ECEN 460
Power System Operation and Control
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Lecture 16: Power System Stability

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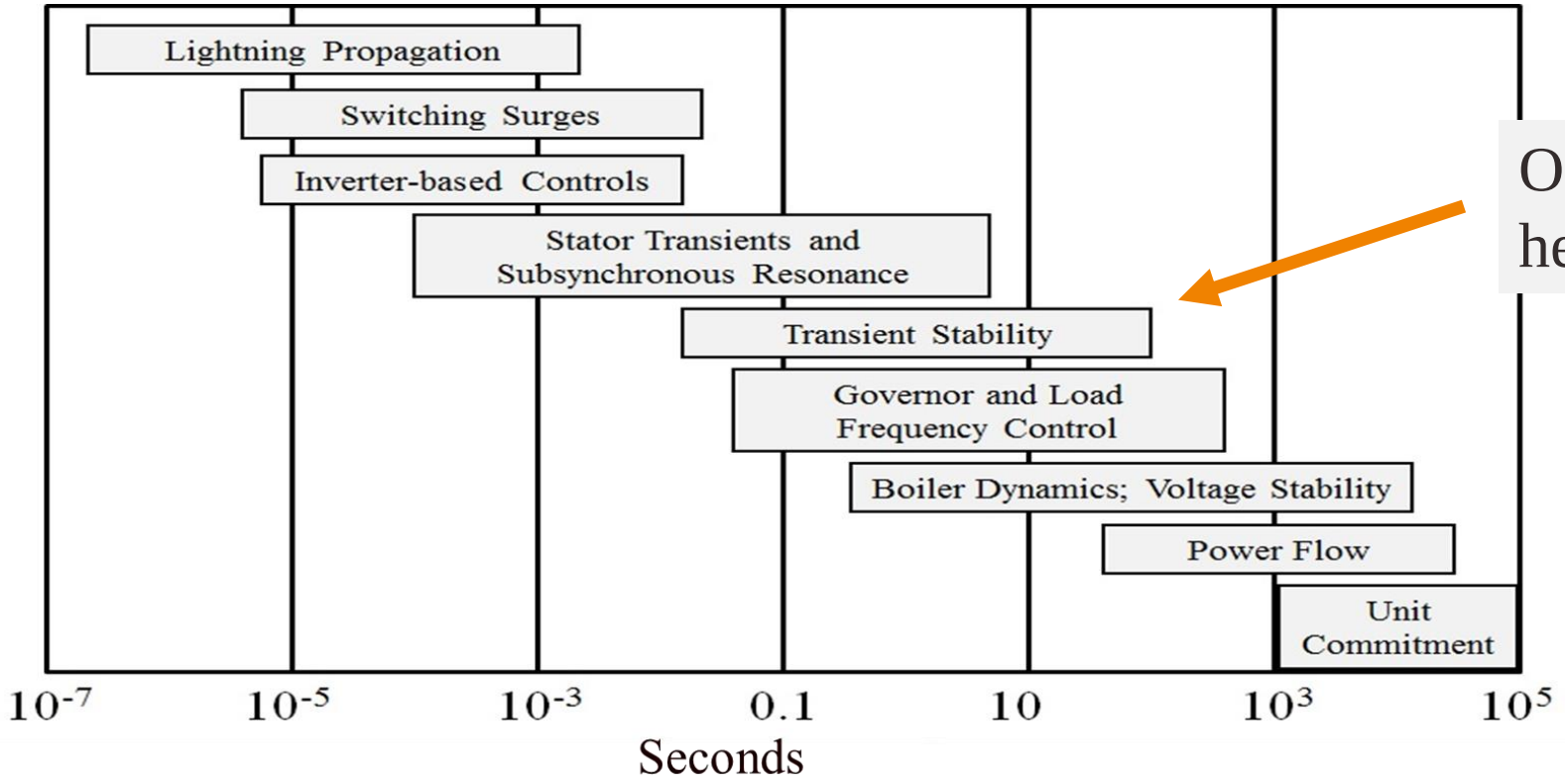
Power System Stability

- The focus of the next part of the class is on power system dynamics, with a focus on time frames shorter than steady-state (power flow)



Our focus will mostly be here

Image source: P.W. Sauer, M.A. Pai, Power System Dynamics and Stability, 2006, Fig 1.2, modified

A Few Definitions

- The words model or modeling have lots of definitions. A germane one is
  - "Modeling and simulation (M&S) is the use of a physical or logical representation of a given system to generate data and help determine decisions or make predictions about the system."
- Modeling is crucial for power system dynamics and stability since we can't (easily) physically build the system being considered
- *Dynamics* also has several definitions, with a common one "the study of how moving objects behave" (here the "moving objects" includes electrical values
- Likewise *Stability* has several definitions, with a germane one here is "the property of a body (or system) that causes it to return to its original condition when disturbed."

As Before Keeping in Mind the Modeling Cautions!

- "All models are wrong, but some are useful," George Box, *Empirical Model-Building and Response Surfaces*, (1987, p. 424)
  - Models are an approximation to reality, not reality, so they always have some degree of approximation
  - Box went on to say that the practical question is how wrong to they have to be to not be useful
- A good part of engineering is deciding what is the appropriate level of modeling, and knowing under what conditions the model will fail
- Always keep in mind what problem you are trying to solve!

A Few Definitions, cont.

- An *equilibrium point* (ep) of a dynamic systems is a point in which the system doesn't change with time
- Large-scale electric grids are never really at an equilibrium point because something is always changing with time. Here we can talk about a quasi-static ep, which is how the system would appear on the power flow time frame
  - This is what you would observe if you went into a control room and looked at the displays; usually things would appear to be pretty constant

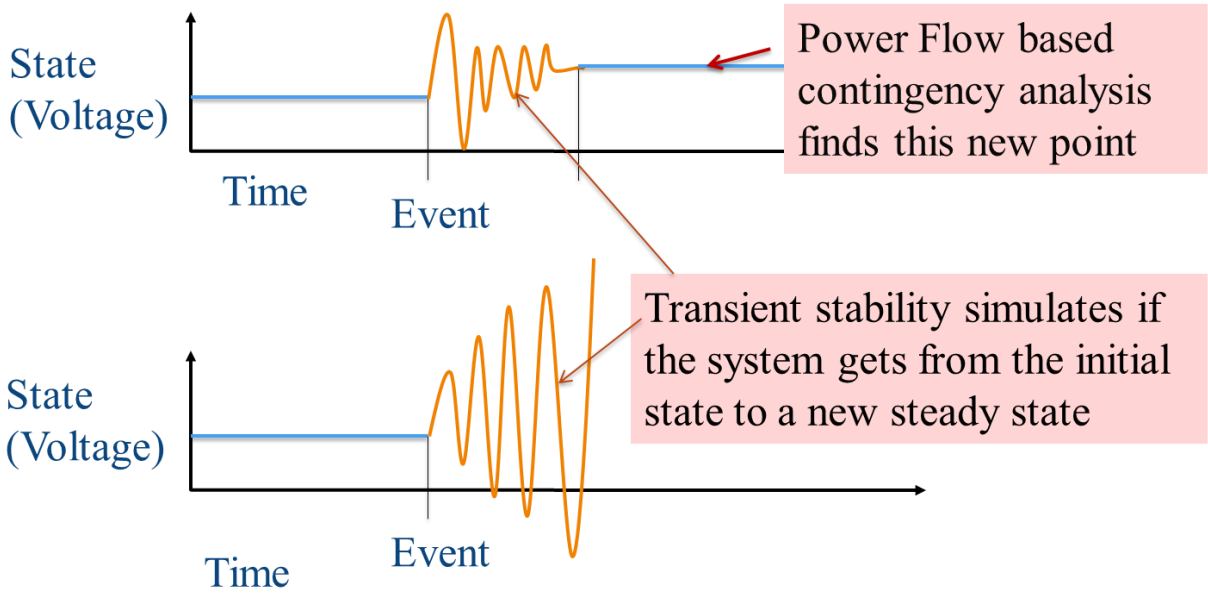
Image Source: why.org from 3/17/20 of PJM control room

Slow versus Fast Dynamics

- Key analysis question in setting up and solving models is to determine the time frame of interest
- Values that change slowing (relative to the time frame of interest) can be assumed as constant
  - Power flow example is the load real and reactive values are assumed constant (sometimes voltage dependence is included)
- Values that change quickly (relative to the time frame of interest) can be assumed to be algebraic
  - A generator's terminal voltage in power flow is an algebraic constraint, but not in transient stability
  - In power flow and transient stability the network power balance equations are assumed algebraic

Contingencies (in a Dynamic Sense)

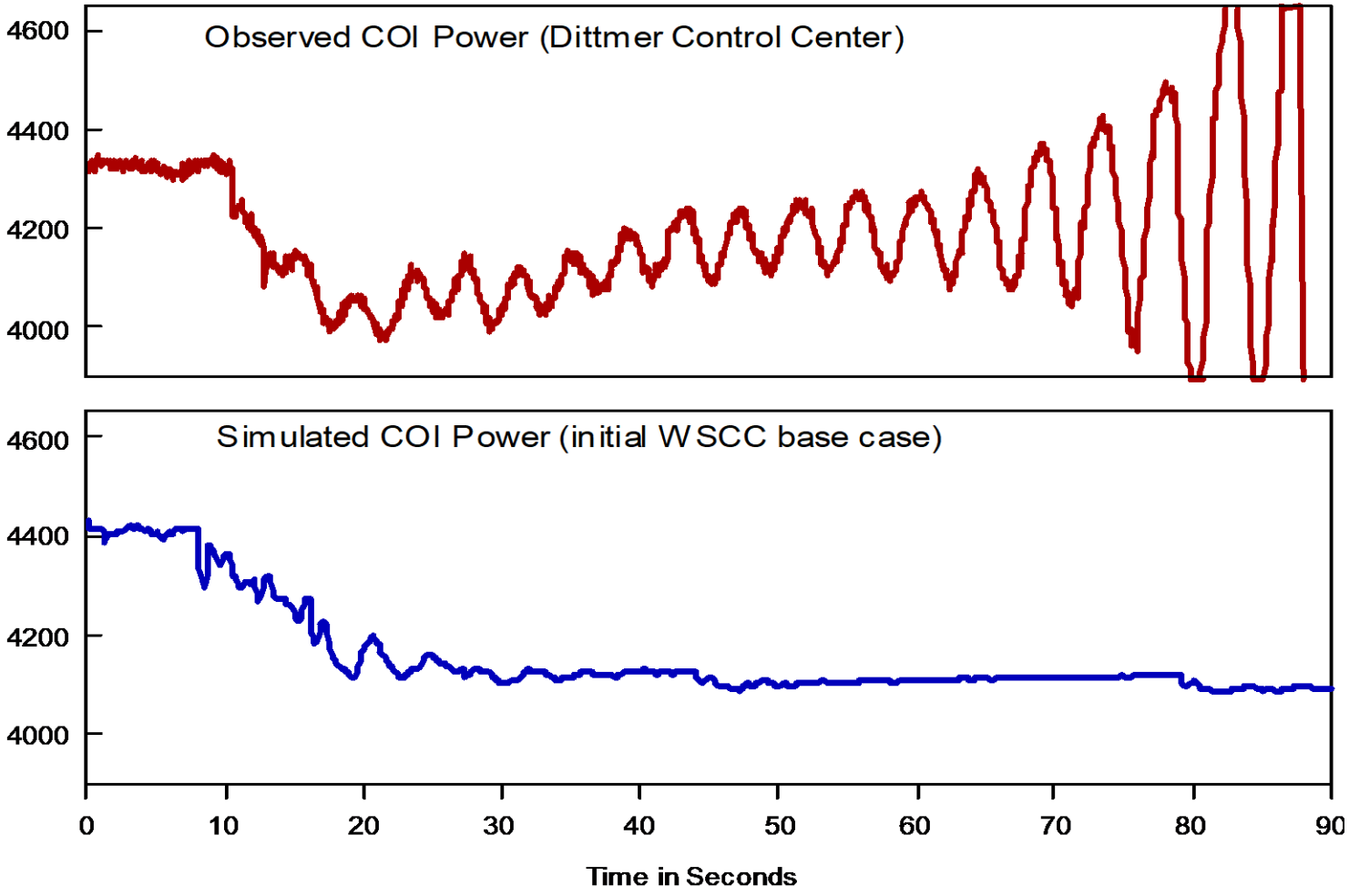
- Contingencies (or sometimes known as events) perturb (kick) the system operating point away from its equilibrium point; power system stability analysis looks at whether the system returns to a new equilibrium point
  - Best case is a new ep exists and the system is able to reach this new ep.
  - However, a new ep may exist, but the system can't get there
  - Or a new ep doesn't exist



- The electric grid protection system plays a major role in how the system results to different contingencies

Dynamics Example 1: WECC 1996 Blackout

1996: Transient Stability Model Errors Lead to Blackouts



Dynamics Example 2: August 14 Blackout

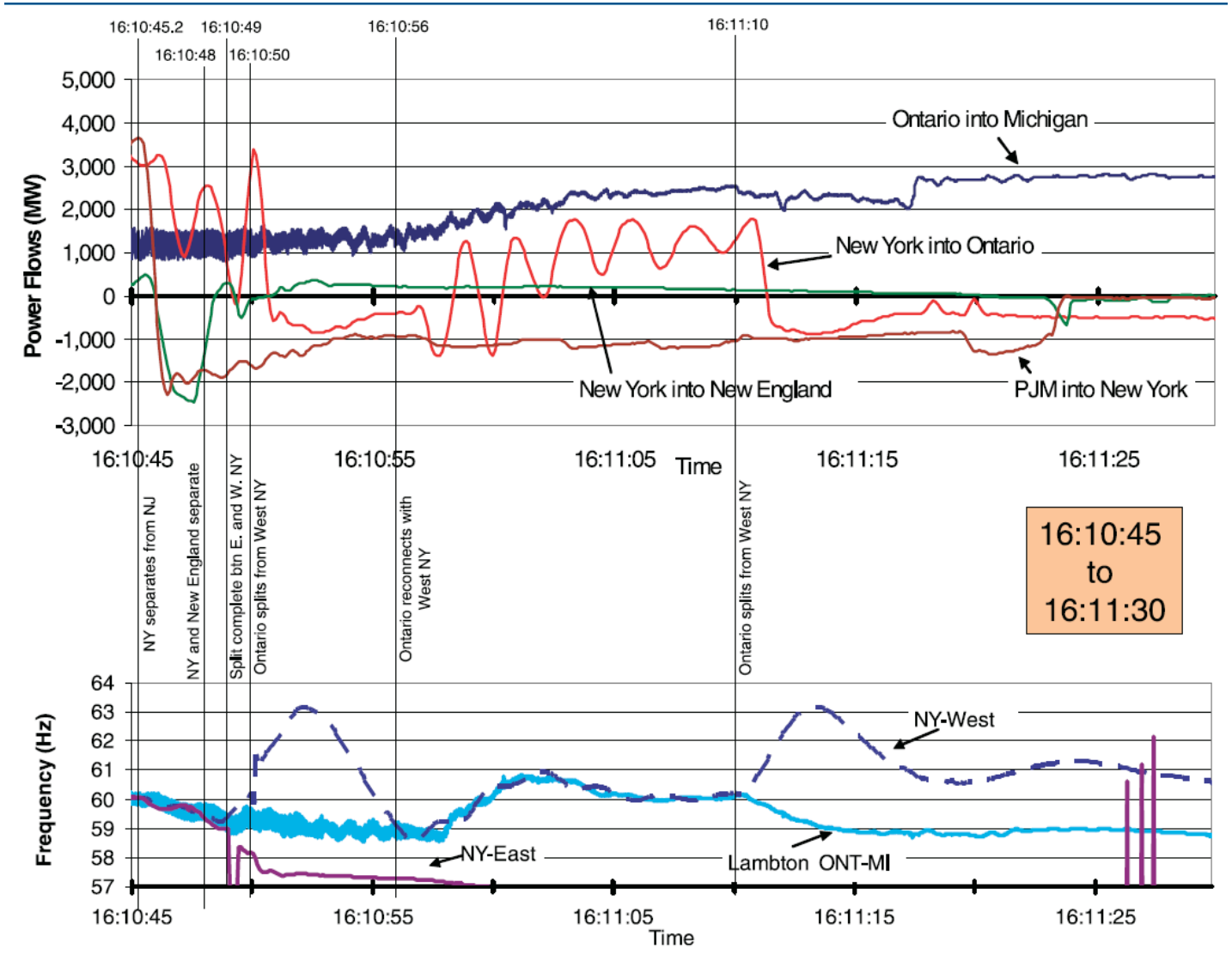
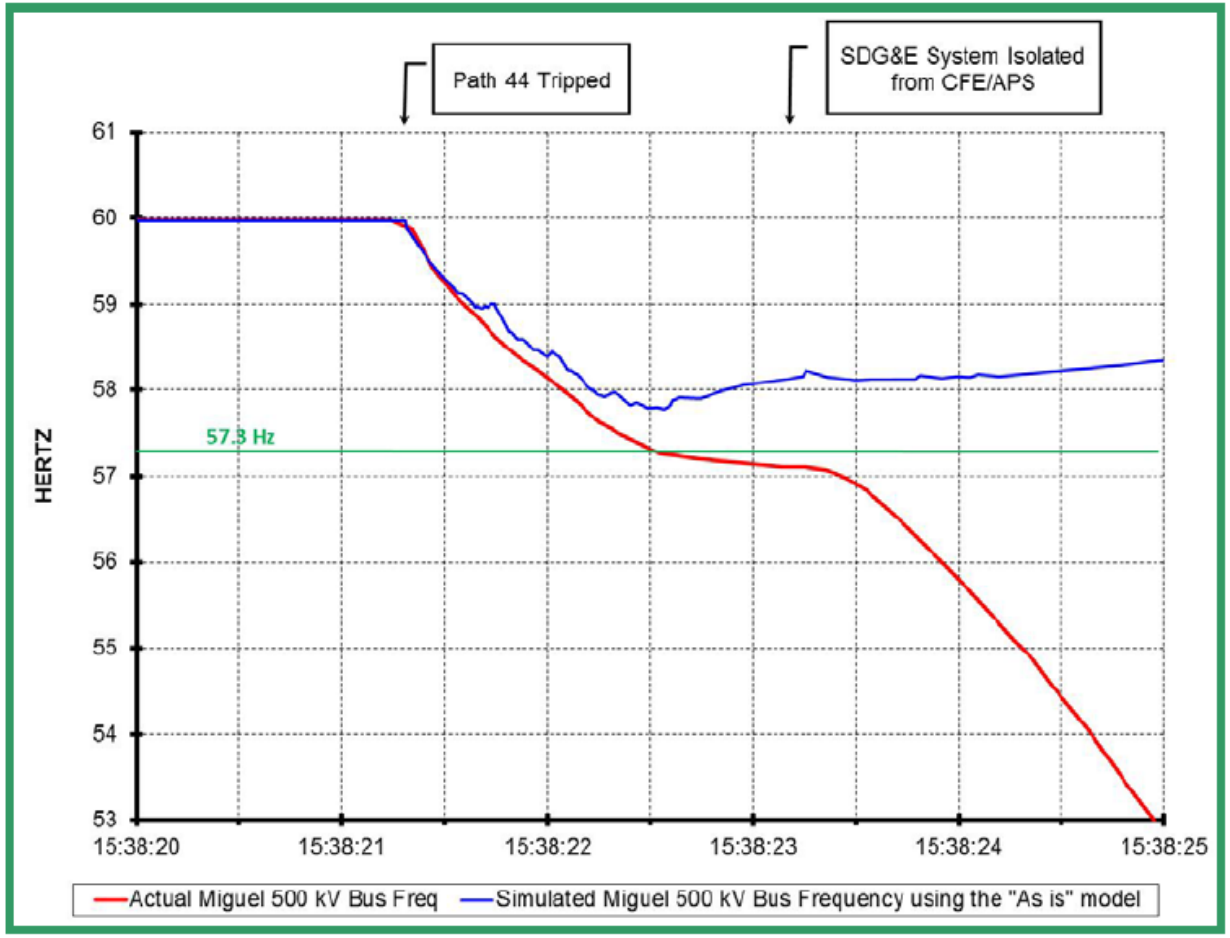


Image from August 14, 2003 Blackout Final Report, energy.gov, Figure 6.26

Dynamics Example 3: Arizona-Southern CA 2011

Figure 14: Actual and Simulated Frequency at Miguel 500 kV Bus



We've come a long ways since 1996 towards improved simulations. Still,
a finding from the 2011 Blackout is the simulations
didn't match the actual system response and need to be improved.

Source: *Arizona-Southern California Outages n September 8, 2011 Report*, FERC and NERC, April 2012

Power System Stability Terms

- The terms continue to evolve, but a good reference is [a]; the image shows Figure 4 from this reference

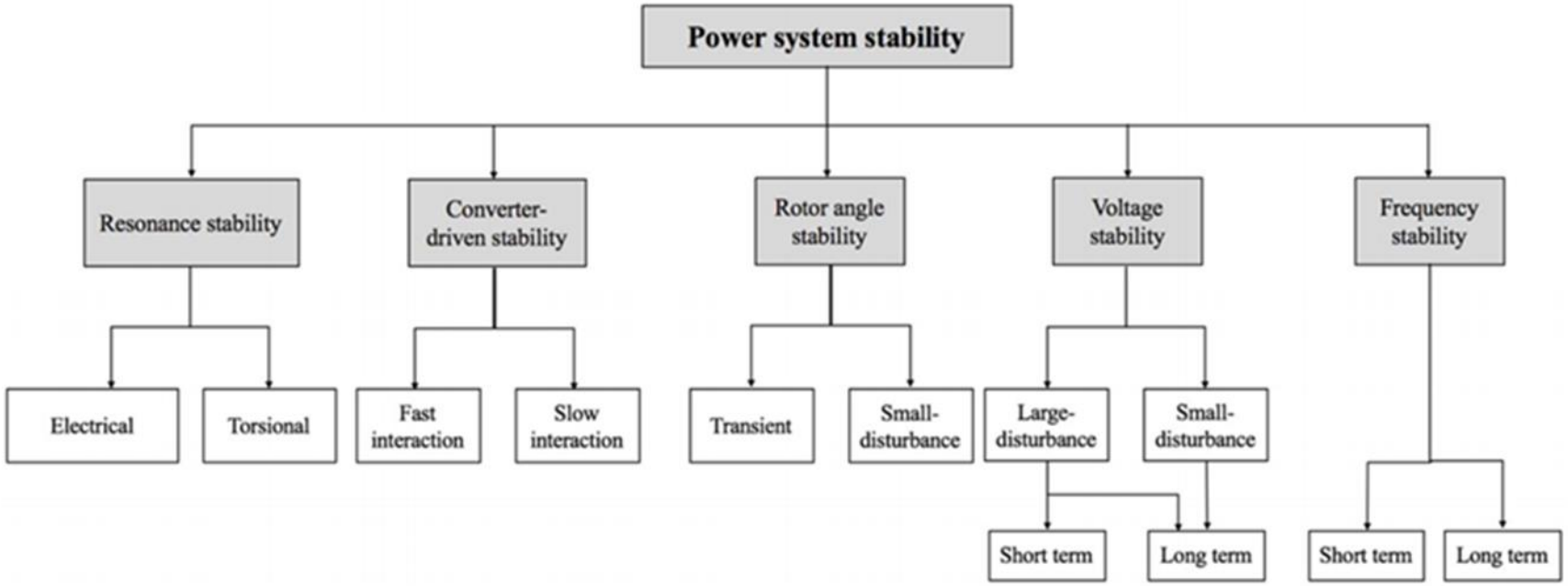


Fig. 4. Classification of power system stability

[a] IEEE/PES Power System Dynamic Performance Committee, "Stability definitions and characterization of dynamic behavior in systems with high penetration of power electronic interfaced technologies", PES-TR77, April 2020

An Example: Lightning Striking a Transmission Line

- The sequence of events might be as follows
  - Lightning hits a transmission line, setting up an ionized path to ground
    - There are at least 30 million lightning strikes per year in the US; a typical stroke might have 25,000 amps with a rise time of 10 μs, dissipated in 200 μs; multiple strokes can occur in a single flash, causing the lightning appear to flick with a total event lasting a second
  - After the strike a conduction path is maintained by ionized air after the lightning strike has dissipated, resulting in high fault current (often > 25,000 amps); if this current is not removed it can cause high heating and mechanical stresses
  - Within one to three cycles (16-50 ms) relays at both ends of the line detect high currents, signaling circuit breakers to open the line
    - Nearby locations see decreased voltages
  - The circuit breakers open to de-energize the line in an additional one to two cycles
  - Circuit breakers may reclose after several seconds to restore service

Worldwide Map of Lighting Strikes

Lightning is a major issue in many locations, but not everywhere; where lightning is common transmission lines have ground wires for lightning protection

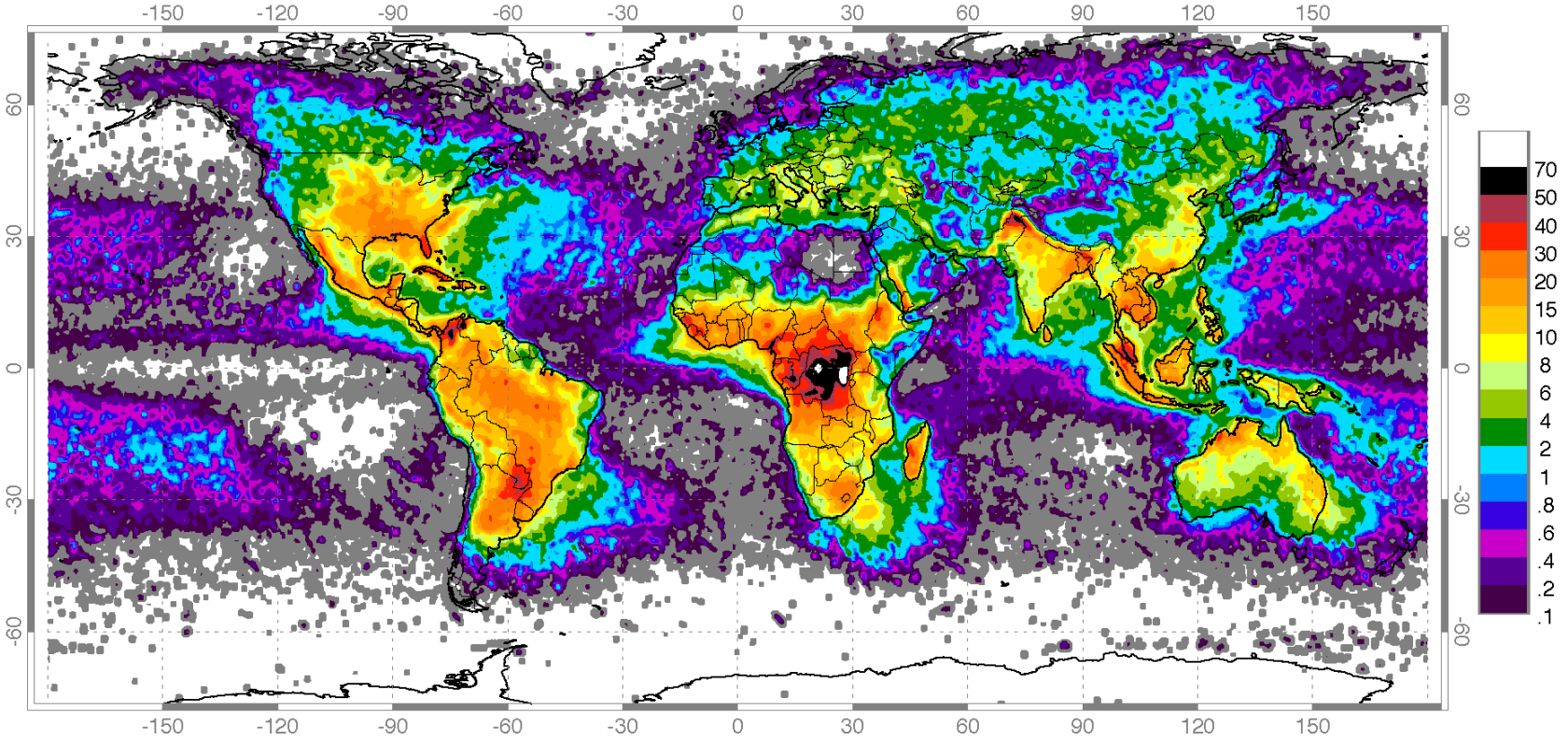


Image source: en.wikipedia.org/wiki/Distribution_of_lightning

Two Different Types of Simulations for Lightning

- Faults caused by lightning are simulated using two different approaches for two different purposes
- Simulations using very fast time steps are done for insulation coordination studies; the goal is to design the grid so it can withstand the initial lightning strike; these simulations packages are known electromagnetic transients program (EMTP)
  - They can use simulation time steps of less than 1 μs, and light only travels a microsecond
  - The small timesteps means either they solve relatively small systems or use lots of computer hardware to do the simulations

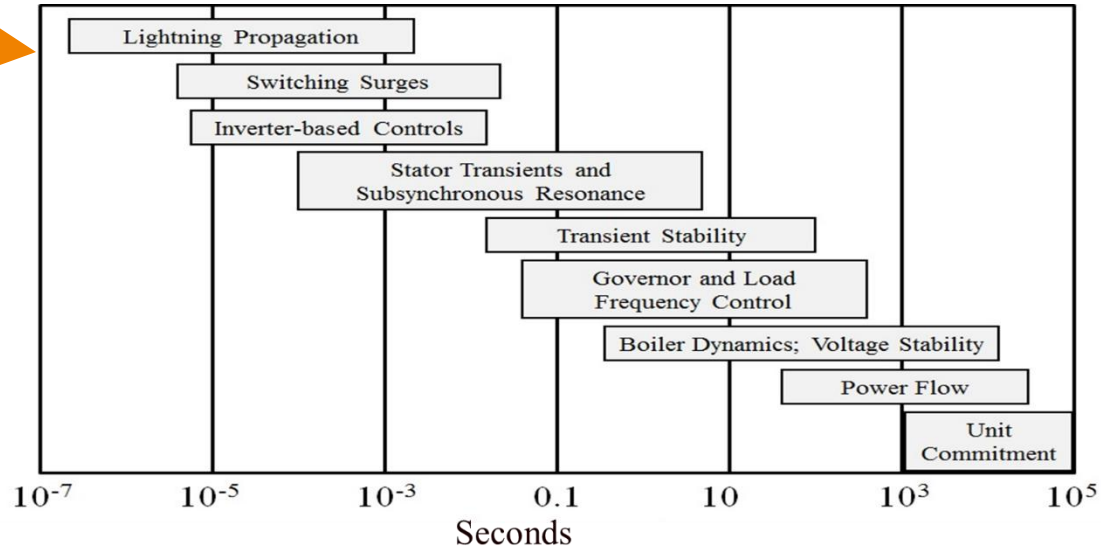
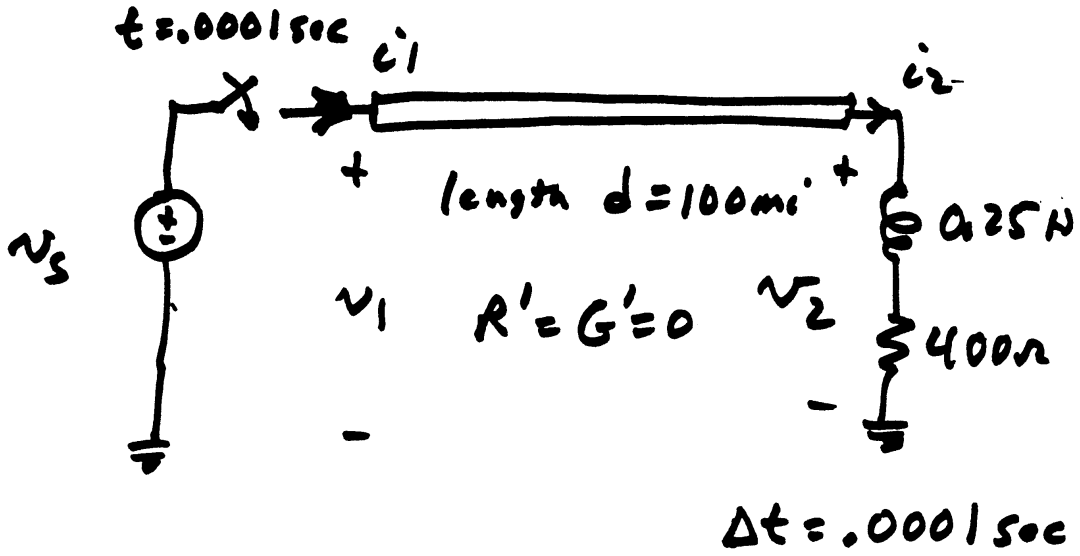


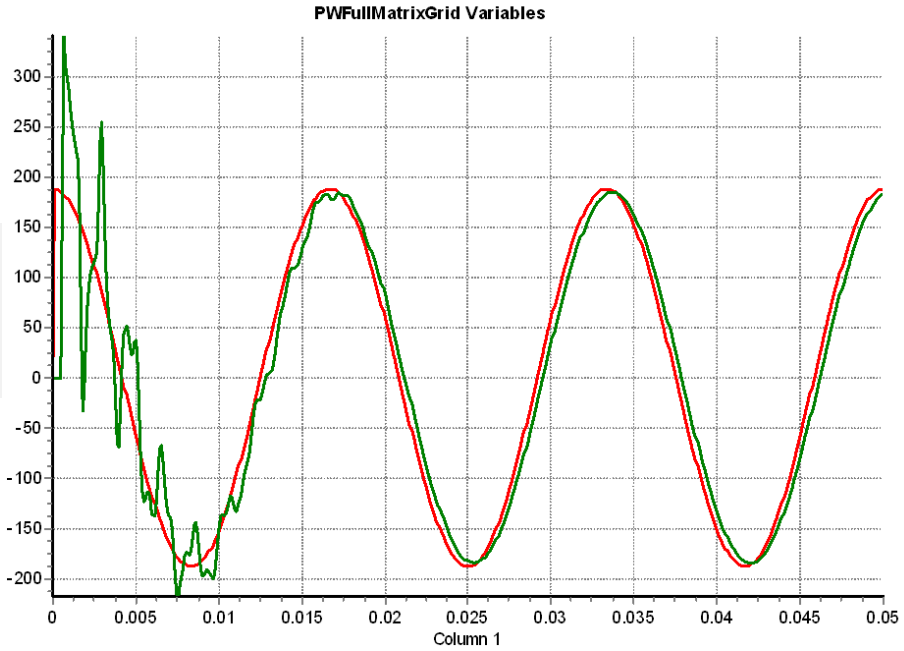
Image source: P.W. Sauer, M.A. Pai, Power System Dynamics and Stability, 2006, Fig 1.2, modified

An Example of a Switching Surge

- On a very fast time-scale, when a transmission line is closed there is a traveling voltage wave that goes down the line, and reflects off the far end; this high frequency oscillations damp out quickly, but need to be considered in the protection system design



Voltage in kV



Time in seconds

Stability Simulations

- The second type of studies are known as stability simulations (or sometimes transient stability) with a focus on determining whether the system will stay together after the fault
  - A traditional focus has been on whether the generators will maintain synchronism
  - These studies typically use time steps on the order of about ¼ to ½ electrical cycle (so around 0.004 to 0.008 seconds)
  - The larger time step allows the study of large systems, often up to an entire interconnect

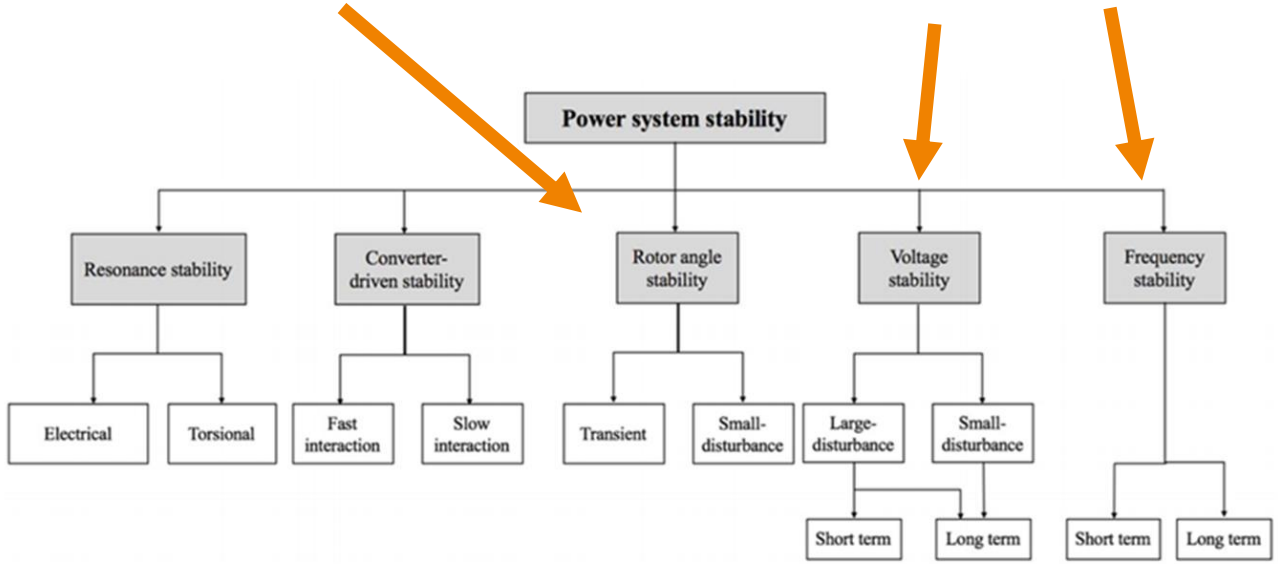
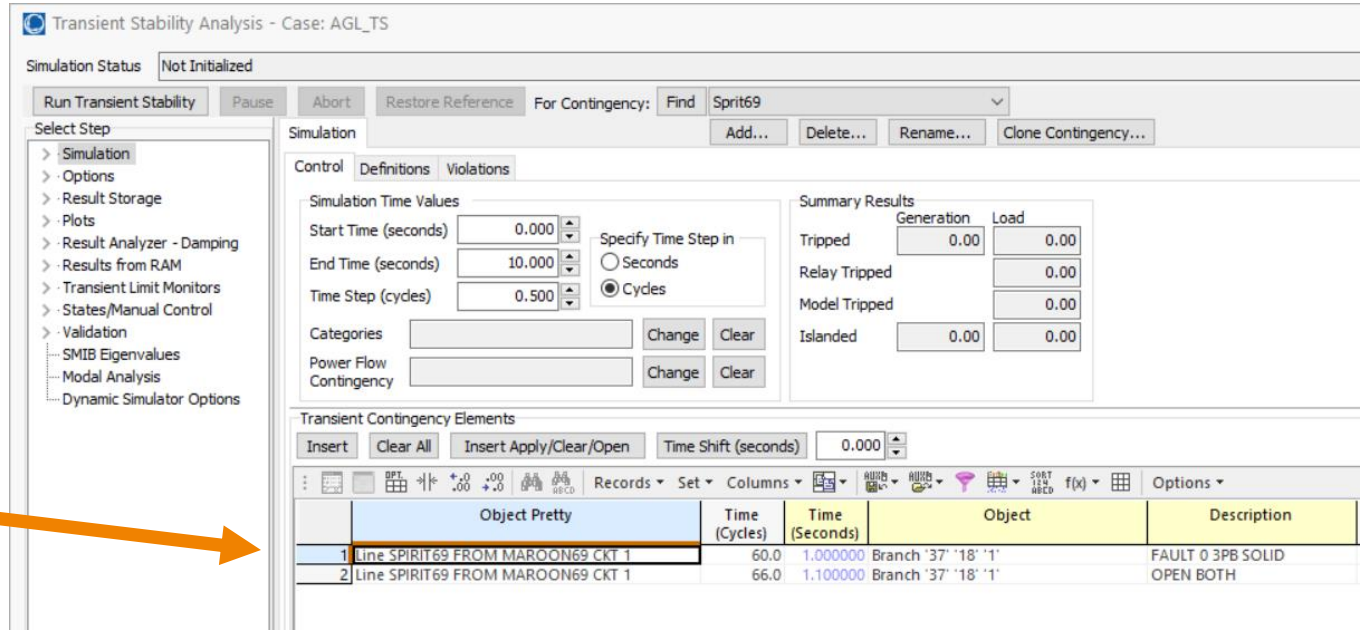


Fig. 4. Classification of power system stability

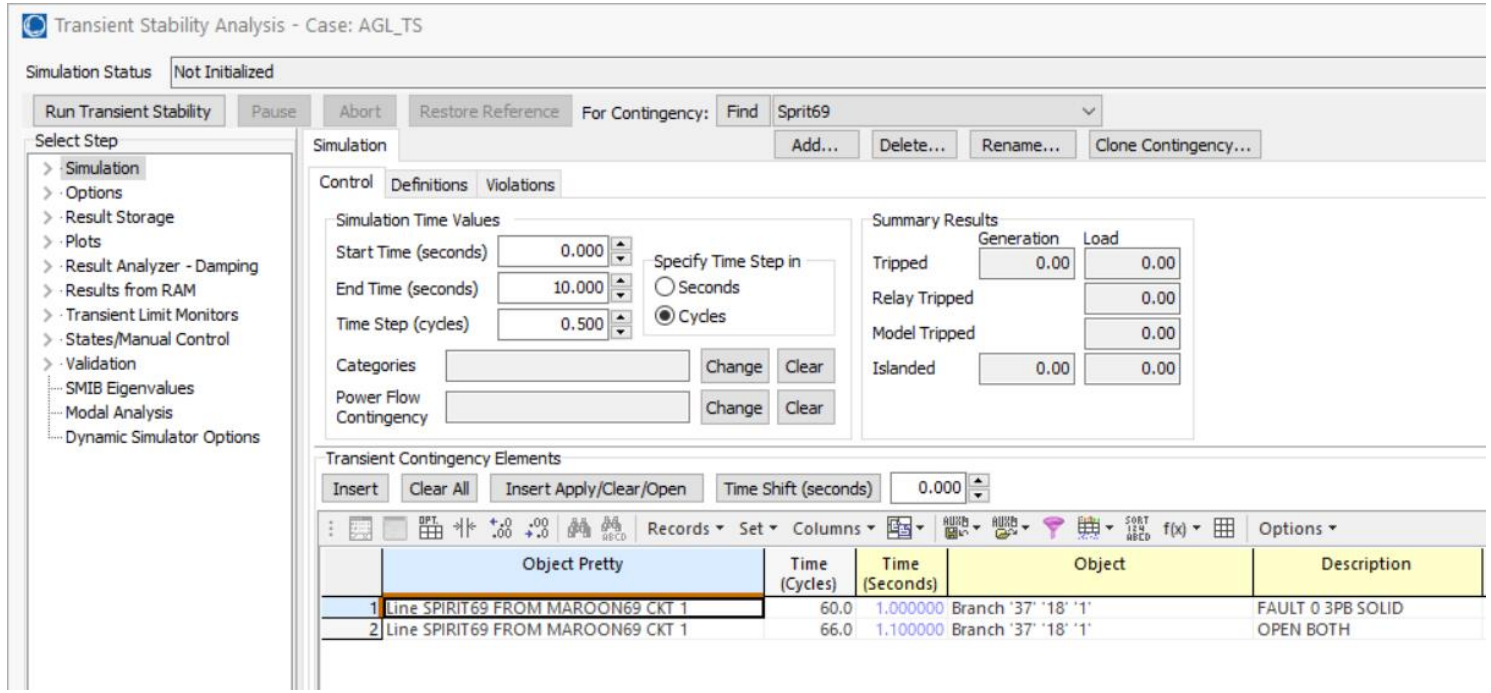
Doing a Stability Simulation

- A good way to introduce stability studies is to do one in PowerWorld using a case that is very similar to the previous 37 bus case, augmented to include dynamic models (which we'll get to in the next few slides)
- Open the case **AGL_TS**, and select **Add Ons, Transient Stability**
- This displays the **Transient Stability Analysis Form**, which is what we'll use to do simulations
- Key to a simulation is defining the sequence of events (contingency elements)



Doing a Stability Simulation

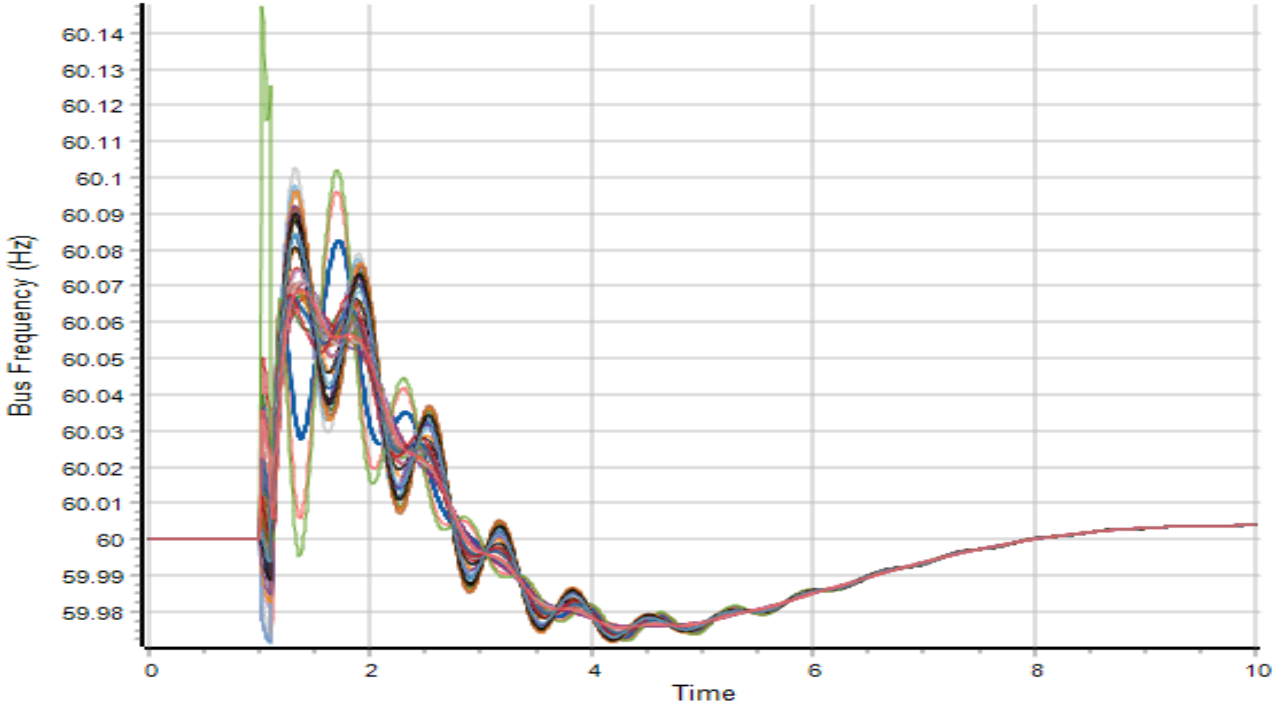
- Doing a stability simulation also involves setting a number of other values, such as the start/end time, a time step size, and what to save. Assuming these are set (which they are here), then doing the simulation just involves pressing the **Run Transient Stability** button

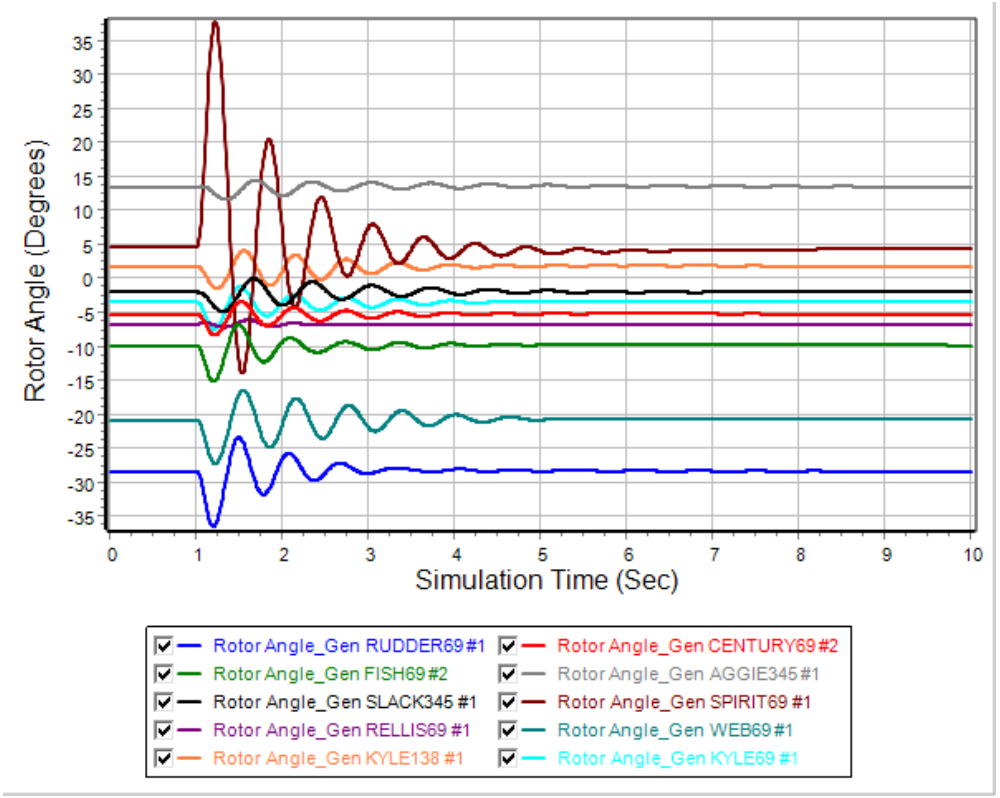


- There are many options for showing the results

Looking at the Stability Results

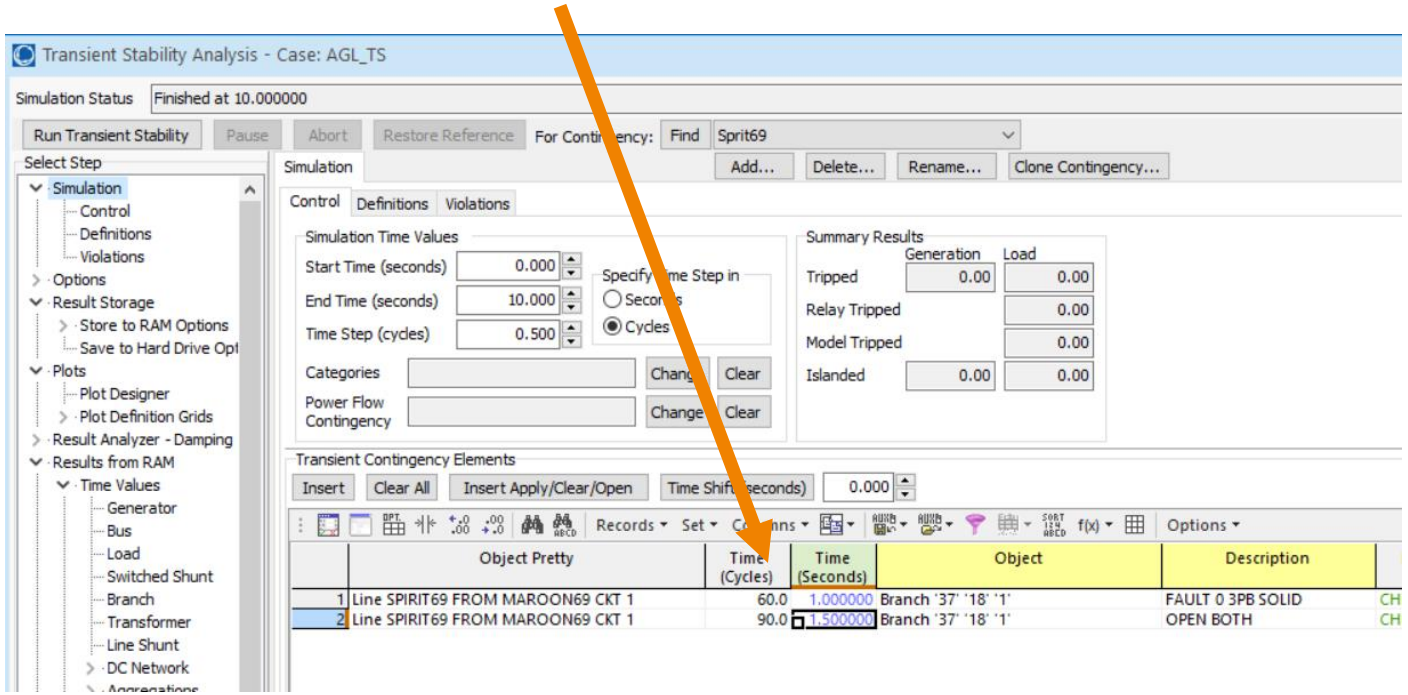
- A common way to look at the results is using plots of the time-variation of values, with the below graphs showing two examples
  - A detailed consideration of the plots is beyond the scope of this class, but these plots do show normal (desired) behavior

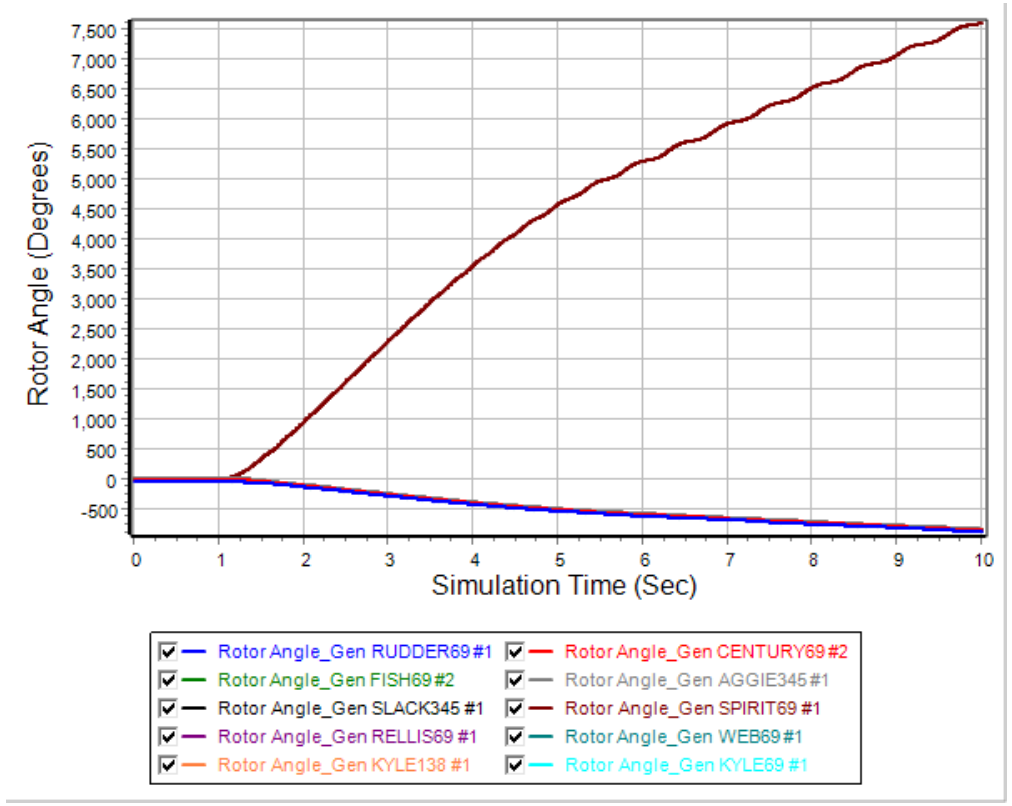




An Unstable Case Example

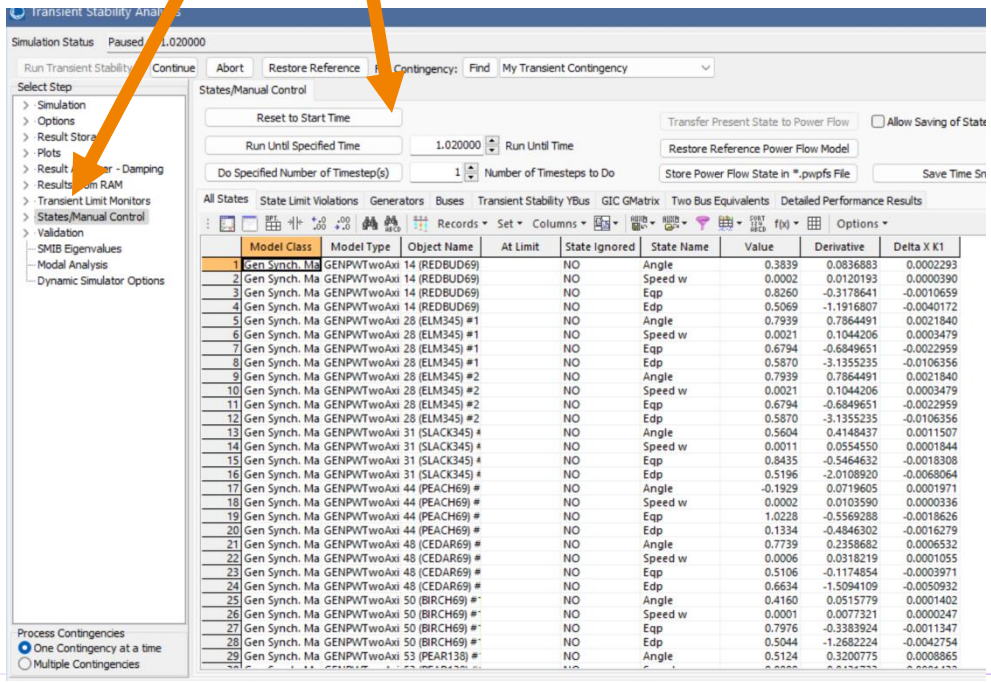
- Change the fault clearing from being at time 1.1 seconds (0.1 seconds after the fault) to being at 1.5 seconds; then re-run; this gives an unstable result

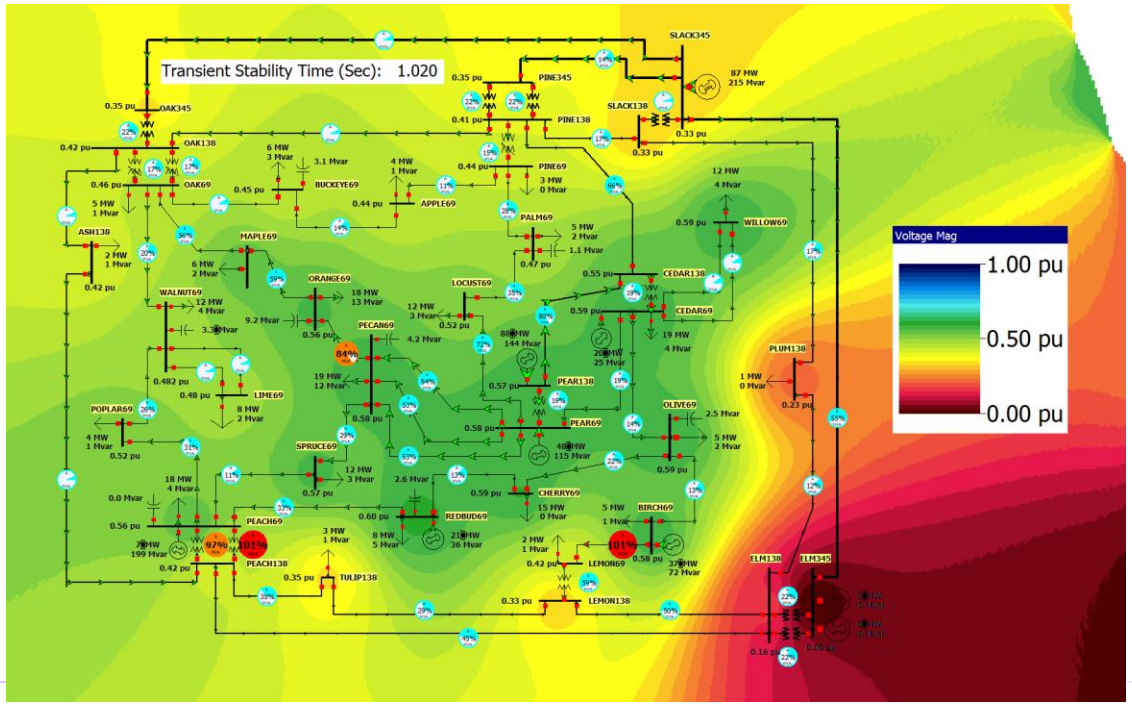




Visualizing Individual Time Points

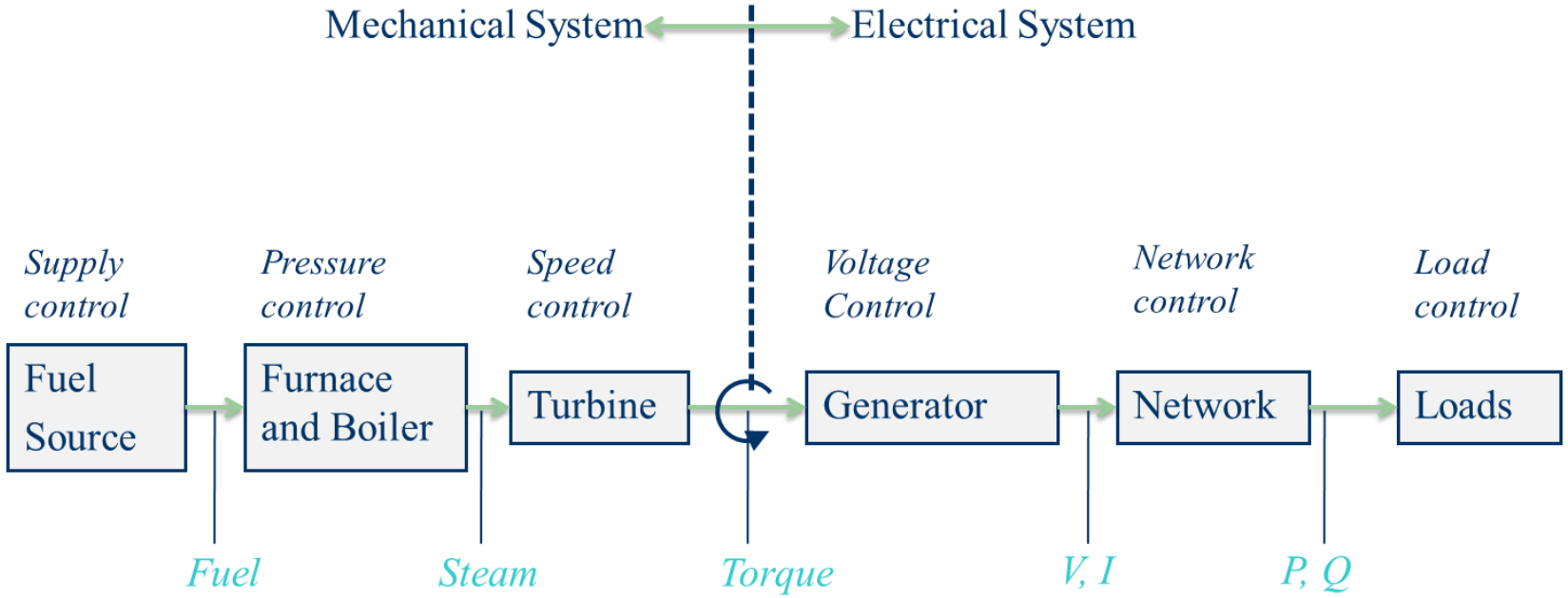
- Do see the simulation results at a particular on the Transient Stability Form select **States/Manual Control** set the **Run Until Specified Time** to 1.02 seconds and click on the **Run Until Specified Time** button
  - The contour shows very low voltages across much of the system; this is why lights "blink" during a fault





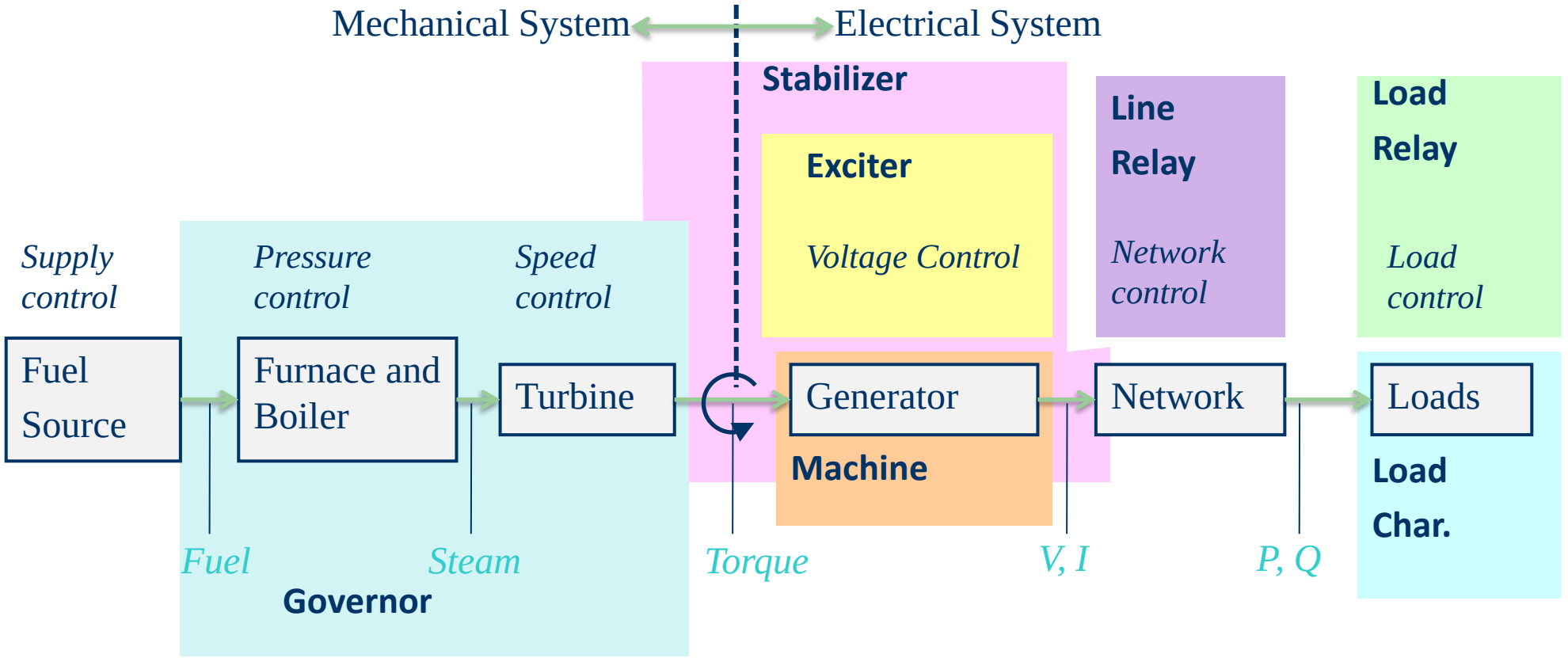
Physical Structure Power System Components

- Doing these simulations requires more detailed models than for the power flow; below are of the devices that need models for a synchronous generator



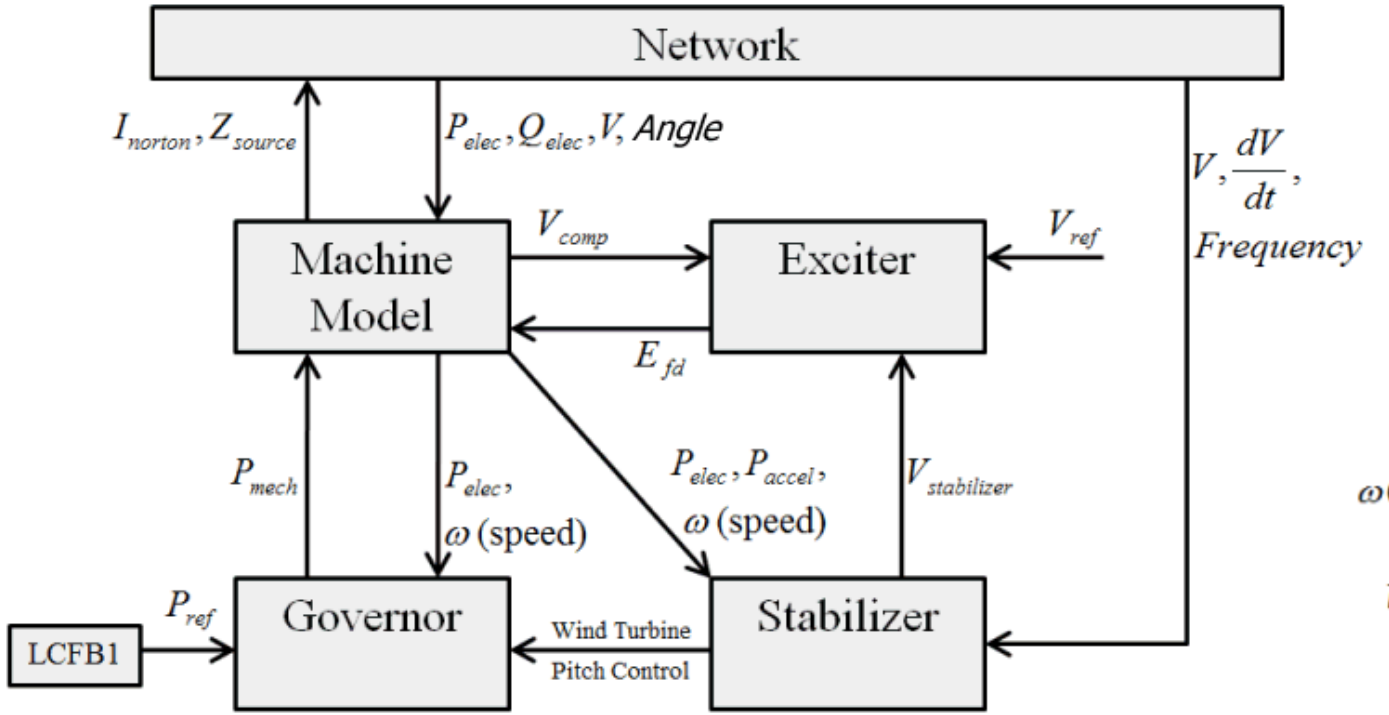
P. Sauer and M. Pai, *Power System Dynamics and Stability*, Stipes Publishing, 2006.

Dynamic Models in the Physical Structure



P. Sauer and M. Pai, *Power System Dynamics and Stability*, Stipes Publishing, 2006.

Synchronous Generator Models



P_{elec} = Electrical Power

Q_{elec} = Electrical Reactive Power

V = Voltage at Terminal Bus

$\frac{dV}{dt}$ = Derivate of Voltage

V_{comp} = Compensated Voltage

P_{mech} = Mechanical Power

ω(speed) = Rotor Speed (often it's deviation from nominal speed)

P_{accel} = Accelerating Power

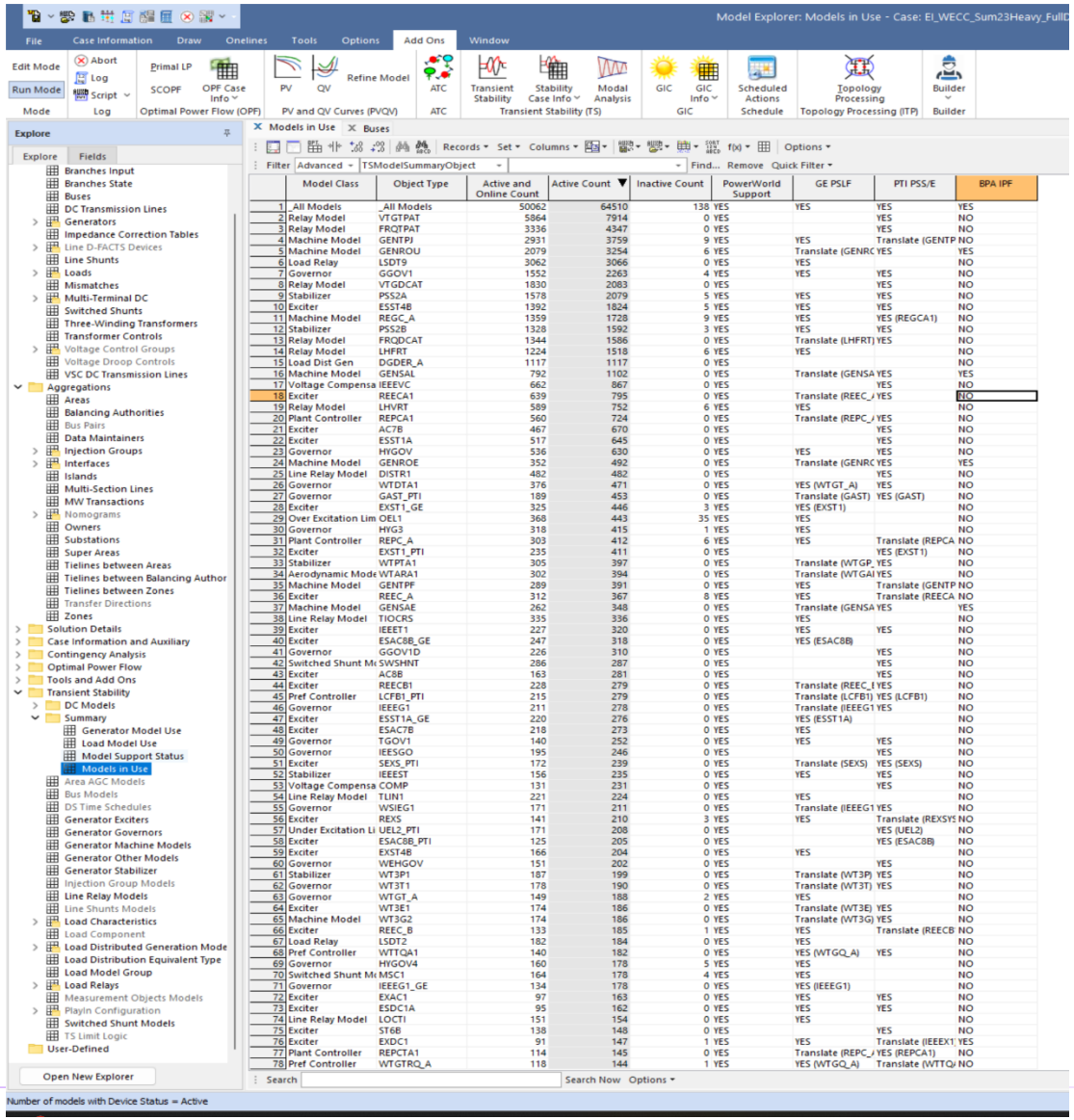
$V_{stabilizer}$ = Output of Stabilizer

V_{ref} = Exciter Control Setpoint (determined during initialization)

P_{ref} = Governor Control Setpoint (determined during initialization)

There can be Hundreds of Different Types of Models

- In a project we are doing looking at connecting the North American Eastern and Western grids we have a case with 120,000 buses, and 248 different types of dynamic models, and a total of 64,500 different dynamic model instances
  - Each instance can have many different parameters



Infinite Bus Modeling

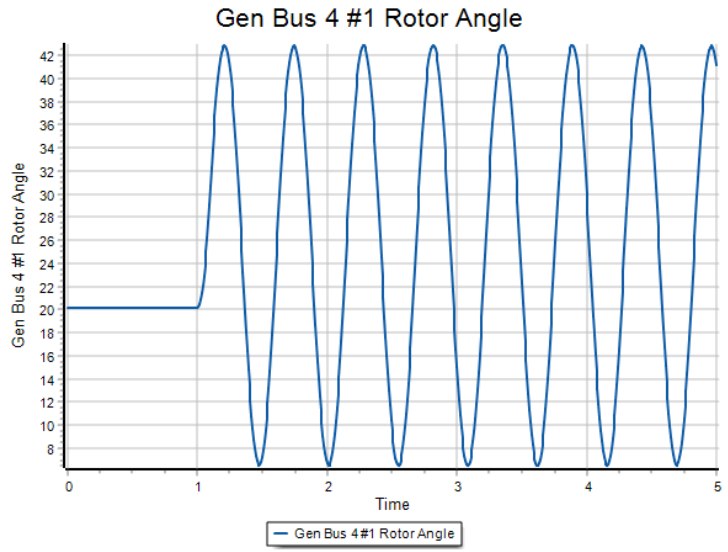
- An infinite bus is assumed to have a fixed voltage magnitude and angle; hence its frequency is also fixed at the nominal value.
  - Infinite buses obviously do not exist, but at least one (e.g., a slack bus) is needed in every power flow island
  - Infinite buses can be a useful concept when learning about transient stability and when “debugging models”
  - By default PowerWorld Simulator does NOT treat the slack bus as an infinite bus, but does provide an option.
  - Here we will use this option in creating a simple case by selecting **Options** and the **Power System Model** tab; set **Infinite Bus Modeling** to “Model the power flow slack bus(es) as infinite buses”

Quickly Setting Up a Dynamics Case

- Open the case Example_12_4_NoModels; this is a four bus power flow case with no dynamic models
- To add a model, right-click on the Bus 4 generator, select **Generator Information Dialog**; go to the **Stability page**; on the Machine Models tab click **Insert** and select GENCLS; click **OK**
  - This added a very simple dynamic model for the generator
- Select **Add Ons, Transient Stability**; click **Run Transient Stability**
  - This does the simulation, but nothing occurs because no contingency events have been defined

Quickly Setting Up a Dynamics Case, cont.

- On the **Transient Contingency Elements** tab click **Insert/Apply/Clear/Open** to put in a fault that is subsequently cleared; pick Bus 3 rerun the simulation
- Got to the **Results from RAM** page and view the generator results
  - To see a plot of the results, right-click on any result column, and select **Plot Column**
  - The result shows the generator oscillating as a result of the fault (the GENCLS model does not have implicit damping)
- In PowerWorld there are many ways to further customize and expand the simulation

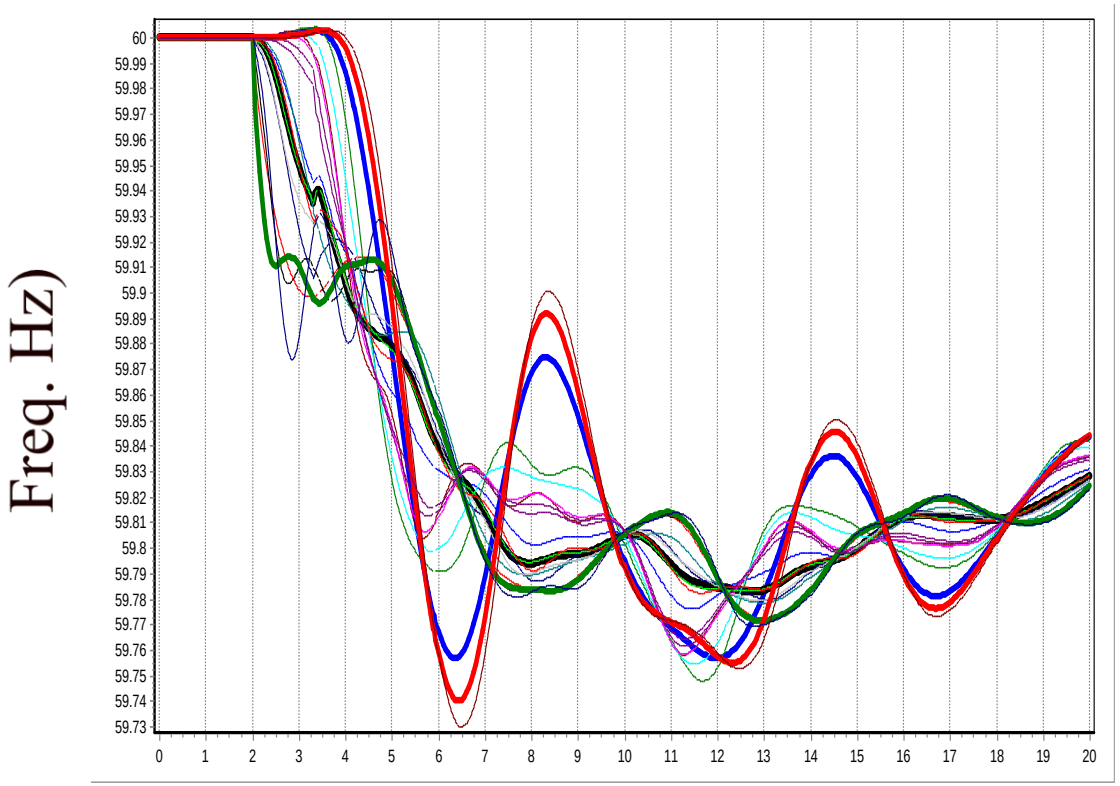


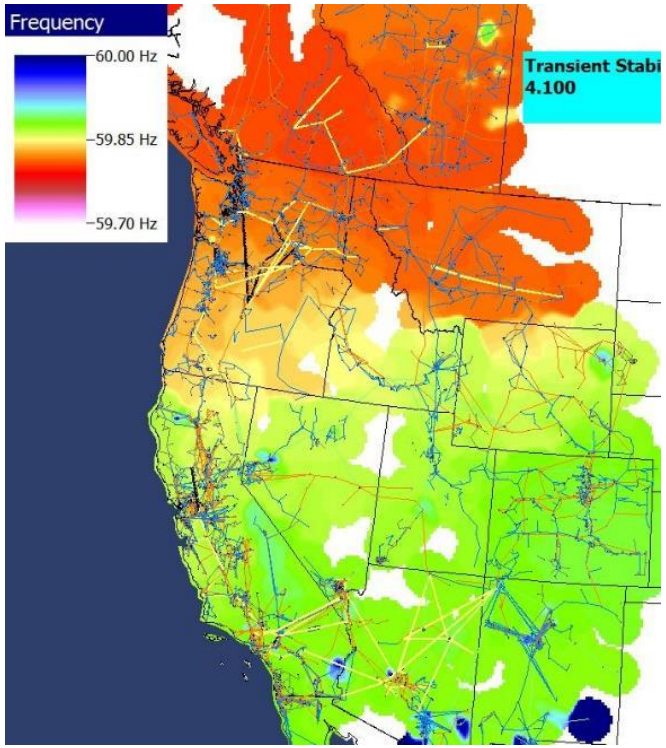
Frequency Response for Generation Loss

- A common contingency is the response of the grid to the loss of a large generator
- In response to a rapid loss of generation, in the initial seconds the system frequency will decrease as energy stored in the rotating masses is transformed into electric energy
  - Some generation, such as solar PV has no inertia, and for most new wind turbines the inertia is not seen by the system
- Within seconds governors respond, increasing the power output of controllable generation
  - Many conventional units are operated so they only respond to over frequency situations
  - Solar PV and wind are usually operated in North America at maximum power so they have no reserves to contribute

Short Term (20 Seconds) Example

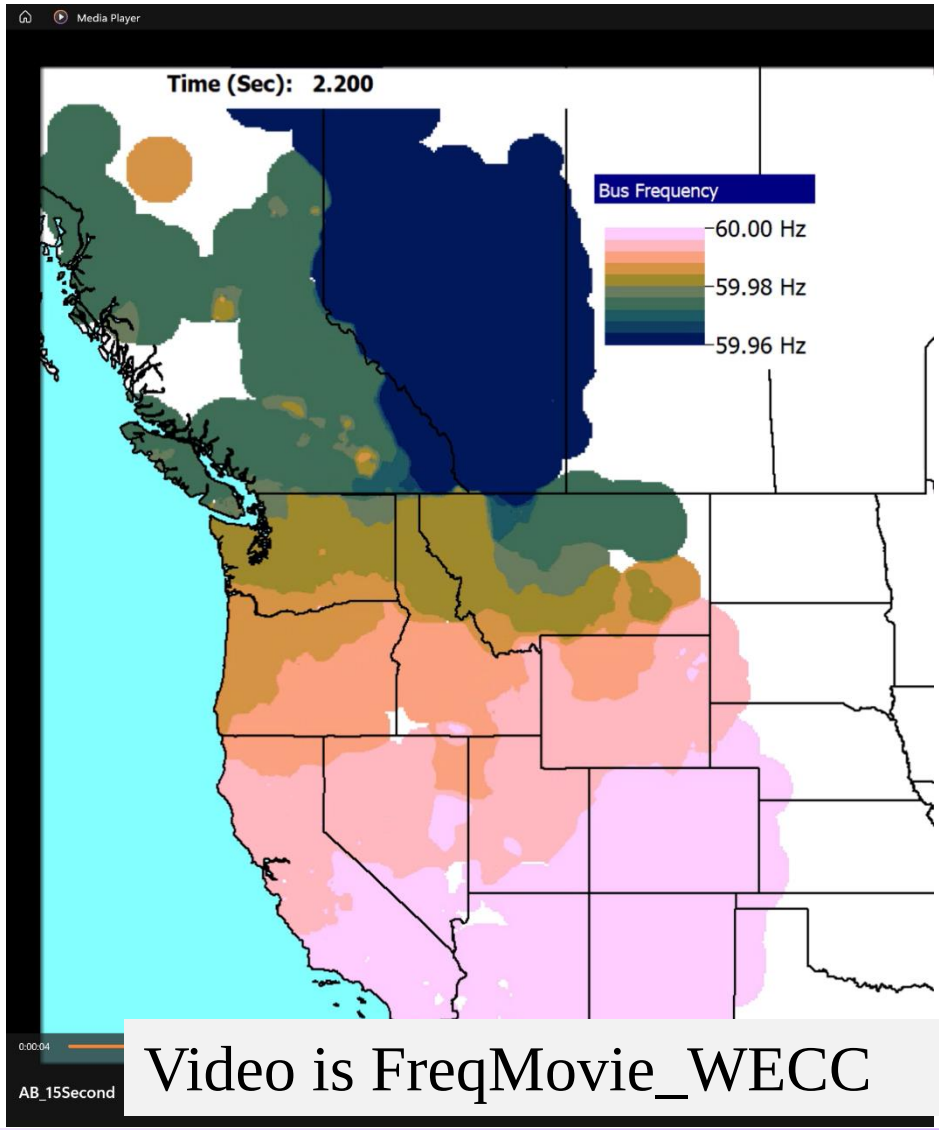
- Figures show the frequency change as a result of the sudden loss of a large amount of generation in the Southern WECC



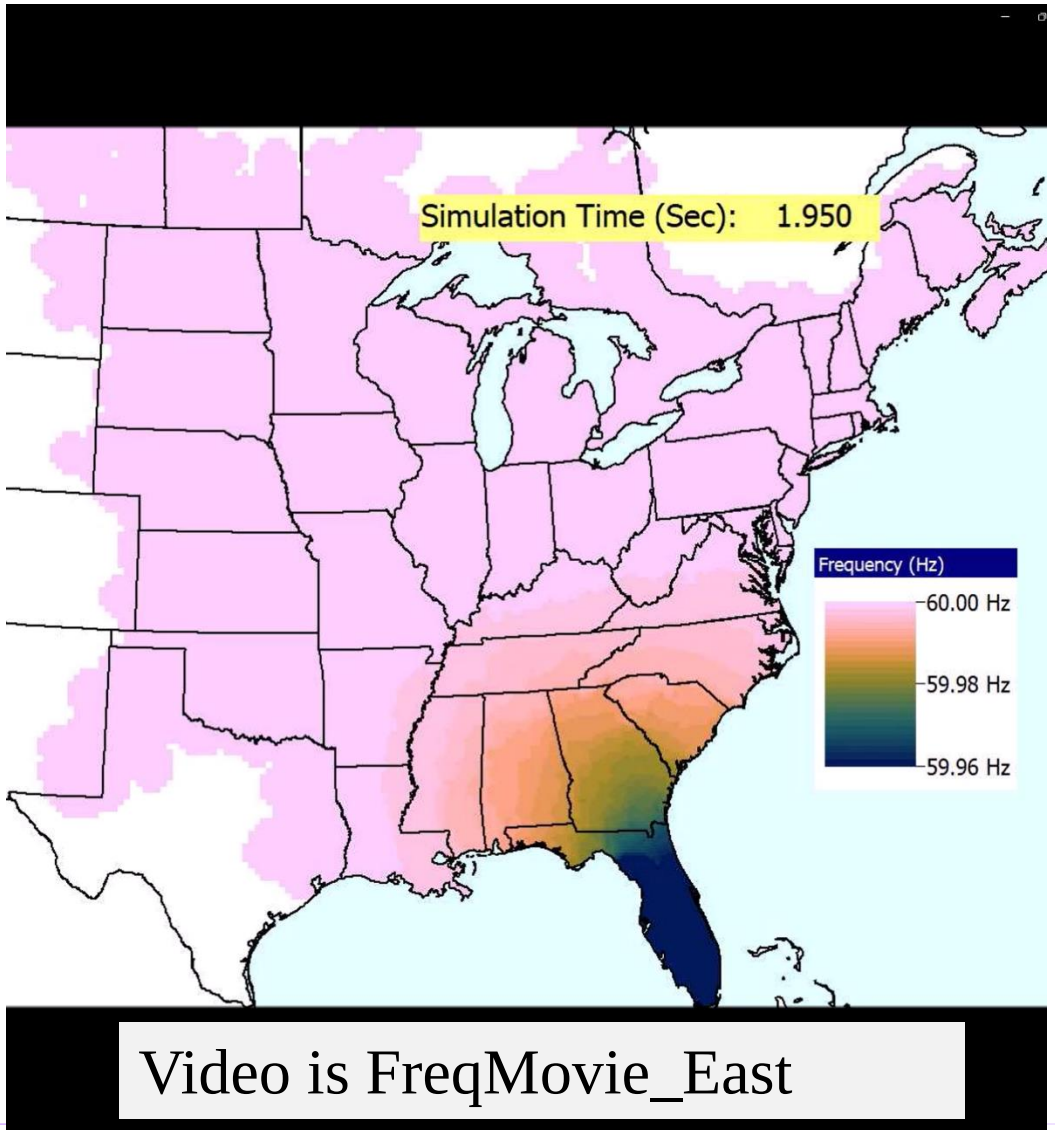


Frequency Contour

Frequency Contour Videos for the West and East



Video is FreqMovie_WECC



Video is FreqMovie_East