ECEN 460, Spring 2026
Power System Operation and Control

Class 10: Power System Control Principles

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Exam 1

- Tuesday, Feb. 17th, 2026, in-class (75 minutes)
- Closed-book, closed-notes, except you may use one 8.5”x11” handwritten note sheet, front and back
- Main topics:
  - Three-phase AC circuit analysis
  - Power systems overview, structure, and history
  - Generators
  - Transformers and per-unit
  - Transmission lines
  - Power system operations and control topics (this week and in lab)
- Make sure to study (1) quizzes (2) lecture notes (3) homework (4) labs (5) book Chapters 1-5.

Control in a Power System

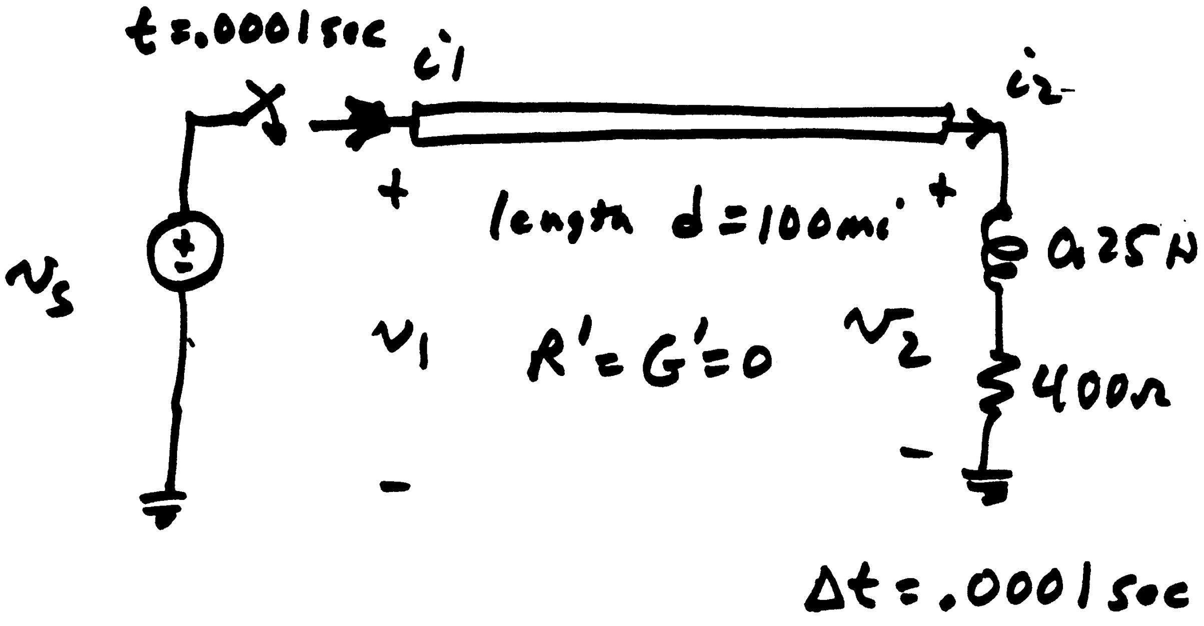
- We're going to focus on control of two things in the power system
  1. **Real power flow through transmission lines**
  2. **Bus voltage**

Direct Power Flow Control

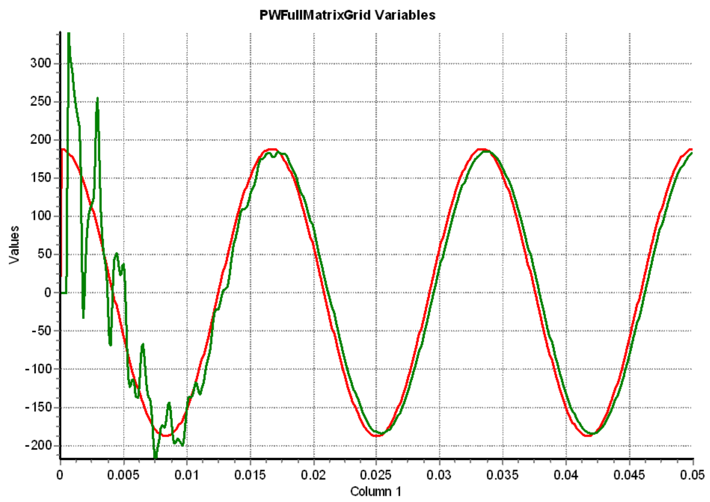
- **The only direct way to control the power through a line is by opening and closing its associated circuit breakers**
  - This will cause the line flow to almost instantaneously change.
  - There is no other way to directly control line flow – i.e. no "valves" as in piping.
  - Note that opening a line because it is overloaded is usually a bad idea, because the flows will have to redistributed to other lines, potentially causing a cascade!

Modeling Consideration – Change is Not Really Instantaneous!

- The change isn't really instantaneous because of propagation delays, which are near the speed of light; there also wave reflection issues
  - This is covered in chapters 5 and 13

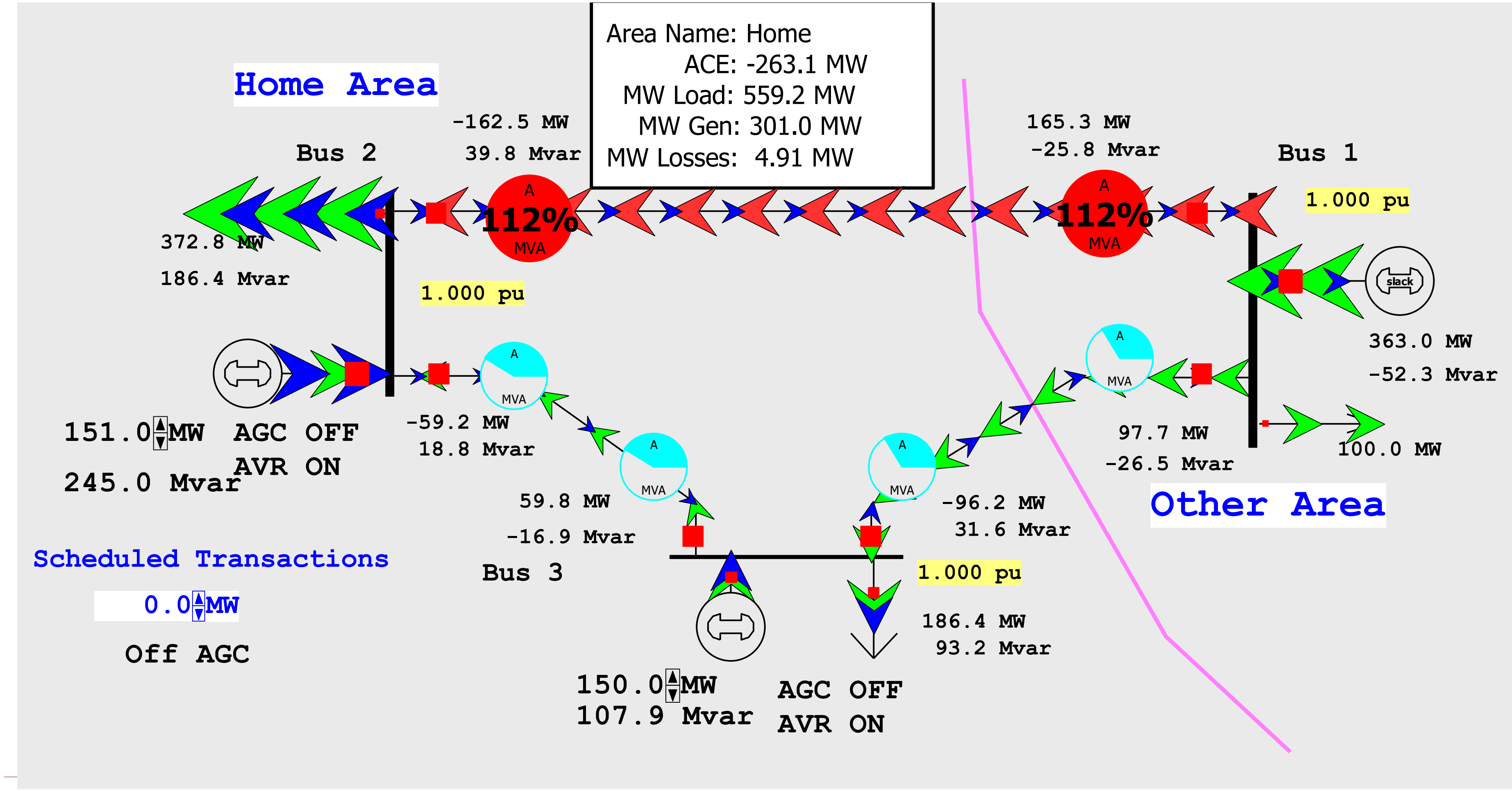


Red is the v_s end, green the v_2 end



Indirect Transmission Flow Control

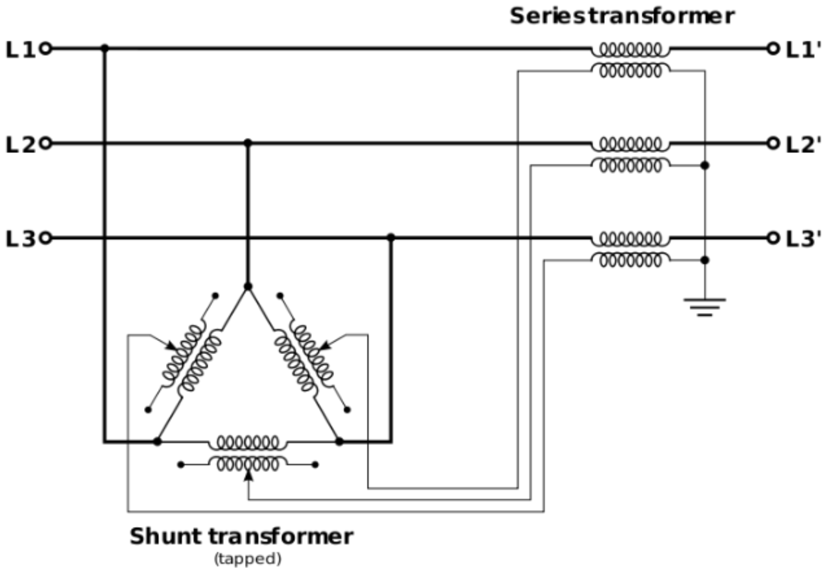
- **Indirect transmission flow control can be done by changing generator outputs.**



Example of an overloaded transmission line. To fix this, indirectly change the flow by adjusting generator outputs.

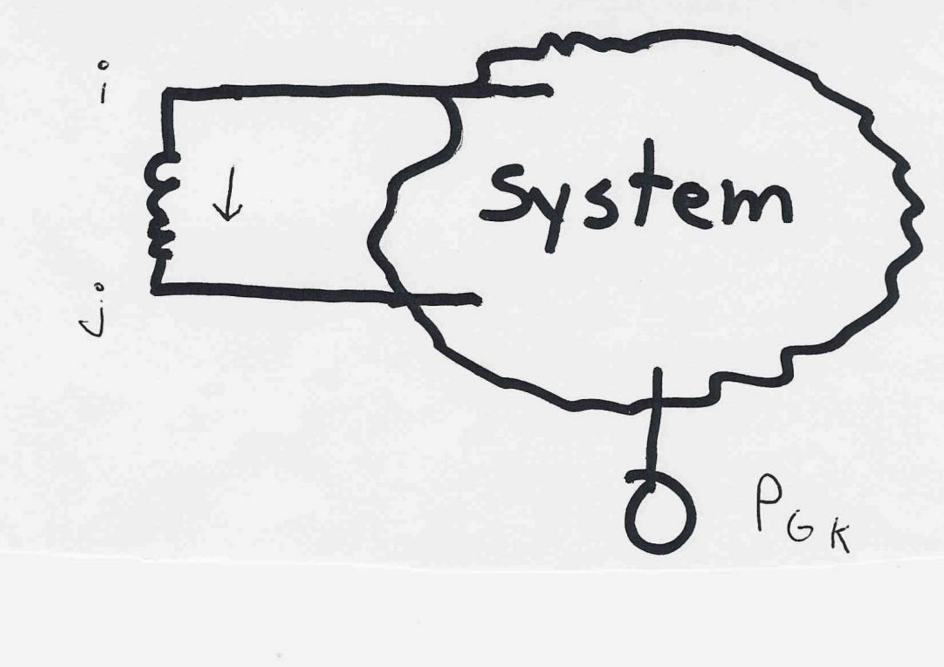
Adjusting Angles for Power Flow Control

- **Real power flow is closely tied with the phase angle of the bus voltage.**
  - We will see why when we write out the power flow equations
  - A general rule of thumb is that real power will flow from larger angles to smaller angles
  - This is also why phase angle regulating transformers can be used to help control real power flows indirectly.



Sensitivities for Power Flow Control

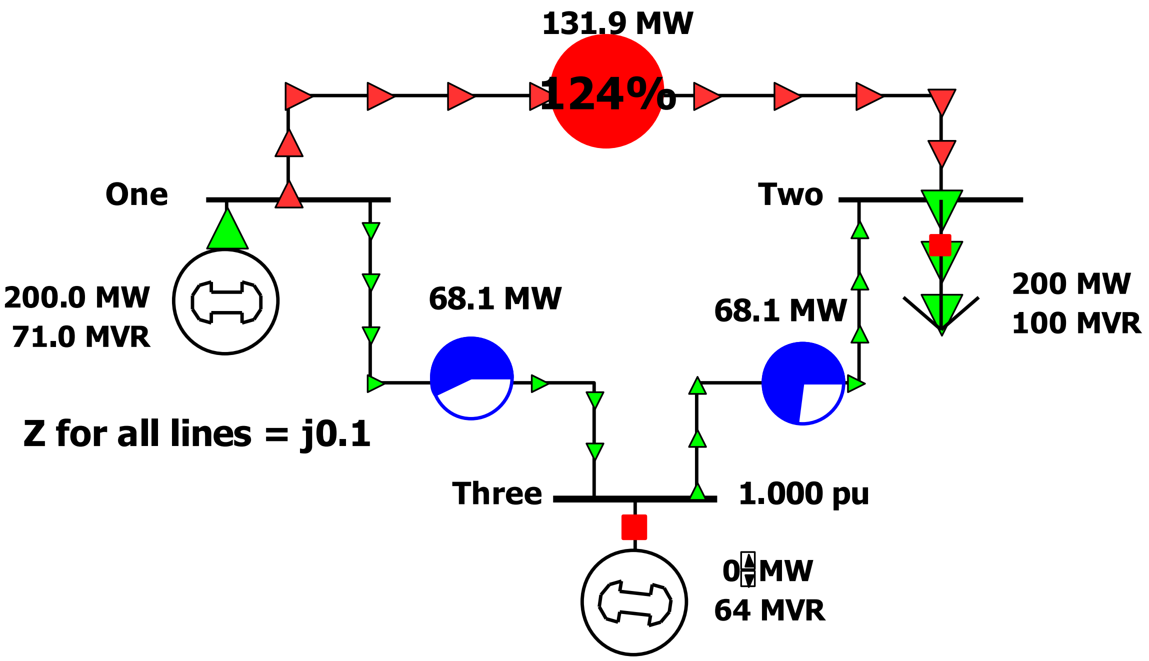
- **Sensitivities can be helpful to explain how different power values are related to each other, to give insights into control.**



The assumption is that the change in generation is absorbed by a “slack bus” which we will introduce later

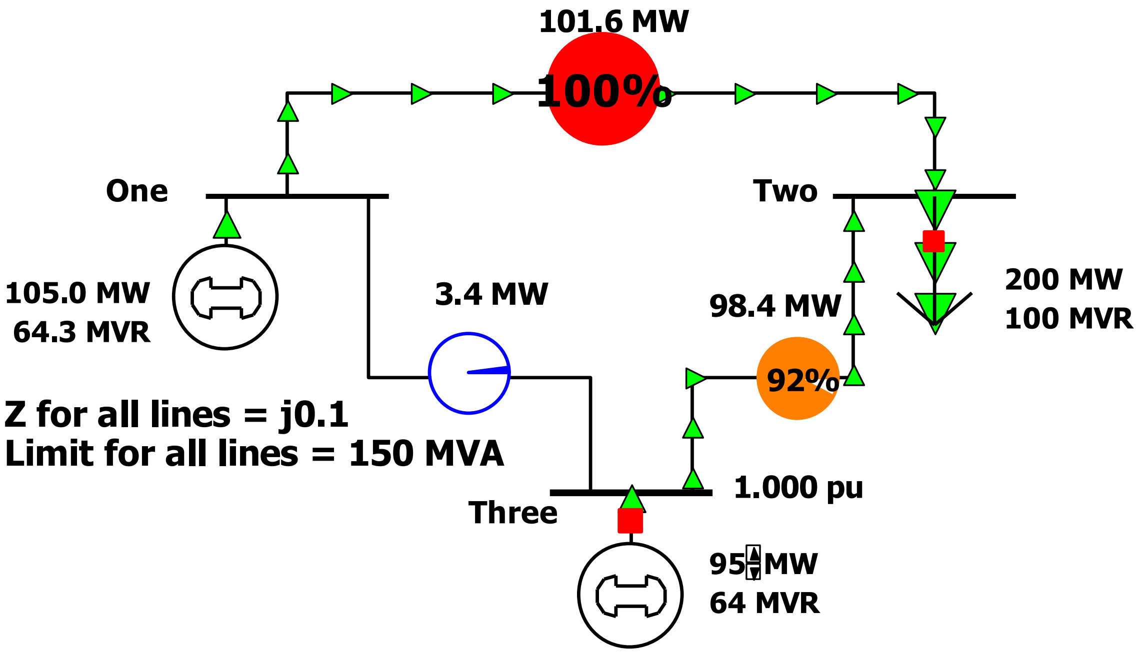
Power Flow Simulation - Before

- One way to determine the impact of a generator change is to compare a before/after power flow.
- For example below is a three bus case with an overload



Power Flow Simulation - After

- Increasing the generation at bus 3 by 95 MW (and hence decreasing it at bus 1 by a corresponding amount), results in a 30.3 MW drop in the MW flow on the line from bus 1 to 2, and a 64.7 MW drop on the flow from 1 to 3.



Expressed as a percent, 30.3/95 =32% and 64.7/95=68%

Analytic Calculation of Sensitivities

- Calculating control sensitivities by repeat power flow solutions is tedious and would require many power flow solutions. An alternative approach is to analytically calculate these values

The power flow from bus i to bus j is

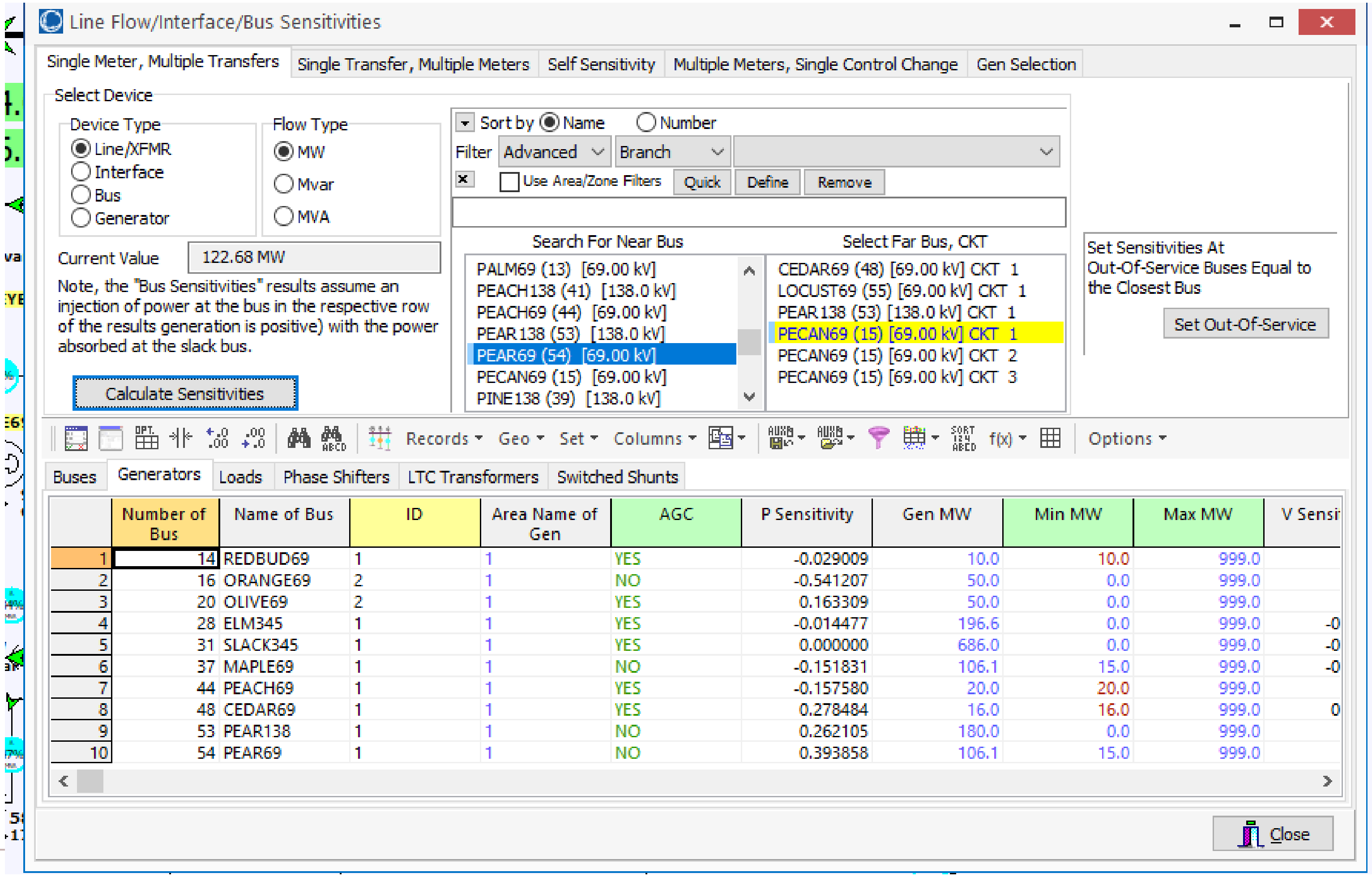
$$P_{ij} \approx \frac{|V_i||V_j|}{X_{ij}} \sin(\theta_i - \theta_j) \approx \frac{\theta_i - \theta_j}{X_{ij}}$$

So $\Delta P_{ij} \approx \dfrac{\Delta\theta_i - \Delta\theta_j}{X_{ij}}$ We just need to get $\dfrac{\Delta\theta_{ij}}{\Delta P_{Gk}}$

- We'll return to this after we do power flow.

PowerWorld Analytic Sensitivities

- Select Tools, Sensitivities, Flow and Voltage Sensitivities to see lots of sensitivities. The below image shows values for our example.



Contour of the Line Flow to Bus Injection Sensitivities

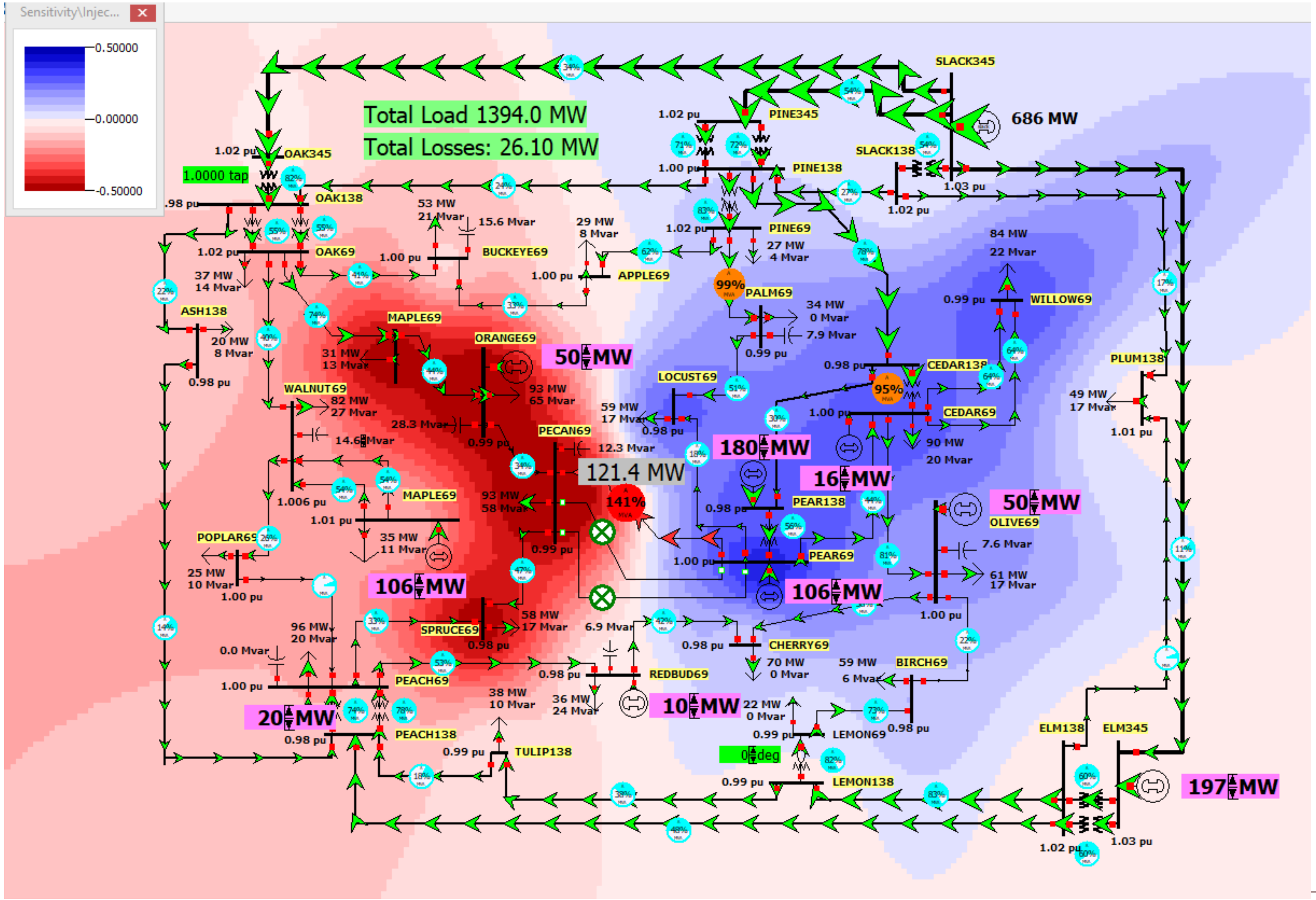


Image shows how a change in injection at a bus affects the flow on the Pear69-Pecan69 line

This is a contour of the bus field: Sensitivity\Injection Value dValue/dP

Power System Sensitivities

Power transfer distribution factors (PTDFs) are an example of sensitivities, showing how a power transfer will travel through the system.

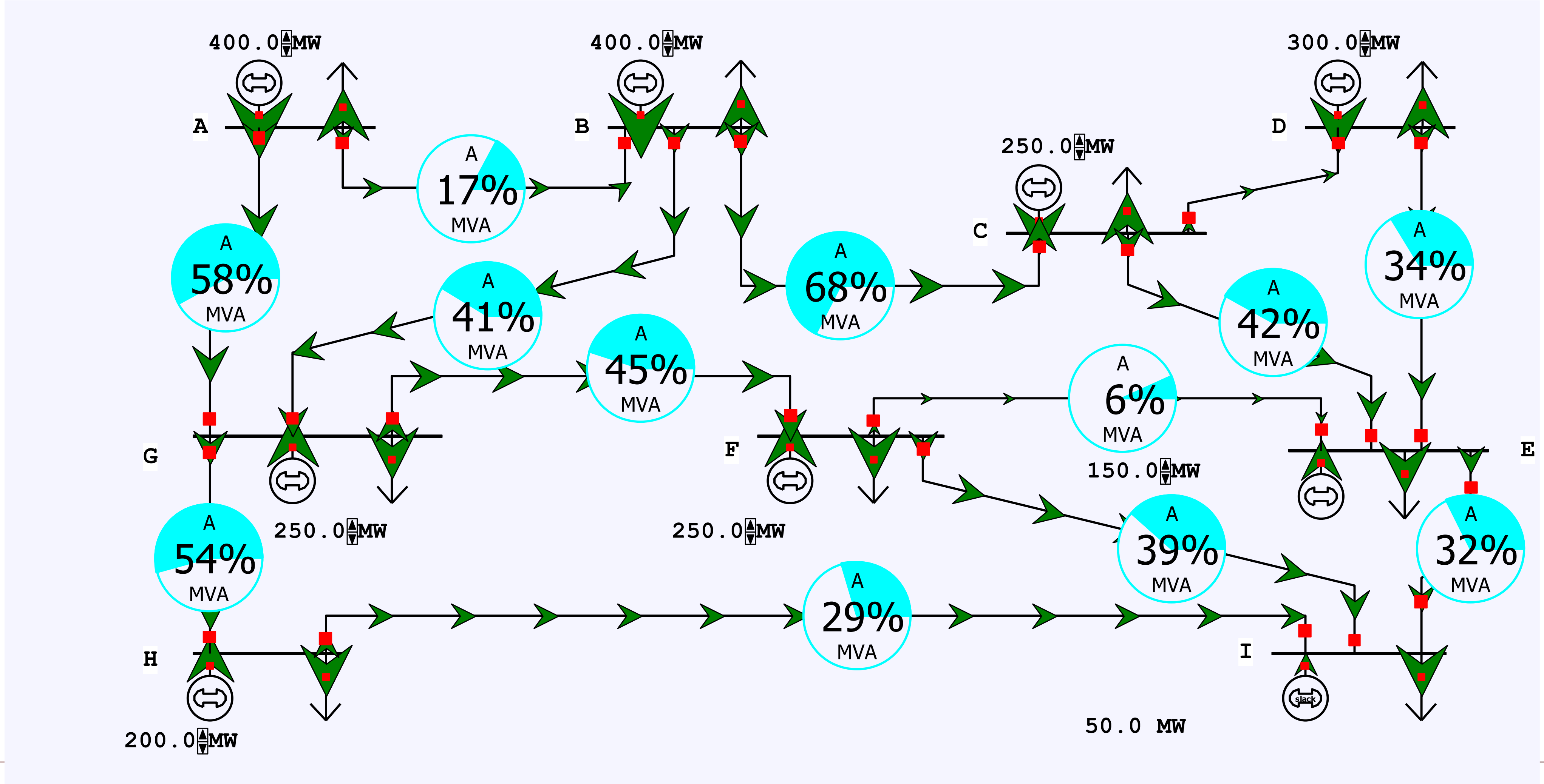
- Power transfer distribution factors (PTDFs) show the linear impact of a transfer of power.
- PTDFs can be calculated using what's known as the the fast decoupled power flow B matrix, which we will introduce later

$$\Delta\boldsymbol{\theta} = \mathbf{B}^{-1}\Delta\mathbf{P}(\mathbf{x})$$

- Once we know $\Delta\boldsymbol{\theta}$ we can derive the change in the transmission line flows
- Except now we modify several elements in $\Delta\mathbf{P}(\mathbf{x})$, in portion to how the specified generators would participate in the power transfer

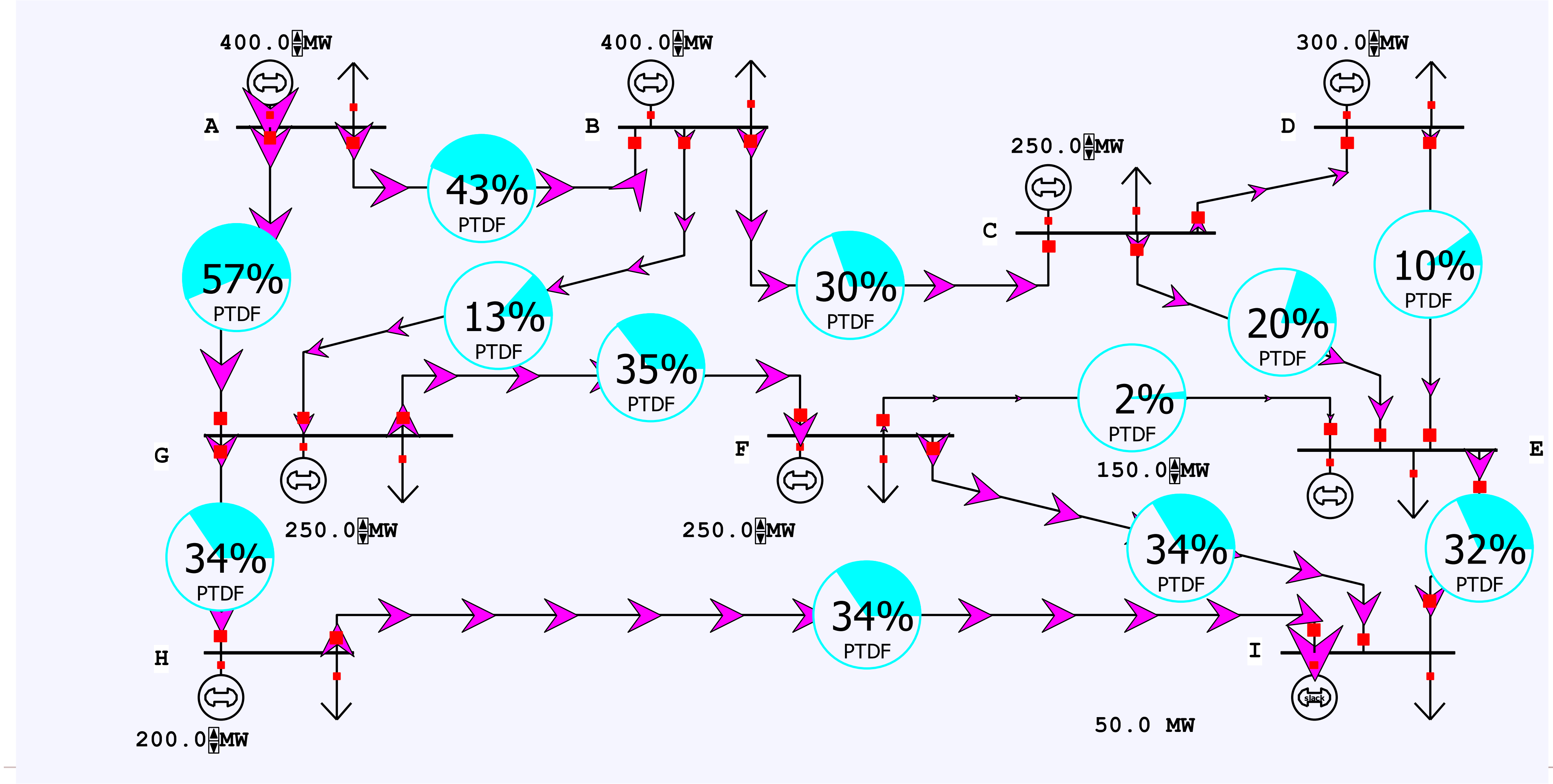
Nine Bus PTDF Example

Figure shows initial flows for a nine bus power system

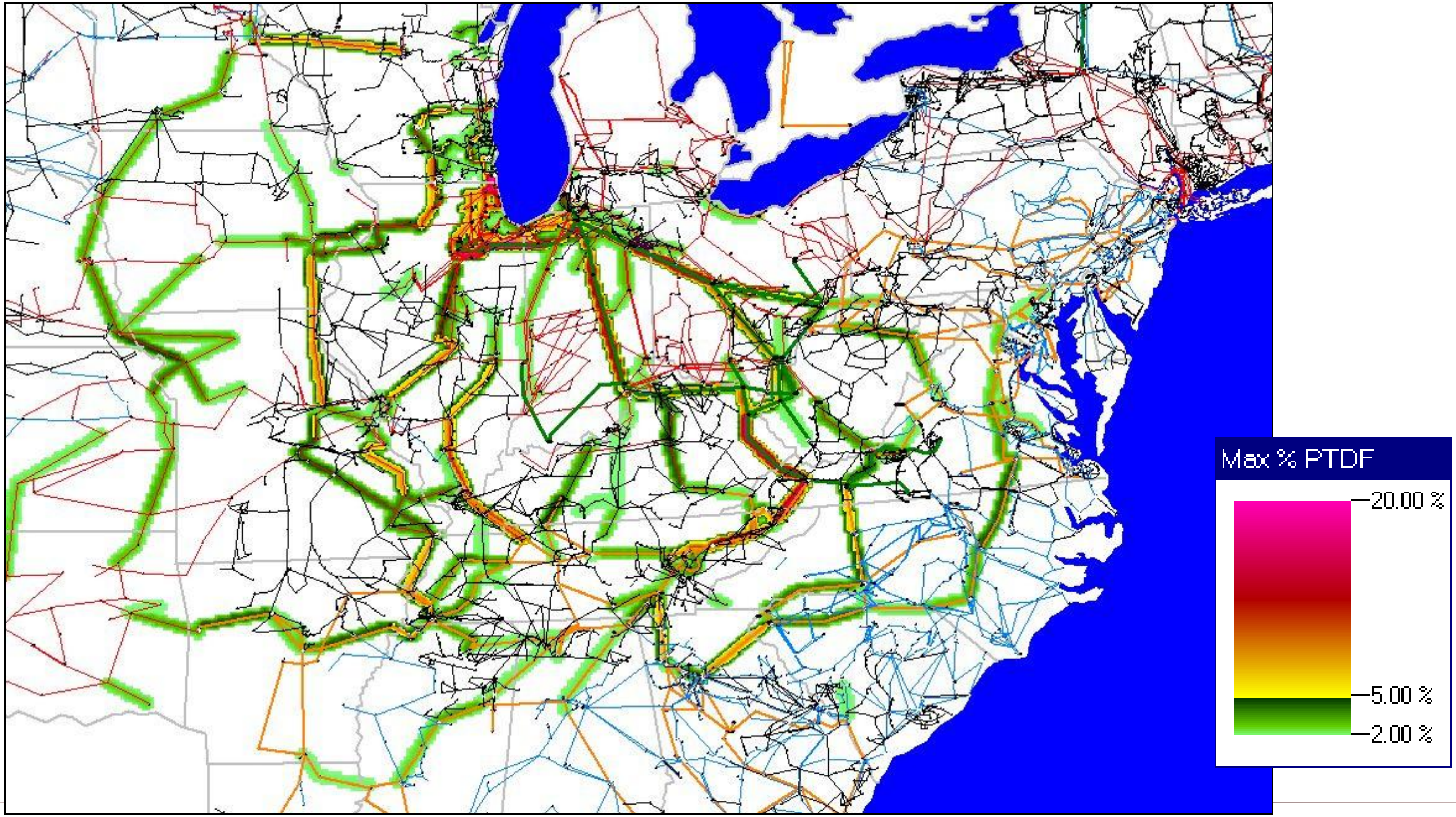


Nine Bus PTDF Example, Cont'd

Figure now shows percentage PTDF flows from A to I

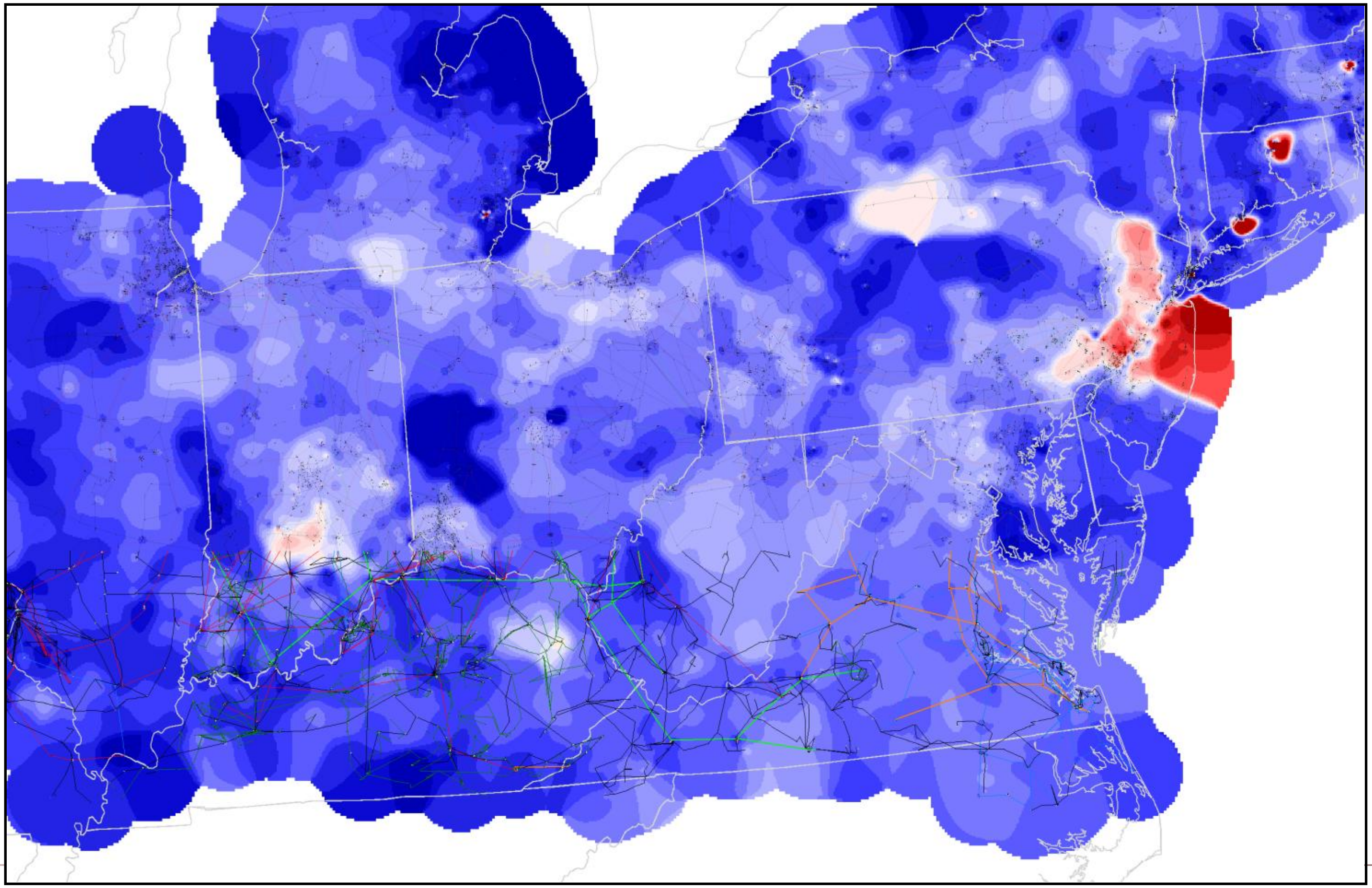


WE to TVA PTDFs



Controlling Power System Bus Voltages

Buses have a minimum and maximum voltage magnitude limit that must be maintained in good operations.



These are also covered by NERC standards. Typical limits would be 0.95 for a minimum limit and 1.08 for a maximum limit

Volt-Var Control

Reactive power flow is closely tied with the voltage magnitude of buses, so volts and vars are often coordinated together

- This can be derived from the following assumptions.

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

- Therefore the sensitivity of P and Q with respect to V and theta are, respectively, quite small. Q-V, however, is well coordinated

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

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

Generator Voltage Control

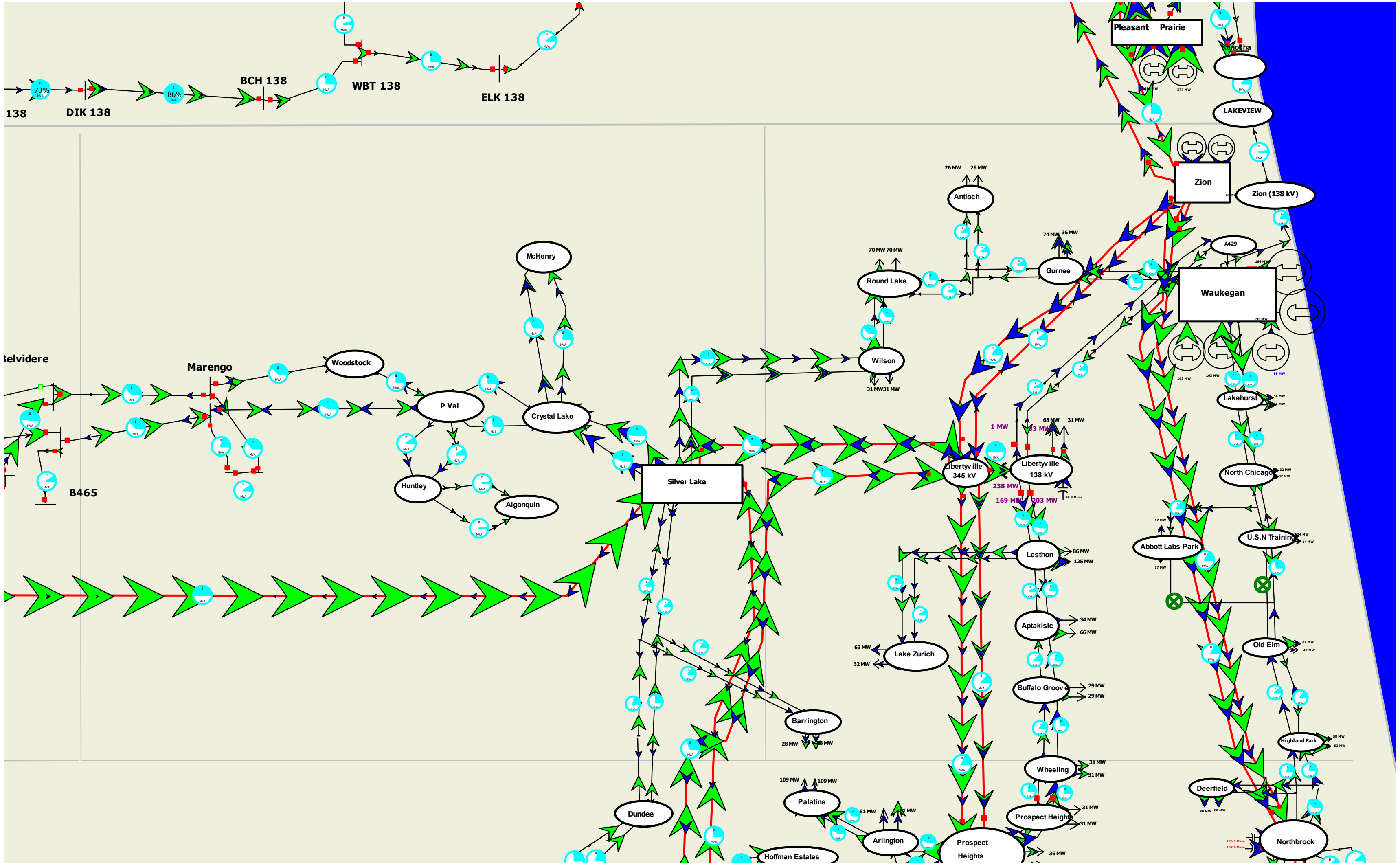
Generator voltage magnitudes are scheduled, with generators changing their reactive power output to control their voltage.

- This is done with a device called an exciter, which changes the field winding voltage of a synchronous machine.

Zion Nuclear Power Plant

- The Zion nuclear power plant, located on Lake Michigan, on the Illinois/Wisconsin border, use to be a 2000 MW generator, commissioned in 1973-74
- In 1997 a control-room operator inserted control rods too far during a shut down, then withdrew them without following procedures
  - NRC also said there were too many people in the control room
  - ComEd ended up shutting down both units because it was too costly to fix the damage (estimated at $435 million!)
- However, the plant was used for many years as a source of reactive power for North Illinois

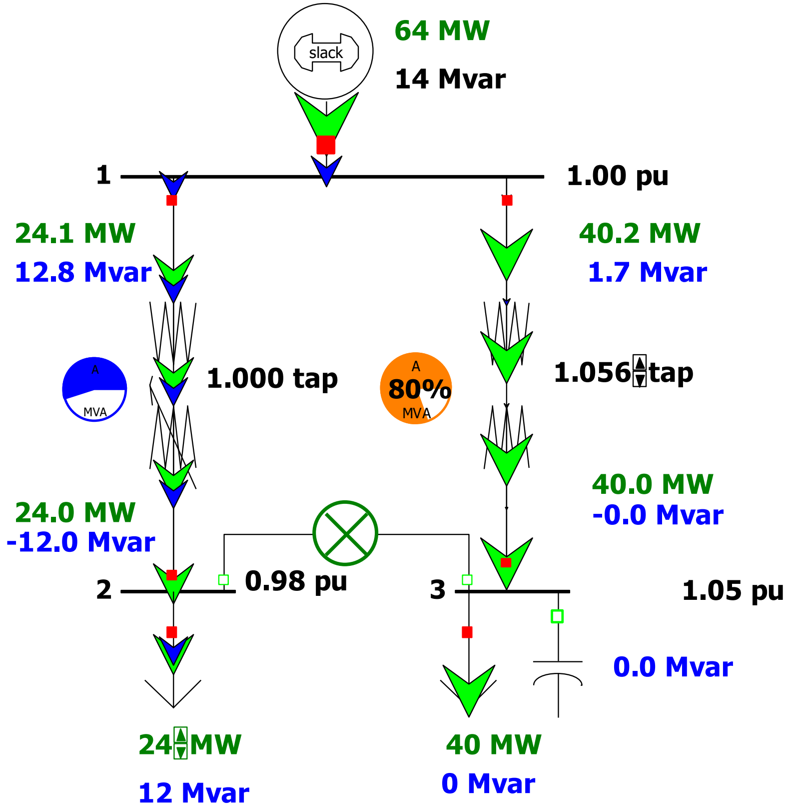
Zion Nuclear Power Plant, cont.



Using Tap-Changing Transformers

Some transformers have variable tap ratios that can be used to control voltage.

- However, we need to watch out for "circulating vars"
- Also remember that the fundamental Q balance of the system is not affected by the taps, i.e. the taps themselves neither produce nor absorb Q



Using Q Resources

Reactive power resources, such a shunt capacitors, static VAR compensators, and synchronous condensers, are primarily used as voltage control devices.

- Reactive power controllers include switched shunts, static var compensators (SVCs), LTC transformers, sometimes generator voltage setpoints
- Goal is to maintain adequate system voltages and reduce losses
- Reactive power control is much less linear than real power control; this is partially due to the much higher reactive power losses because for high voltage transmission lines X is usually much larger than R
  - Losses are very nonlinear
- Vars do not travel far

Effect of Loading on Voltage Control

Under-voltage is typically a problem in heavily loaded systems, needing more capacitor banks

Over-voltage can be a problem in lightly-loaded systems, needing more reactor banks

- The pi model when current is low will produce a lot of reactive power
- The pi model when current is high will consume a lot of reactive power
- Recall, the surge impedance loading (SIL) is on the boundary