ECEN 460
Power System Operation and Control
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Lecture 4: Power System Operations

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Per Unit

- A problem in analyzing power systems is the large number of transformers.
  - It would be very difficult to continually have to refer transformer values (like their impedances) to the different sides of the transformers
- This problem is avoided by a normalization of all variables.
- This normalization is known as per unit analysis

$$\text{quantity in per unit} = \frac{\text{actual quantity}}{\text{base value of quantity}}$$

- Engineers commonly talk about voltages in per unit. A 138 kV (base) transmission line operating at 140 kV is 140/138 = 1.022 p.u.
- We will cover this more once we cover the transformer models

Power System Operations Overview

- Goal is to provide an intuitive feel for power system operation
- Emphasis will be on the impact of the transmission system
- Introduce basic power flow concepts through small system examples

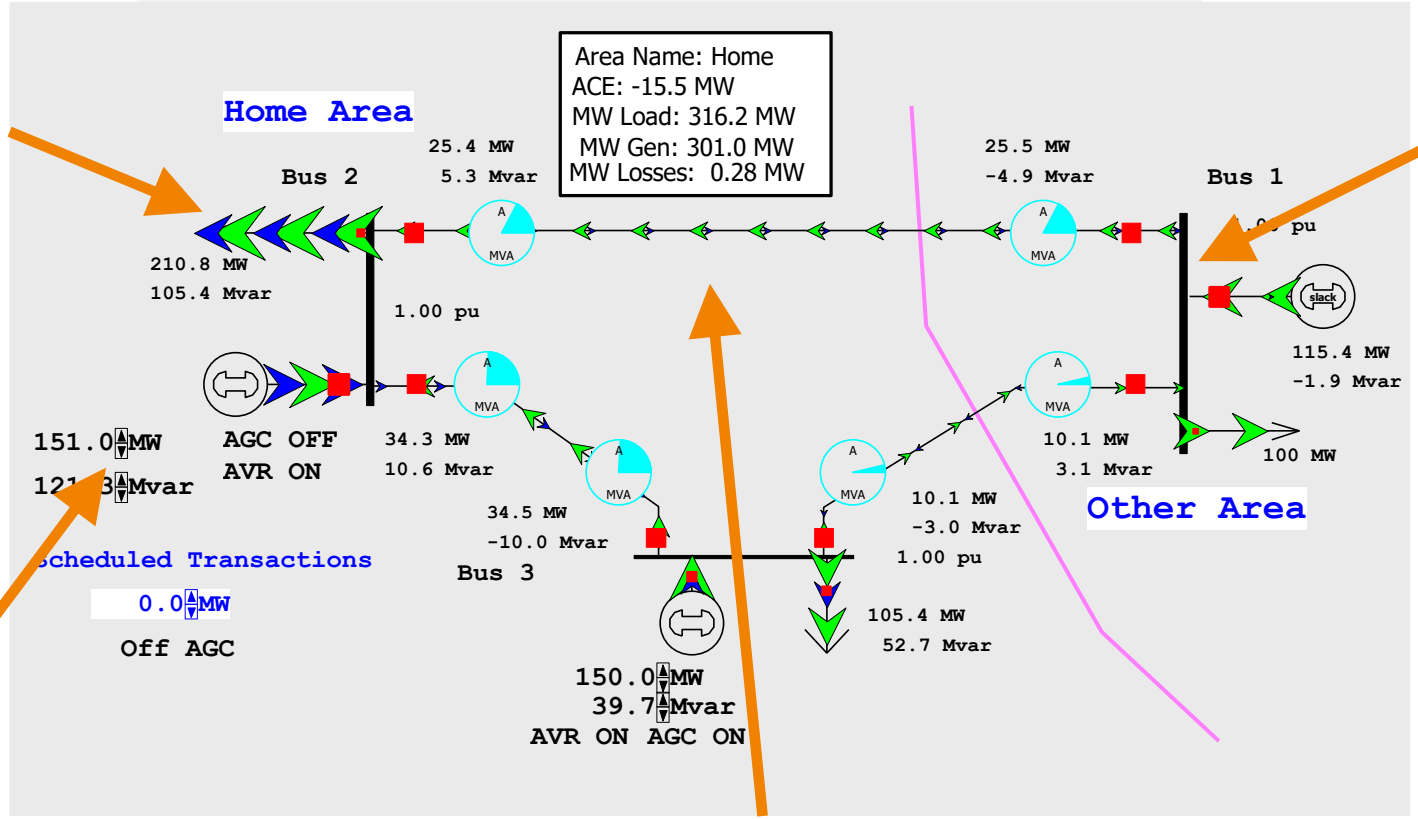
PowerWorld Simulator Basic Operation

- PowerWorld Simulator (PowerWorld) has lots of power system simulation capabilities. Initially we'll just use it to simulate the steady-state (quasi-static) operation of small electric grids
- PowerWorld power system cases are stored using two file types: 1) a *.pwb file to store the power system itself, and 2) a *.pwd file to store the displays. Often when opening a *.pwb it automatically opens a pwd file
- PowerWorld can run as a time-varying simulation; while this isn't the most common way it is used, it is a good place to start
- Start PowerWorld, and select **File, Open Case** and then use the dialog to select the case **B3Slow.pwb**

Three Bus PowerWorld Simulator Case

PowerWorld Case Name: **B3Slow**

Load with green arrows indicating amount of MW flow

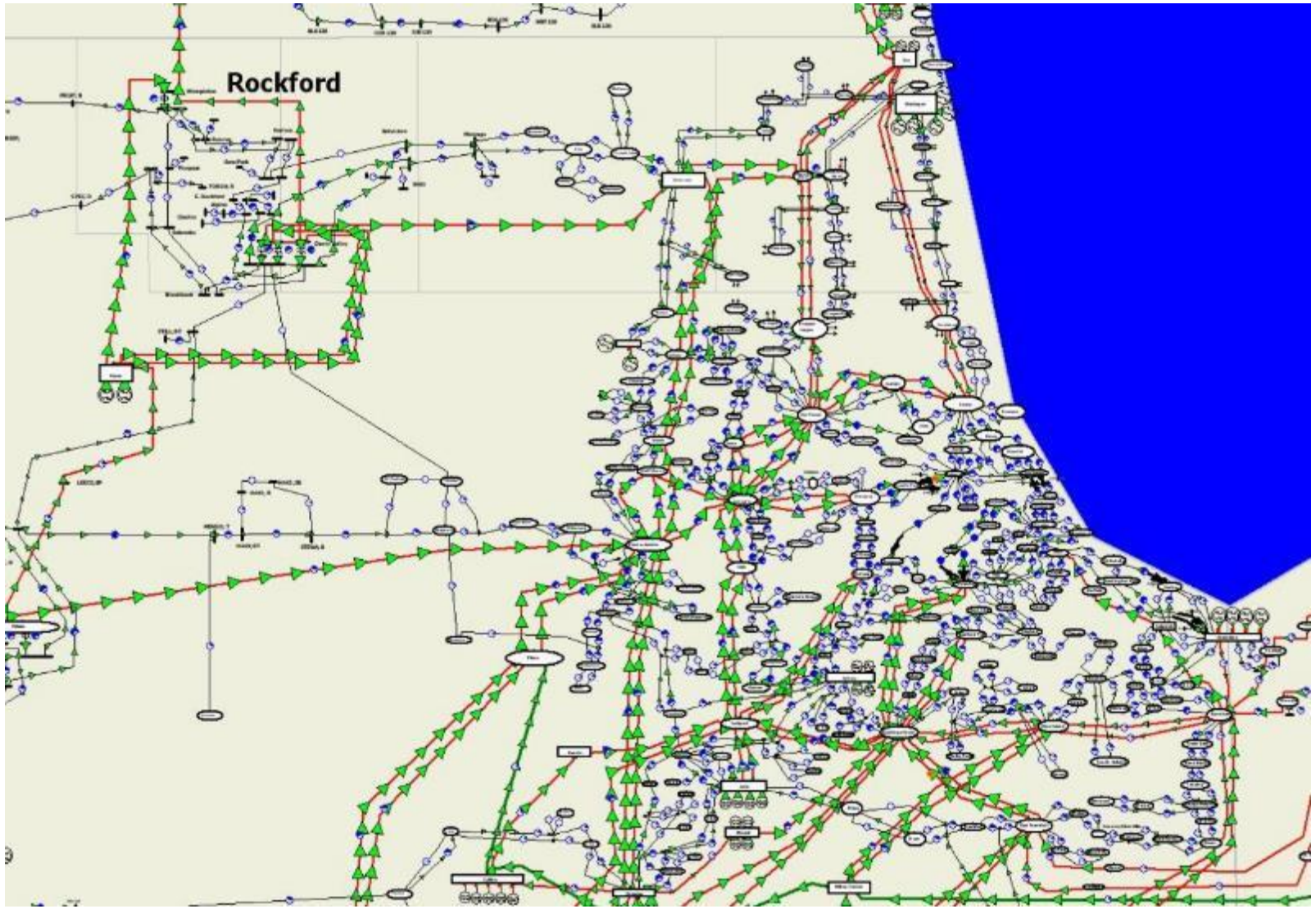


Note the power balance at each bus

Used to control output of generator

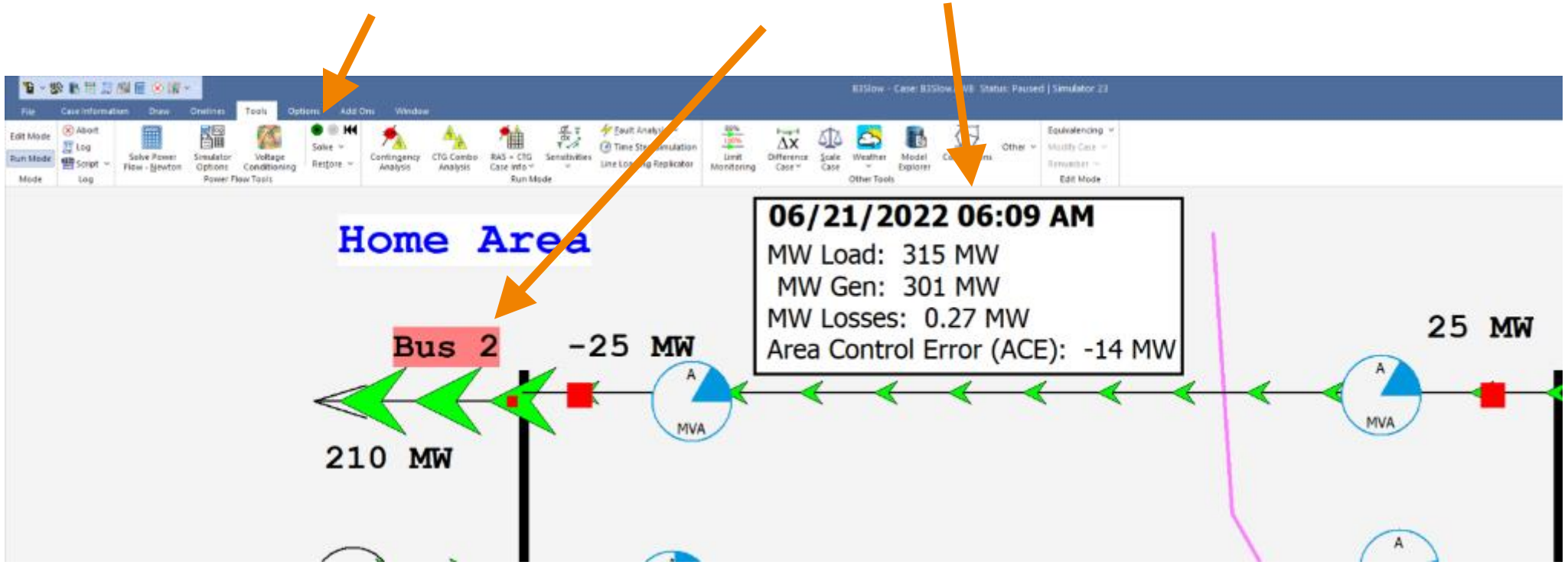
Direction of green arrow is used to indicate direction of real power (MW) flow; the blue arrows show the reactive power

A Larger Example: Metro Chicago Electric Network



Starting the Simulation

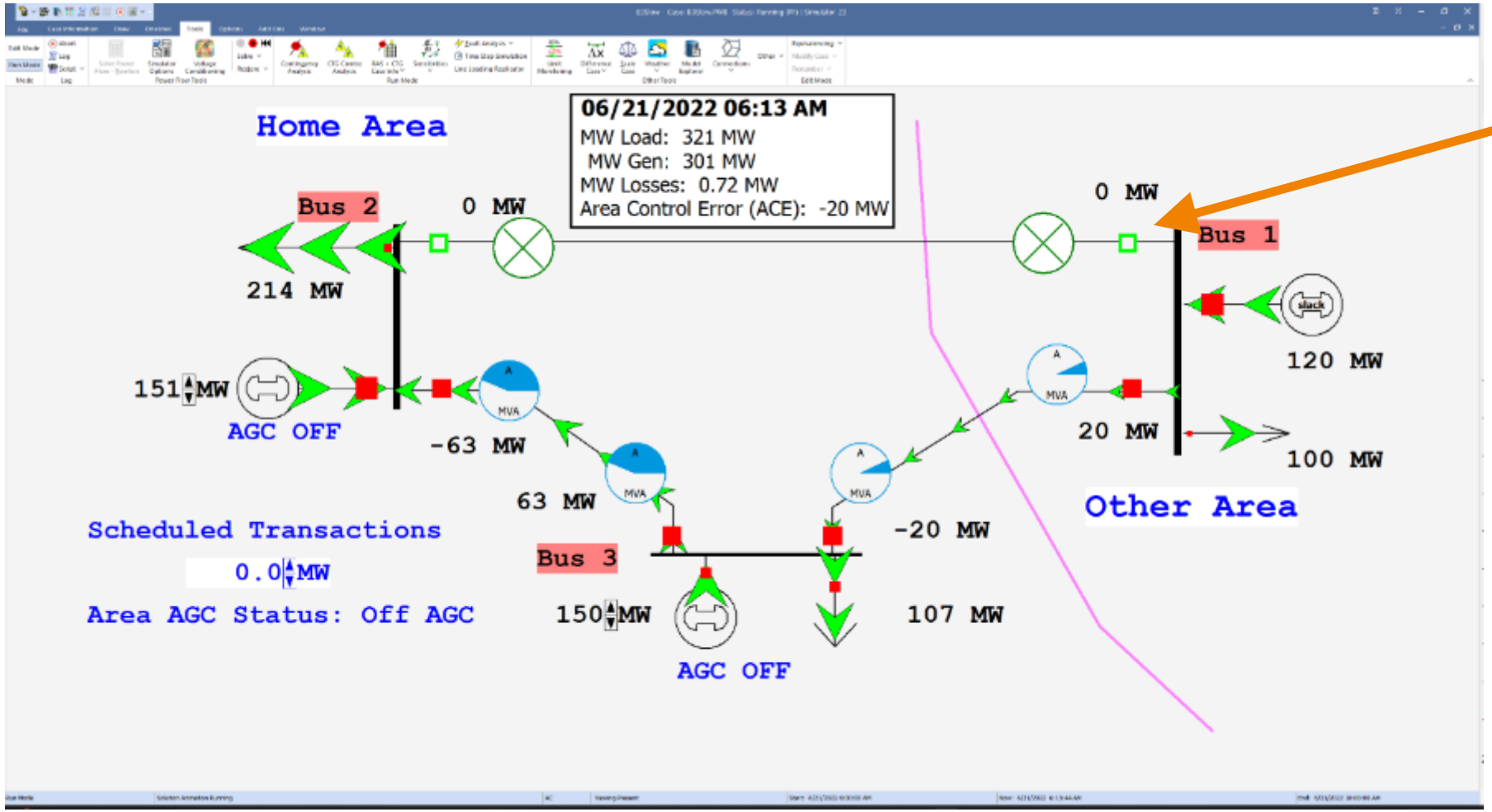
- Click the green arrow button to start the simulation; this is a very small grid the models the increase in the electric load that would occur in the morning



Basic Power Control

- Opening a red circuit breaker causes the power flow to quickly change.
- There is 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.
- The change isn’t really instantaneous because of propagation delays, which are near the speed of light; there also wave reflection issues; however, in the power flow time frame it looks to be instanteous

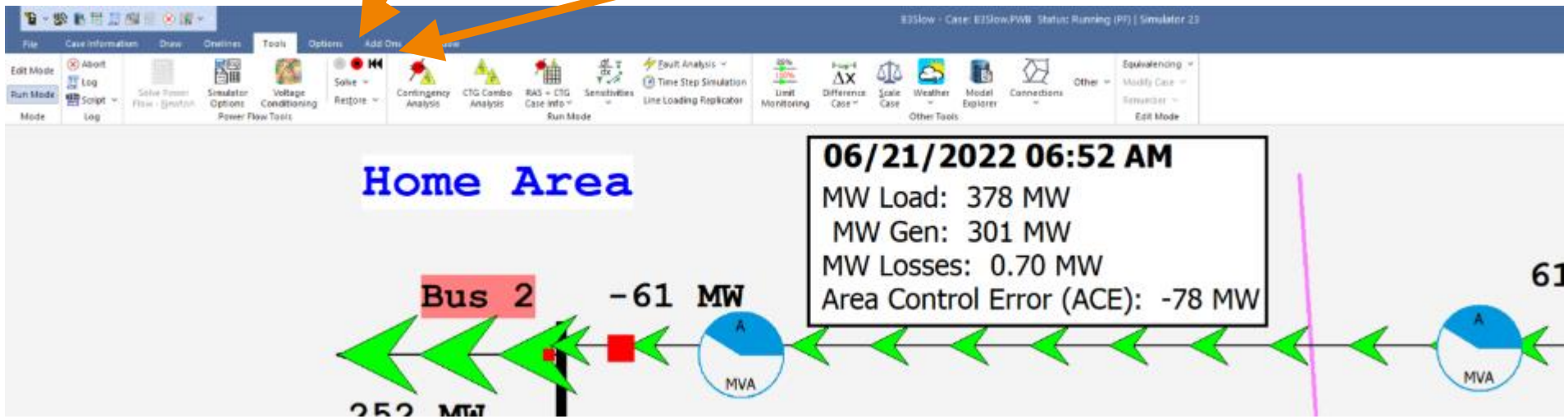
B3Slow Case with Open Line



When open the circuit breaker changes to a hollow green square; click it again to put the line back into service;

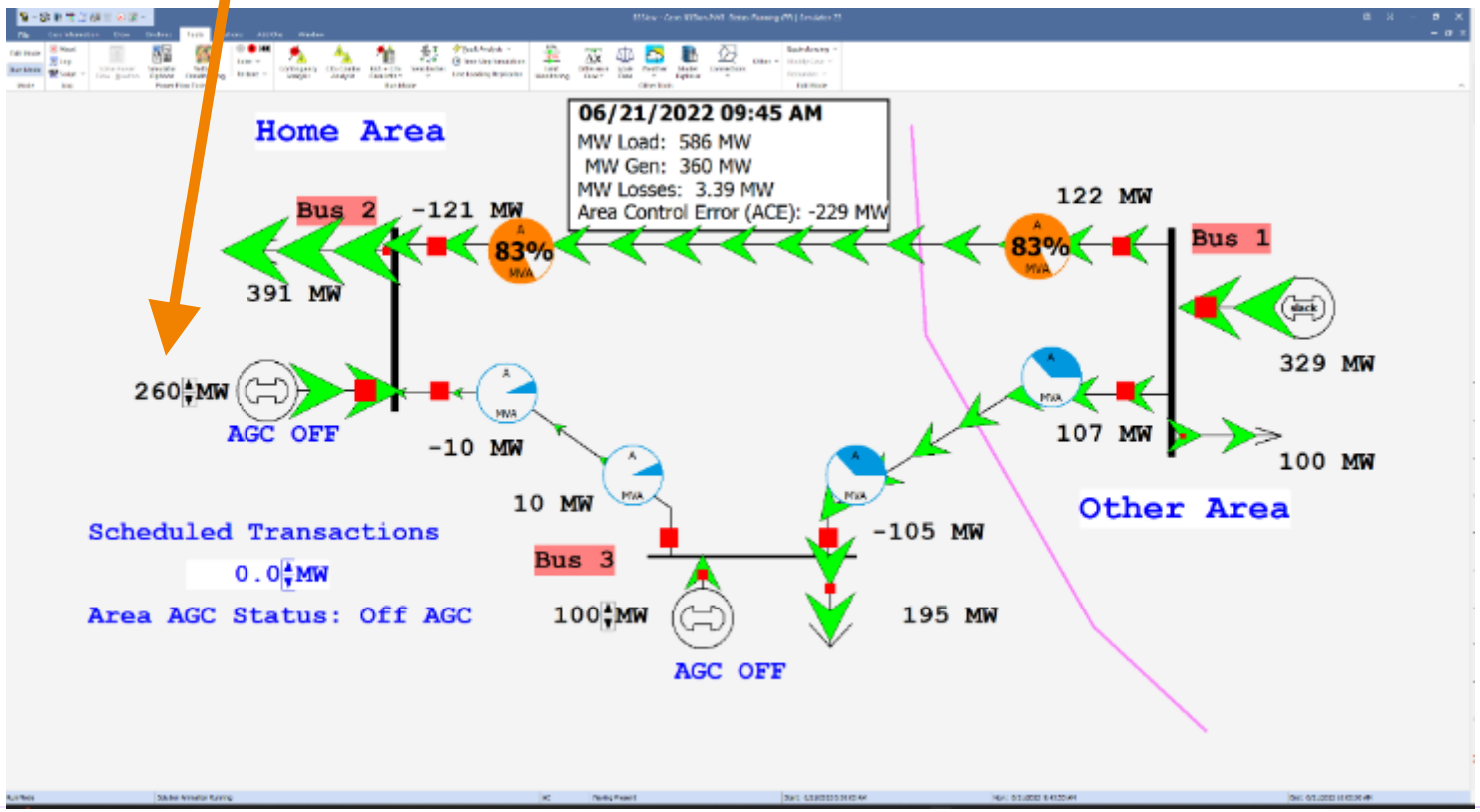
Resetting the Simulation

- The B3Slow simulation runs at 60 times real-time (one minute per second) and goes for 4 hours of simulation time. At any point it can be paused by clicking on the red button or reset using the reset button



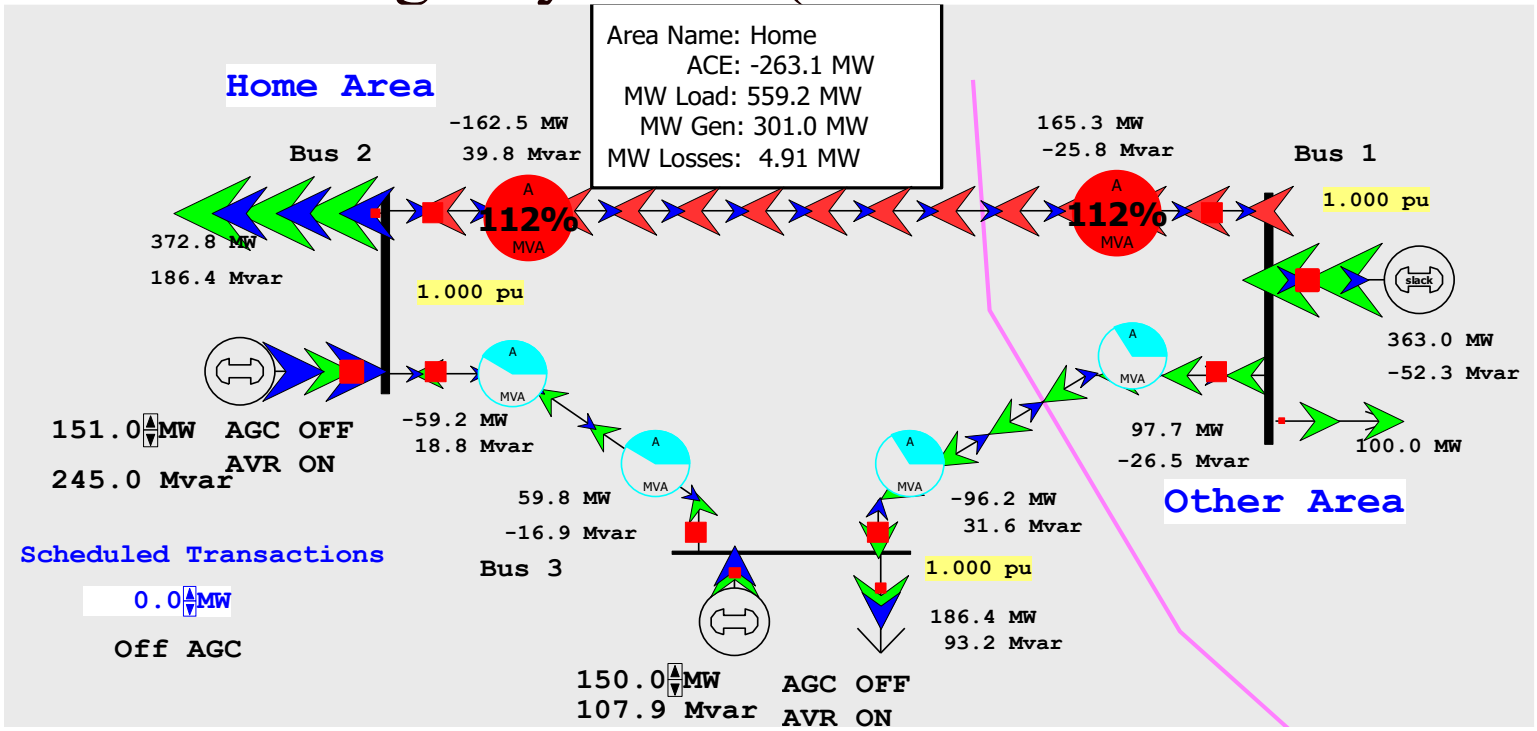
Indirect Line Flow Control By Changing Generation

- The flow on the transmission lines can be indirectly controlled by changing the power output of the generators; click on the arrows next to the Bus 2 and Bus 3 generator to change their outputs



Transmission Line Limits

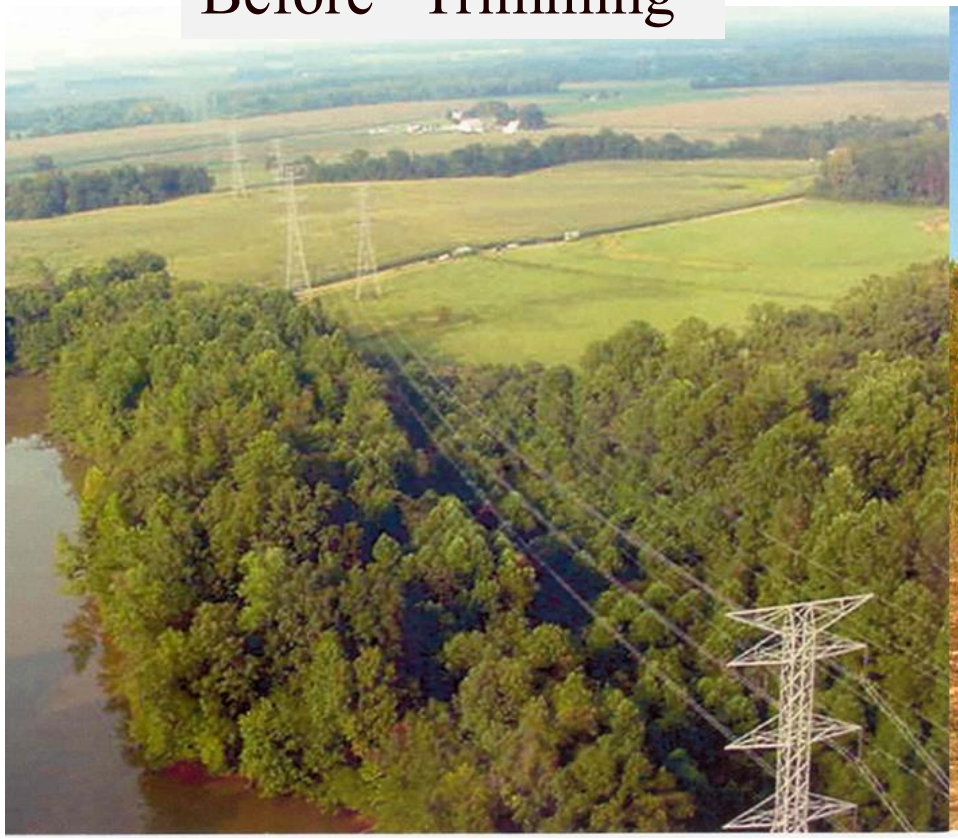
- Power flow in transmission line is limited by heating considerations
  - Losses ($I^2 R$) can heat up the line, causing it to sag
- Each line has a set of limits; many utilities use winter/summer limits and normal/emergency limits (there are other limits we'll consider later)



Transmission Lines and Trees

- We like trees, and they grow; but when trees get close to lines bad things can occur

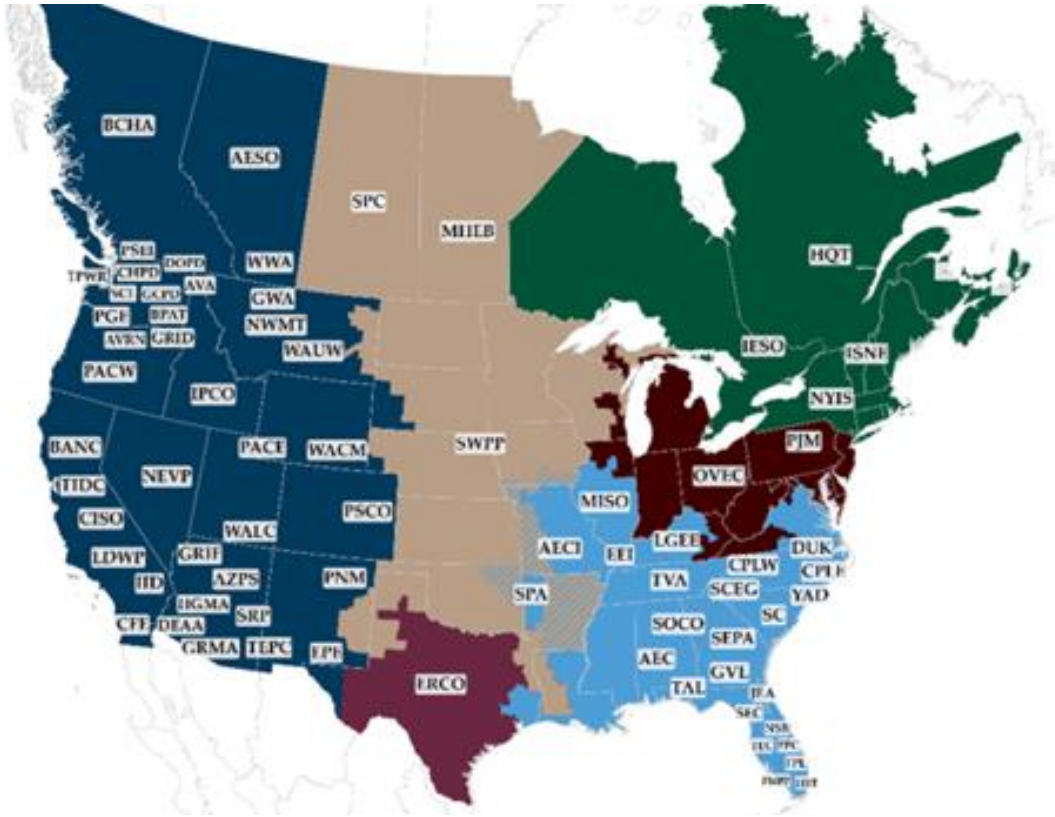
Before “Trimming”



After “Trimming”

Interconnected Operations

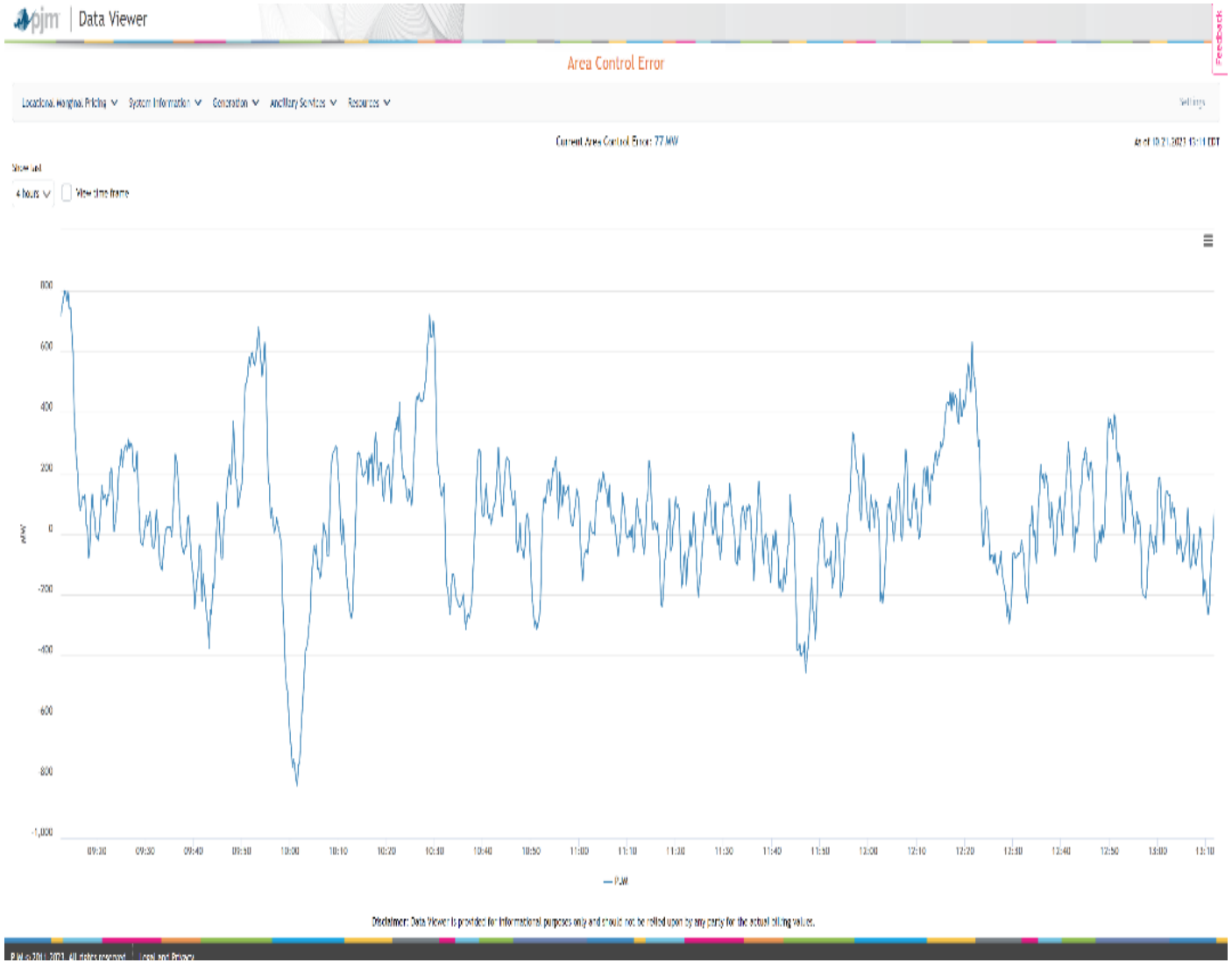
- Power systems are interconnected, with North America having the previously mentioned four large interconnects
- Interconnects are divided into smaller portions, called balancing authority areas (previously called control areas); the power flow between these areas is controlled by a process known as automatic generation control
  - ERCOT is just a single area



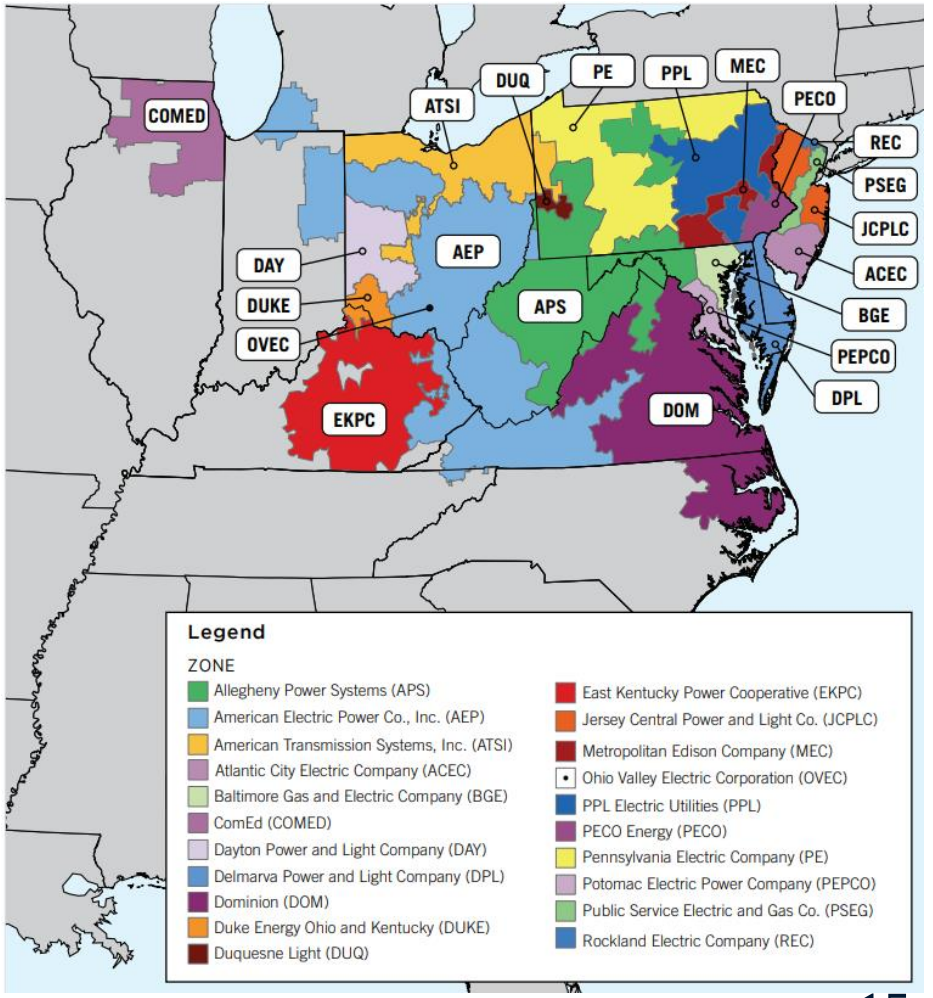
Area Control Error (ACE)

- 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
- In the B3Slow simulation, to visualize the Home Area ACE right click on the Area Control Error field and select **Show Strip Chart**

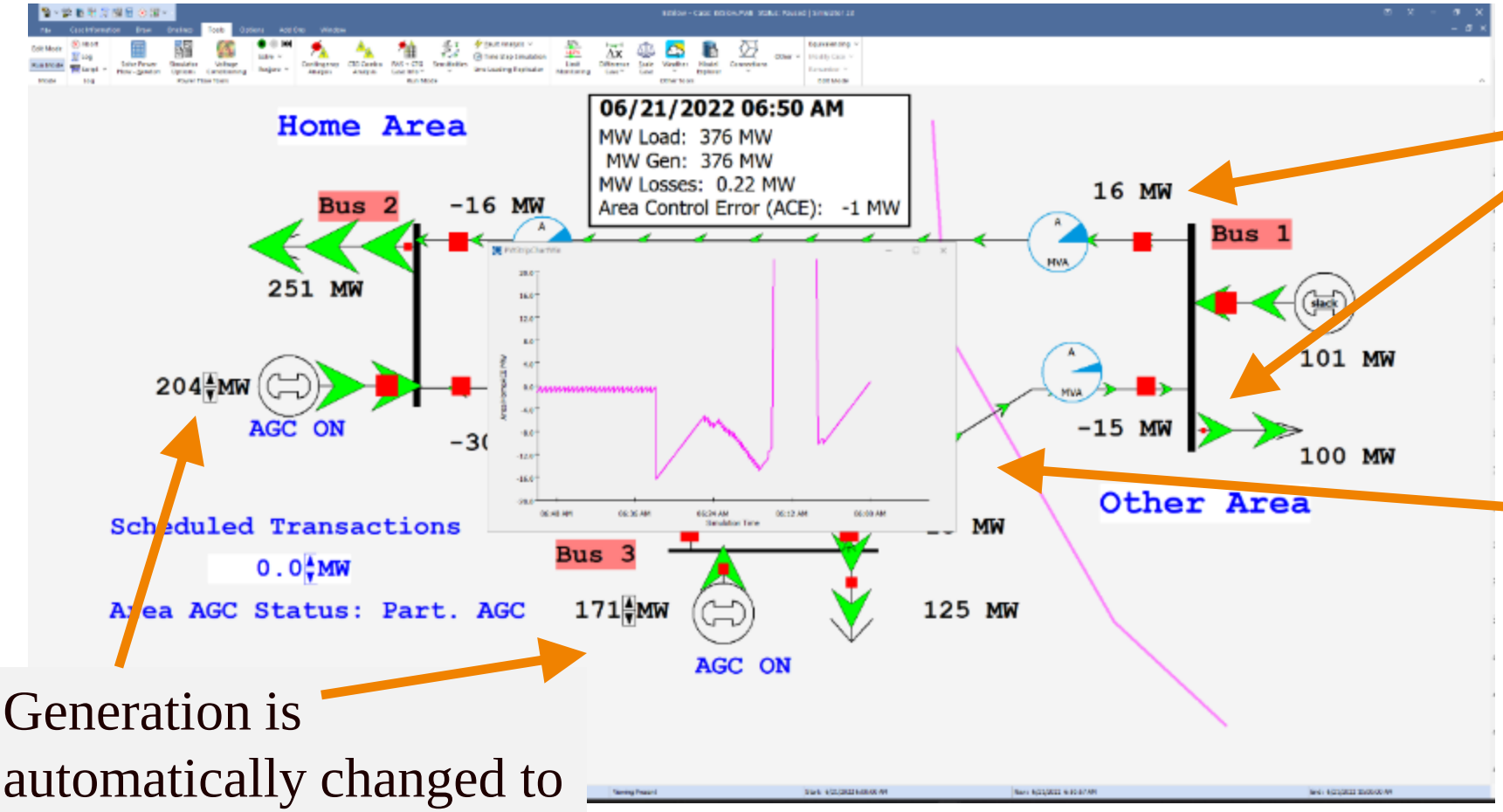
PJM Area Control Error on Oct 21, 2023



PJM Utility Map



Three Bus Case Showing ACE Strip Chart



Net tie flow is close to zero

Strip Chart

Generation is automatically changed to match change in load

Automatic Generation Control

- In PowerWorld one way the ACE can be changed by manually varying the generation in the area, for example increasing it as the load increases
- 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.

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.

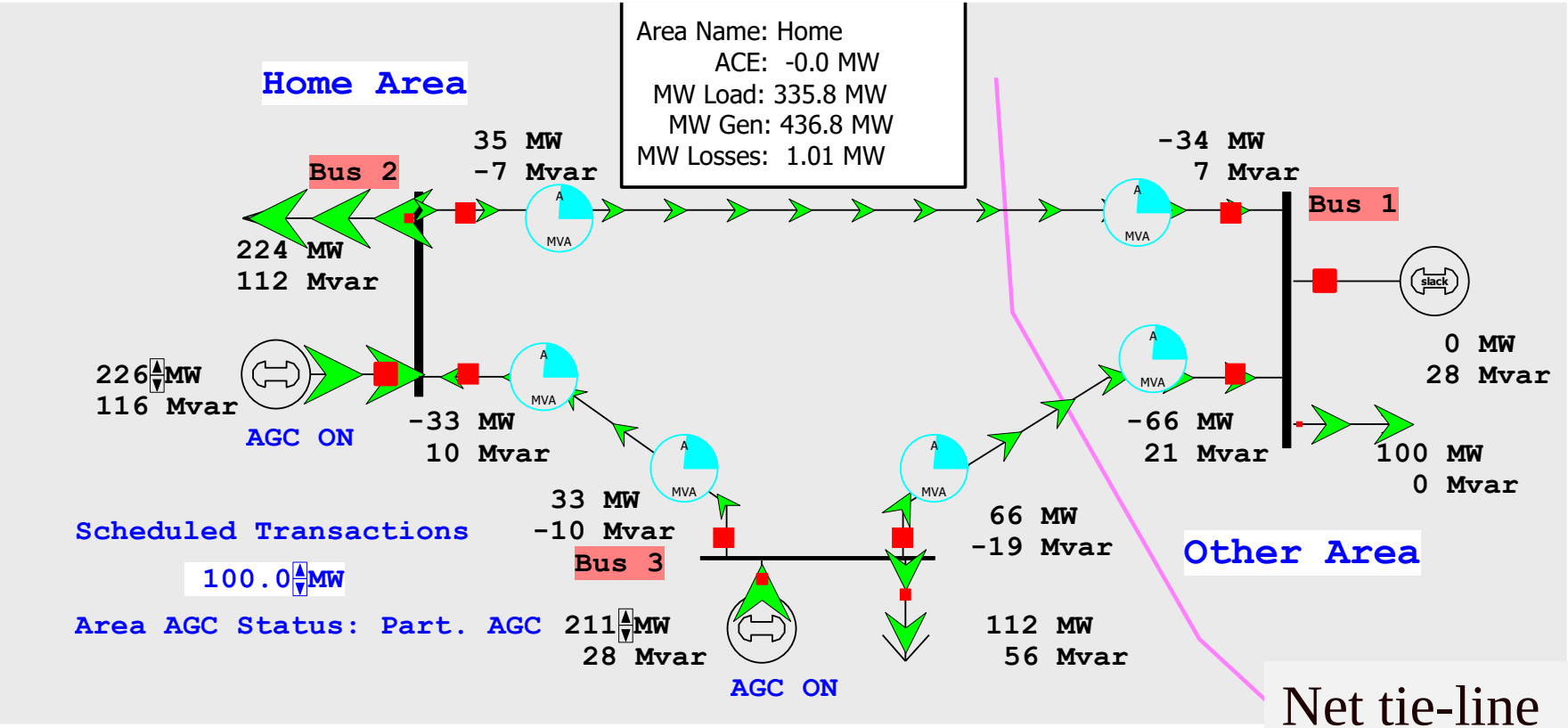
$$IC_1(P_{G,1}) = IC_2(P_{G,2}) = \ldots = IC_m(P_{G,m})$$

Power Transactions

- Power transactions are contracts between areas to transfer power
- 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



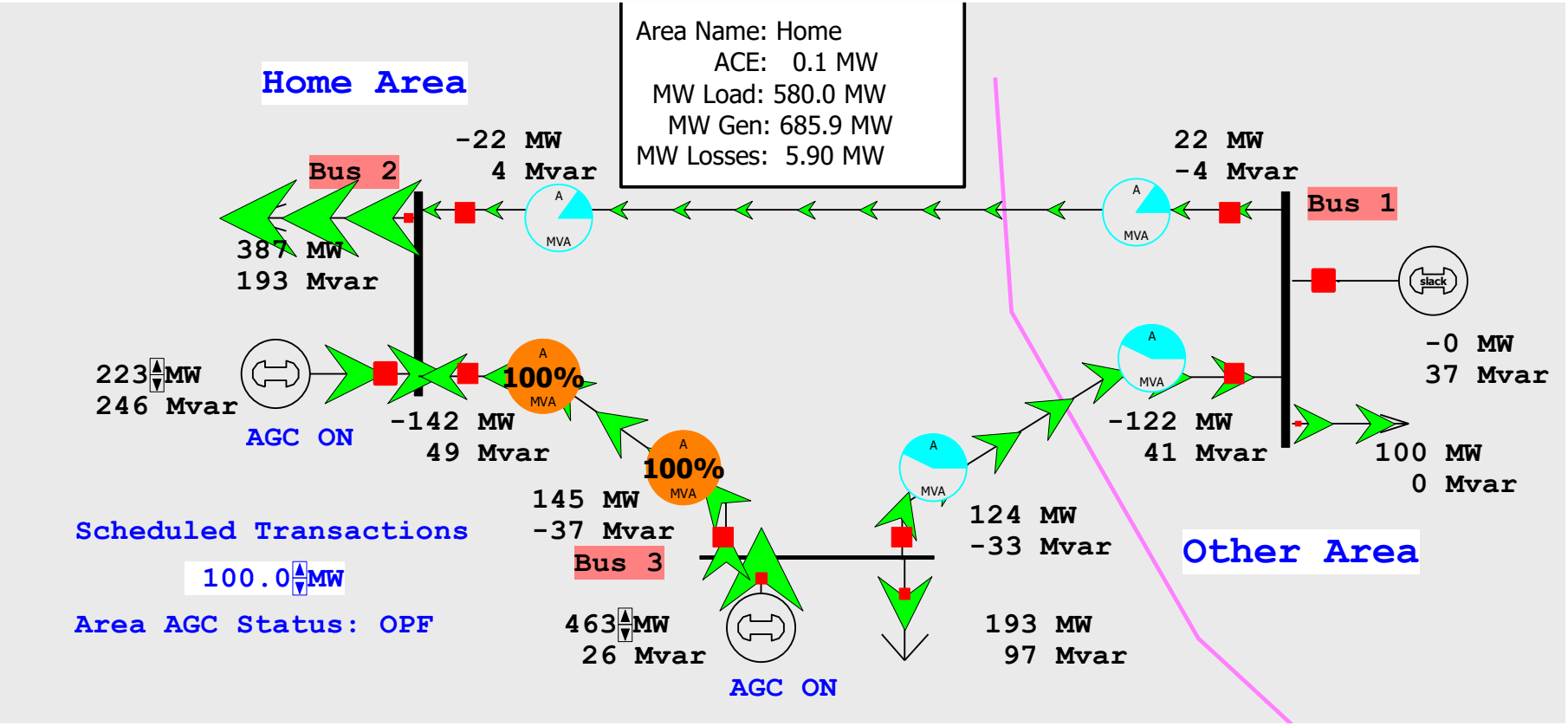
Net tie-line flow is now 100 MW

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

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

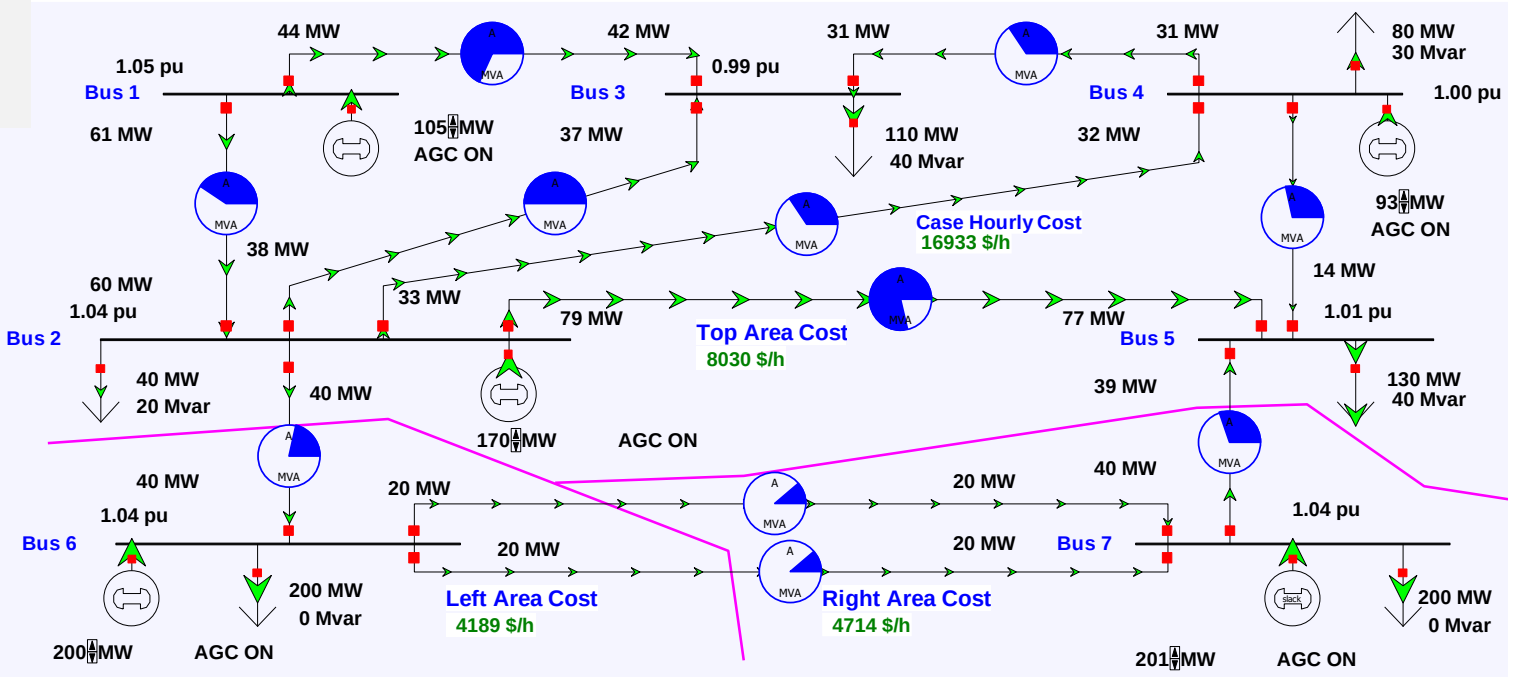
Multi-Area Operation

- 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

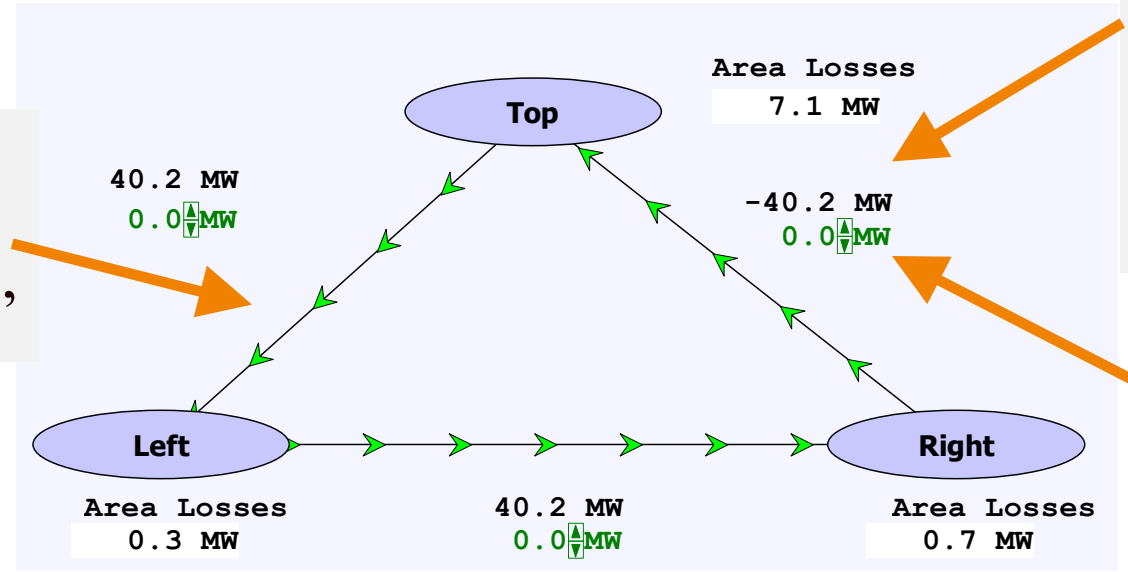


Area Left has one bus

Area Right has one bus

PowerWorld Case: **B7Flat**

Seven Bus Case: Area View



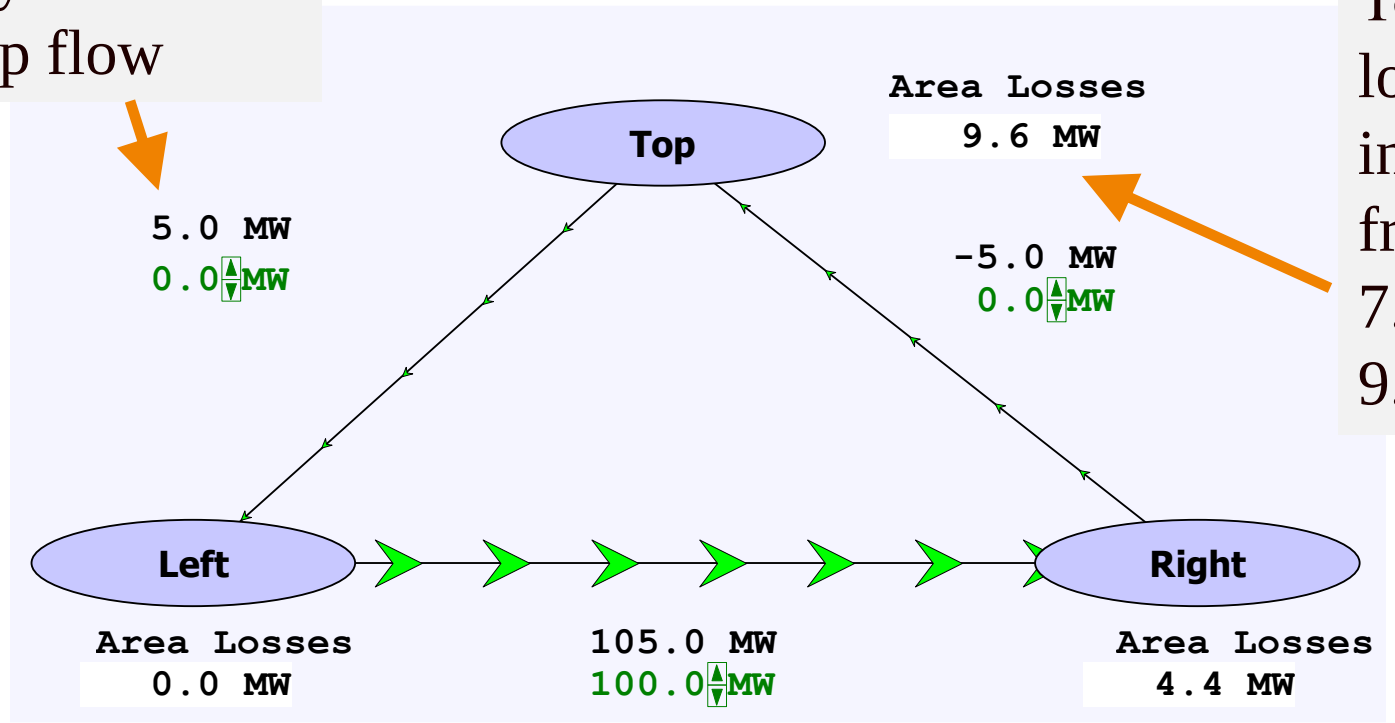
System has 40 MW of "Loop Flow"

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

Reactive Power

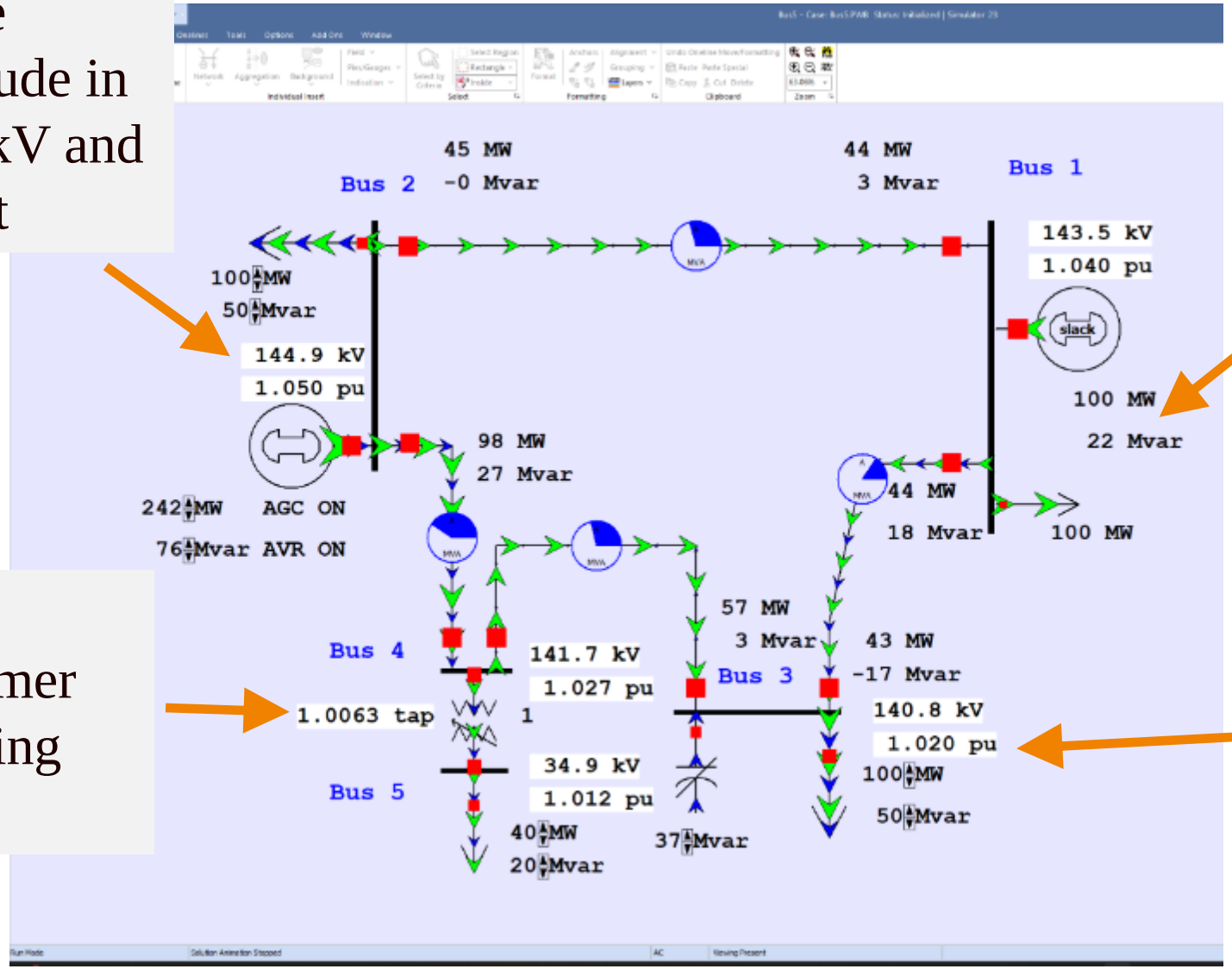
- Reactive (or imaginary) power doesn't really exist, but is rather only defined mathematically. However, power system analysis is much simpler if we think of it as existing
- Hence it is thought of as similar to real power; it is supplied by
  - generators, capacitors, transmission lines
- Reactive power is consumed by
  - loads
  - transmission lines/transformers (high losses)
- Reactive power doesn't travel well - must be supplied locally.
- Reactive must satisfy Kirchhoff's law - total reactive power into a bus MUST be zero.

Voltage Magnitude

- Power systems must supply electric power within a narrow voltage range, typically with 5% of a nominal value.
- For example, wall outlet should supply
  120 volts, with an acceptable range from 114 to 126 volts.
- Voltage regulation performed mostly by generators, LTC transformers and capacitors
- Reactive power and voltage magnitude are quite closely coupled; this is illustrated using the case **Bus5**

Bus 5 Case Illustrating Reactive Power and Voltage

Voltage magnitude in actual kV and per unit



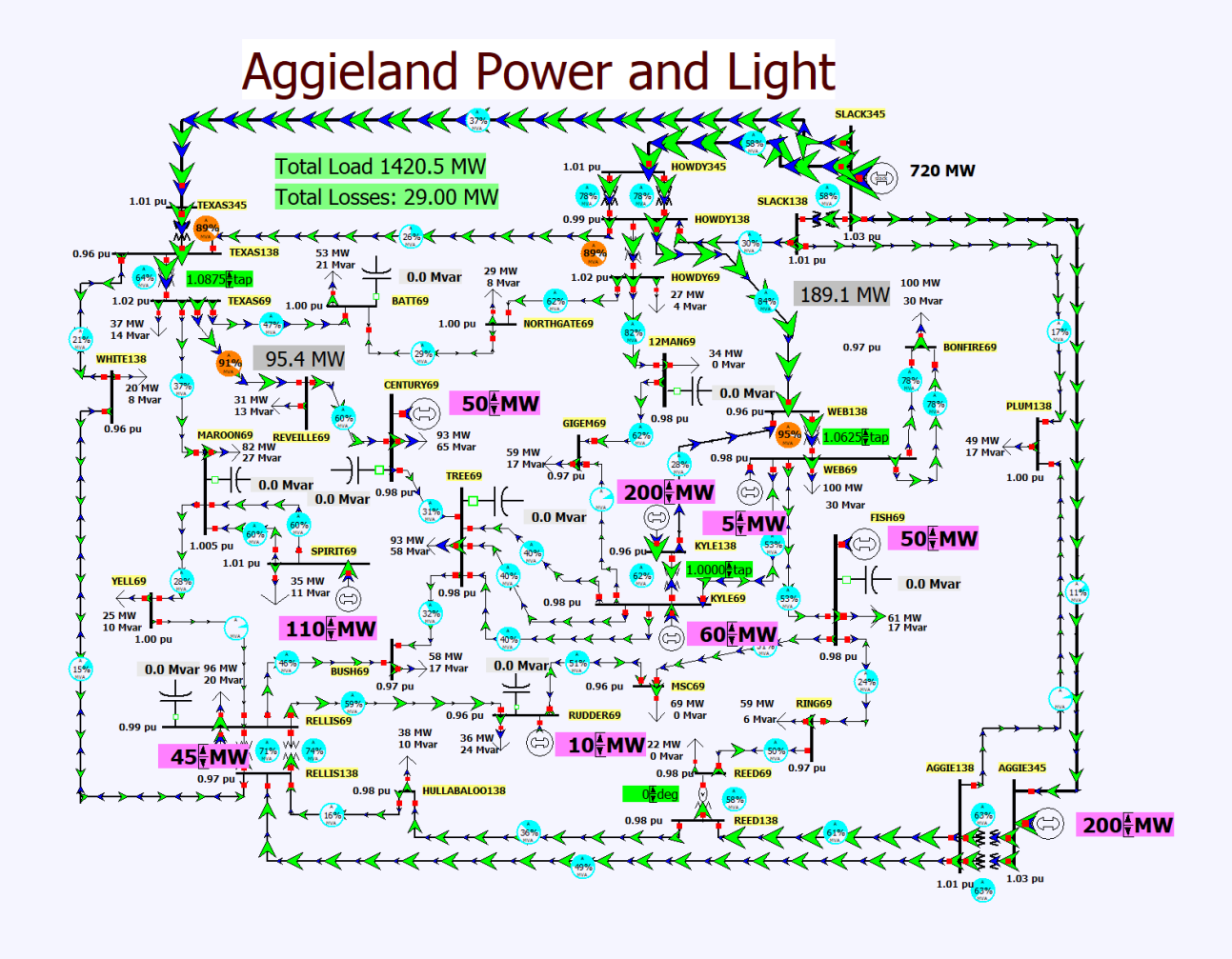
Reactive power supplied by generator

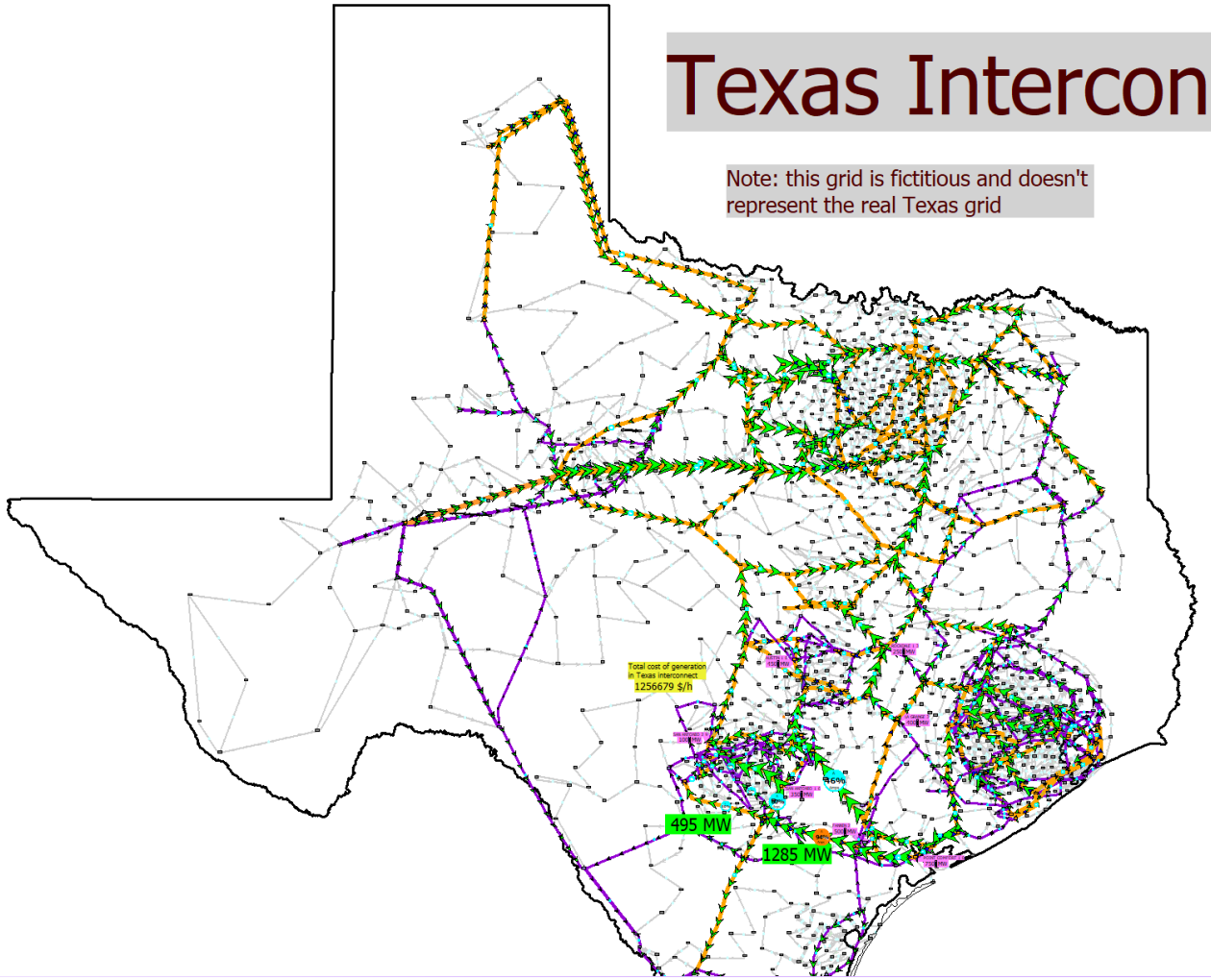
LTC transformer controlling voltage

Voltage magnitude controlled by capacitor

37-Bus Grid

- This is the smaller Lab 2 case, before the initial contingency



2000-Bus Case

- This is the larger Lab 2 case before the initial contingency