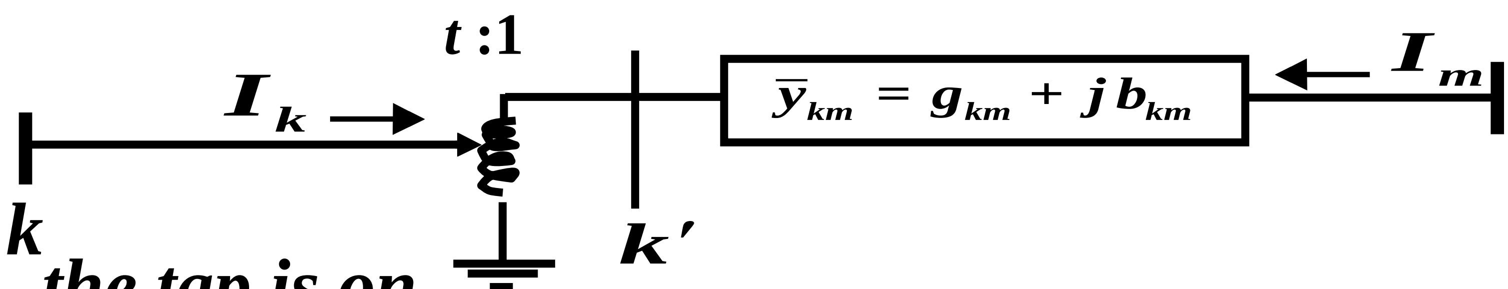
- If transformers have a turns ratio that matches the ratio of the per unit voltages than transformers are modeled in a manner similar to transmission lines.
- However it is common for transformers to have a variable tap ratio; this is known as an "off-nominal" tap ratio
  - The off-nominal tap is t, initially we'll consider it a real number
  - We'll cover phase shifters shortly in which t is complex

Transformer Representation

- The one–line diagram of a branch with a variable tap transformer



- The network representation of a branch with off–nominal turns ratio transformer is



the tap is on

the side of bus k

Transformer Nodal Equations

- From the network representation

$$\bar{I}_m = \bar{I}_{k'} = \bar{y}_{km}\left(\bar{E}_m - \bar{E}_{k'}\right) = \bar{y}_{km}\left(\bar{E}_m - \frac{\bar{E}_k}{t}\right)$$

$$= \left(\bar{y}_{km}\right)\bar{E}_m + \left(-\frac{\bar{y}_{km}}{t}\right)\bar{E}_k$$

- Also

$$\bar{I}_k = -\frac{1}{t}\bar{I}_{k'} = \left(-\frac{\bar{y}_{km}}{t}\right)\bar{E}_m + \left(\frac{\bar{y}_{km}}{t^2}\right)\bar{E}_k$$

Transformer Nodal Equations

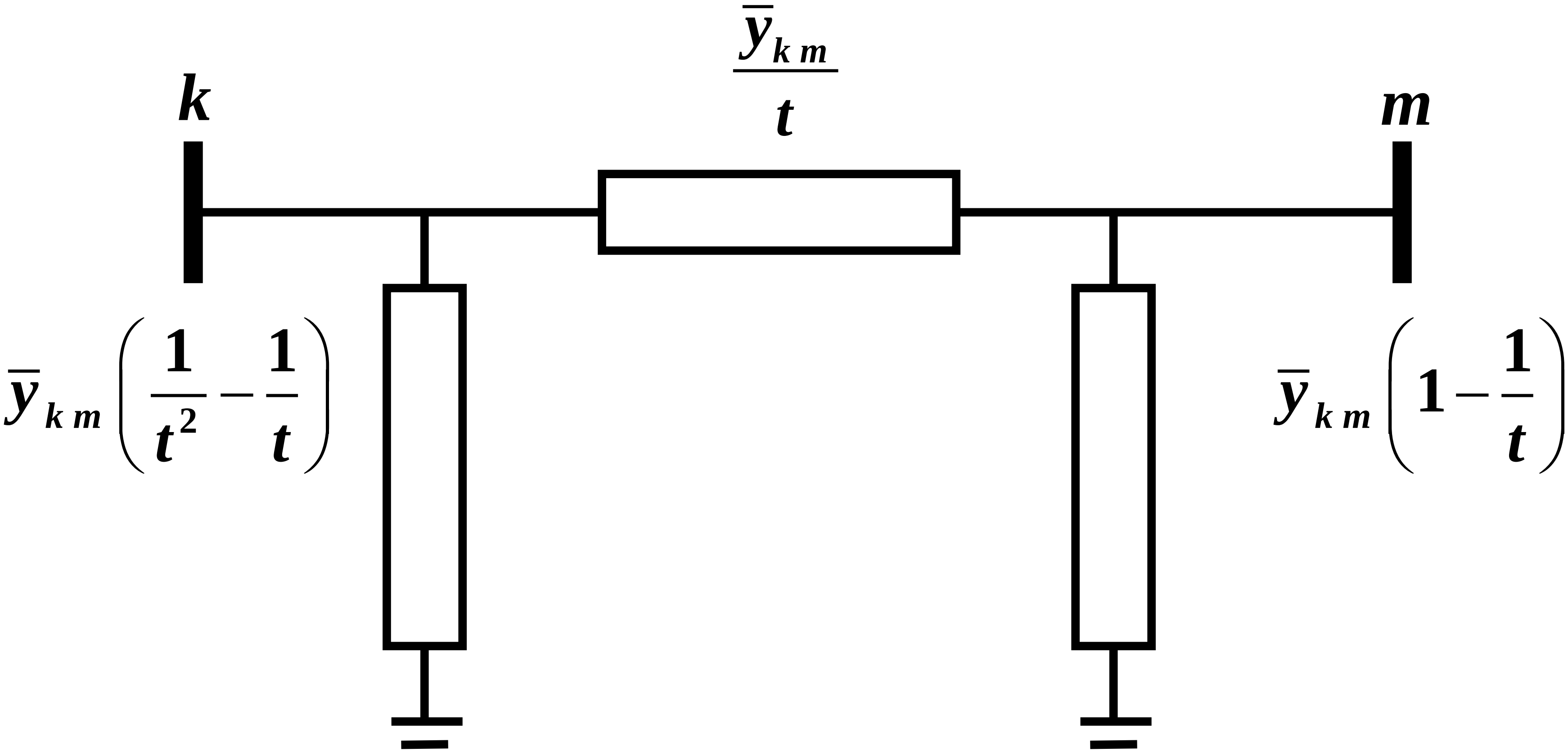
- We may rewrite these two equations as

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

Y$_{\text{bus}}$ is still symmetric here (though this will change with phase shifters)

This approach was first presented in F.L. Alvarado, "Formation of Y-Node using the Primitive Y-Node Concept," IEEE Trans. Power App. and Syst., December 1982

The π-Equivalent Circuit for a Transformer Branch



Variable Tap Voltage Control

- A transformer with a variable tap, i.e., the variable t is not constant, may be used to control the voltage at either the bus on the side of the tap or at the bus on the side away from the tap
- This constitutes an example of single criterion control since we adjust a single control variable (i.e., the transformer tap t) to achieve a specified criterion: the maintenance of a constant voltage at a designated bus
- Names for this type of control are on-load tap changer (LTC) transformer or tap changing under load (TCUL)
- Usually on low side; there may also be taps on high side that can be adjusted when it is de-energized

Variable Tap Voltage Control

- An LTC is a discrete control, often with 32 incremental steps of 0.625% each, giving an automatic range of $\pm$ 10%
- It follows from the π–equivalent model for the transformer that the transfer admittance between the buses of the transformer branch and the contribution to the self admittance at the bus away from the tap explicitly depend on t
- However, the tap changes in discrete steps; there is also a built in time delay in how fast they respond
- Voltage regulators are devices with a unity nominal ratio, and then a similar tap range

Ameren Champaign (IL) Test Facility Voltage Regulators

These are connected on the low side of a 69/12.4 kV transformer; each phase can be regulated separately