

Introduction to Electric Grid Device Models and Simulation



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Power System Modeling

Introduction



- The focus for this talk is on electric grid device models and simulation
- The words model or modeling have lots of definitions. A useful definition here 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
- Definition source:
whatis.techtarget.com/definition/modeling-and-simulation-MS

Modeling Cautions!

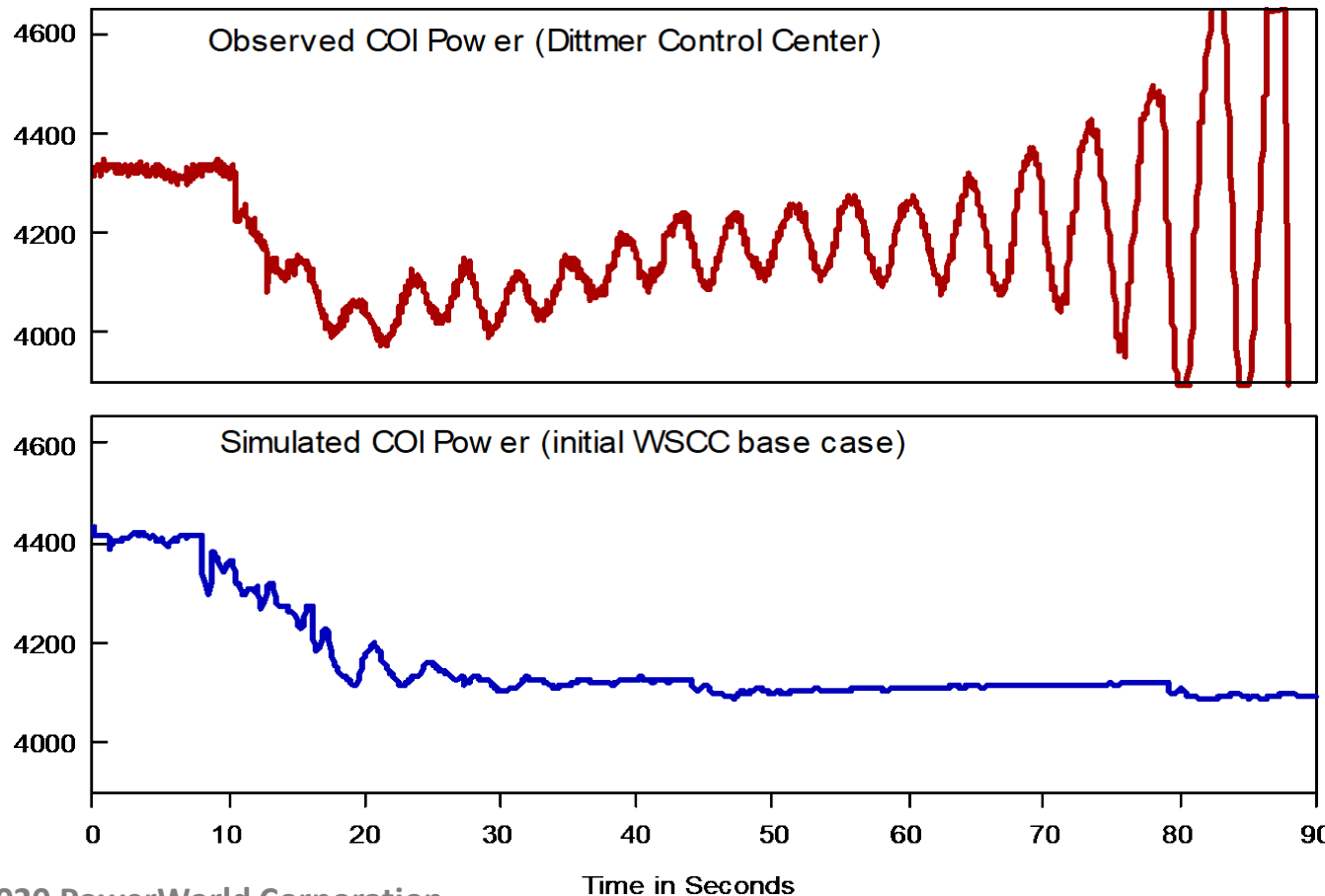


- "All models are wrong but some are useful," George Box, Empirical Model-Building and Response Surfaces, (1987, p. 424)
 - Models are an approximation to reality, not reality, so they always have some degree of approximation
 - Box went on to say that the practical question is how wrong to they have 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!

Dynamics Example 1



1996: Oscillations caused a blackout not matched by the models



Thankfully
the models
have been
greatly
improved
over the
last 23 years!

Dynamics Example 2: August 14 Blackout

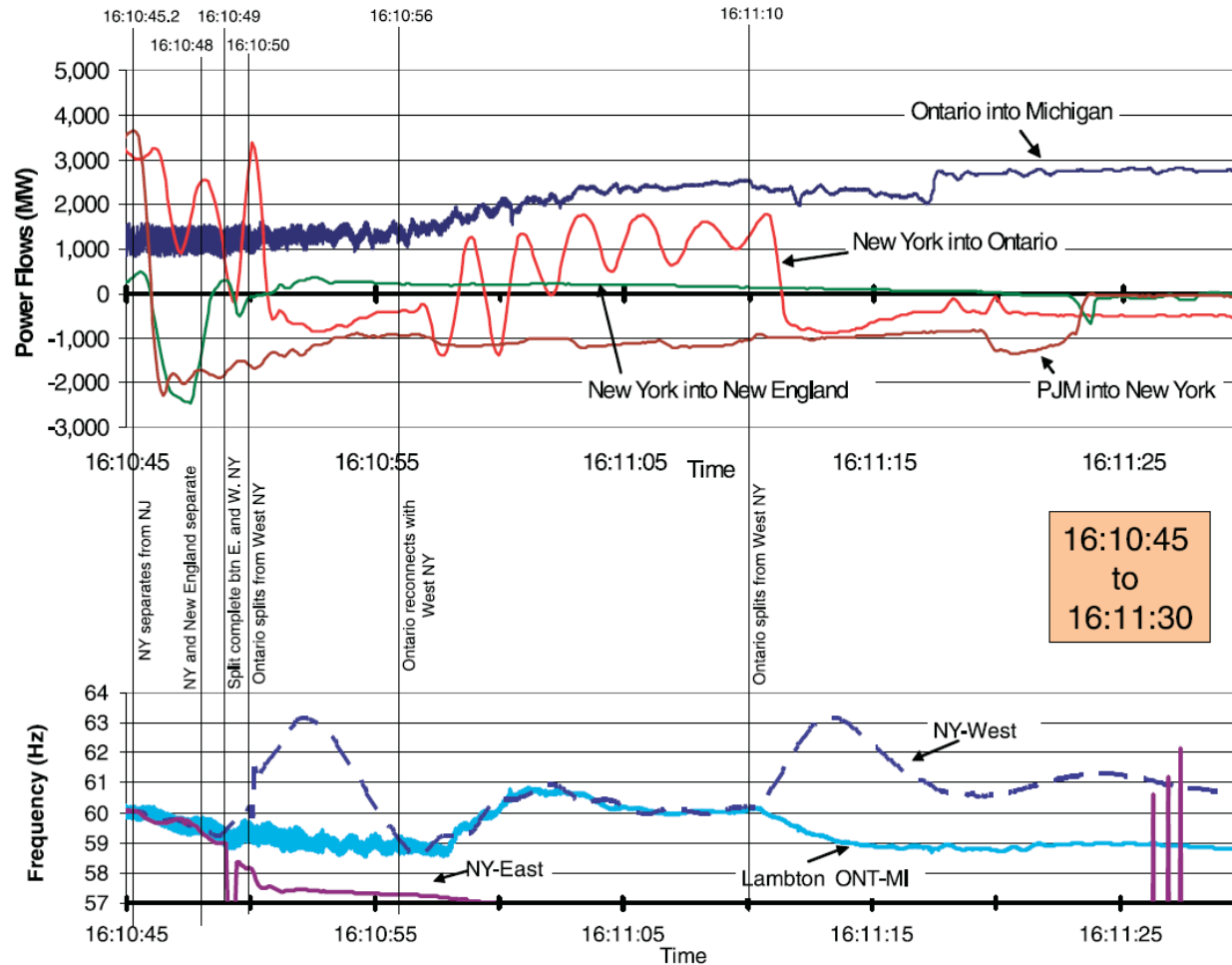
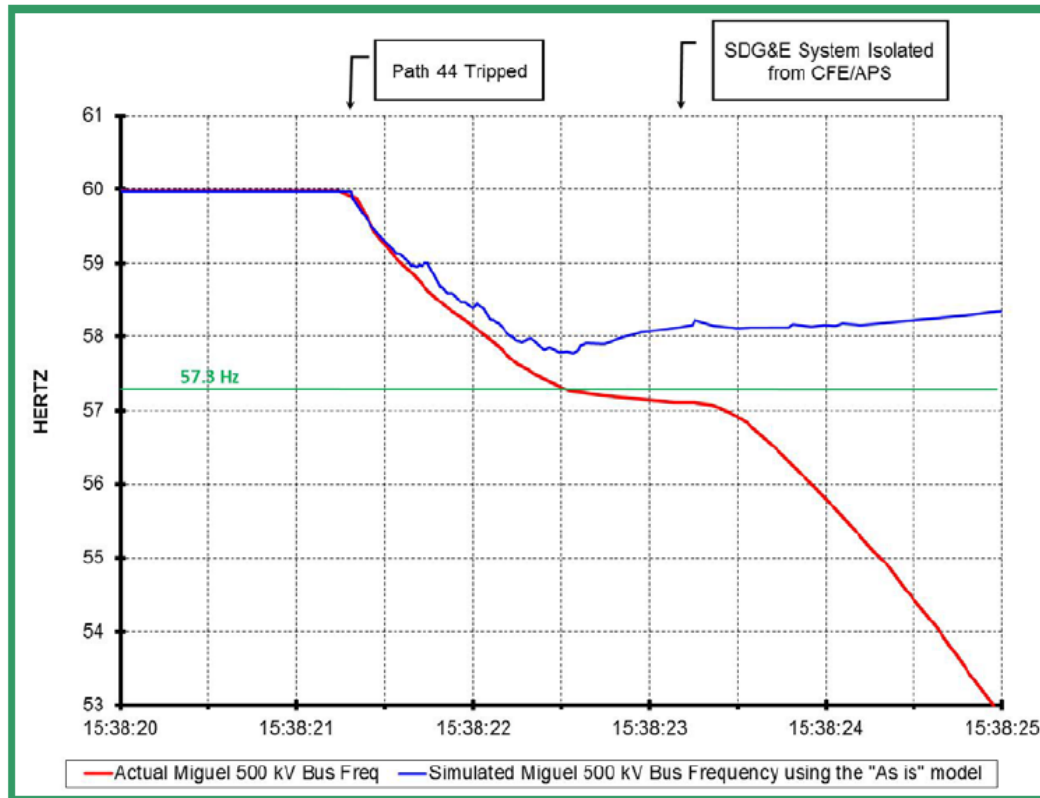


Image from August 14, 2003 Blackout Final Report, energy.gov, Figure 6.26

Dynamics Example 3



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



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

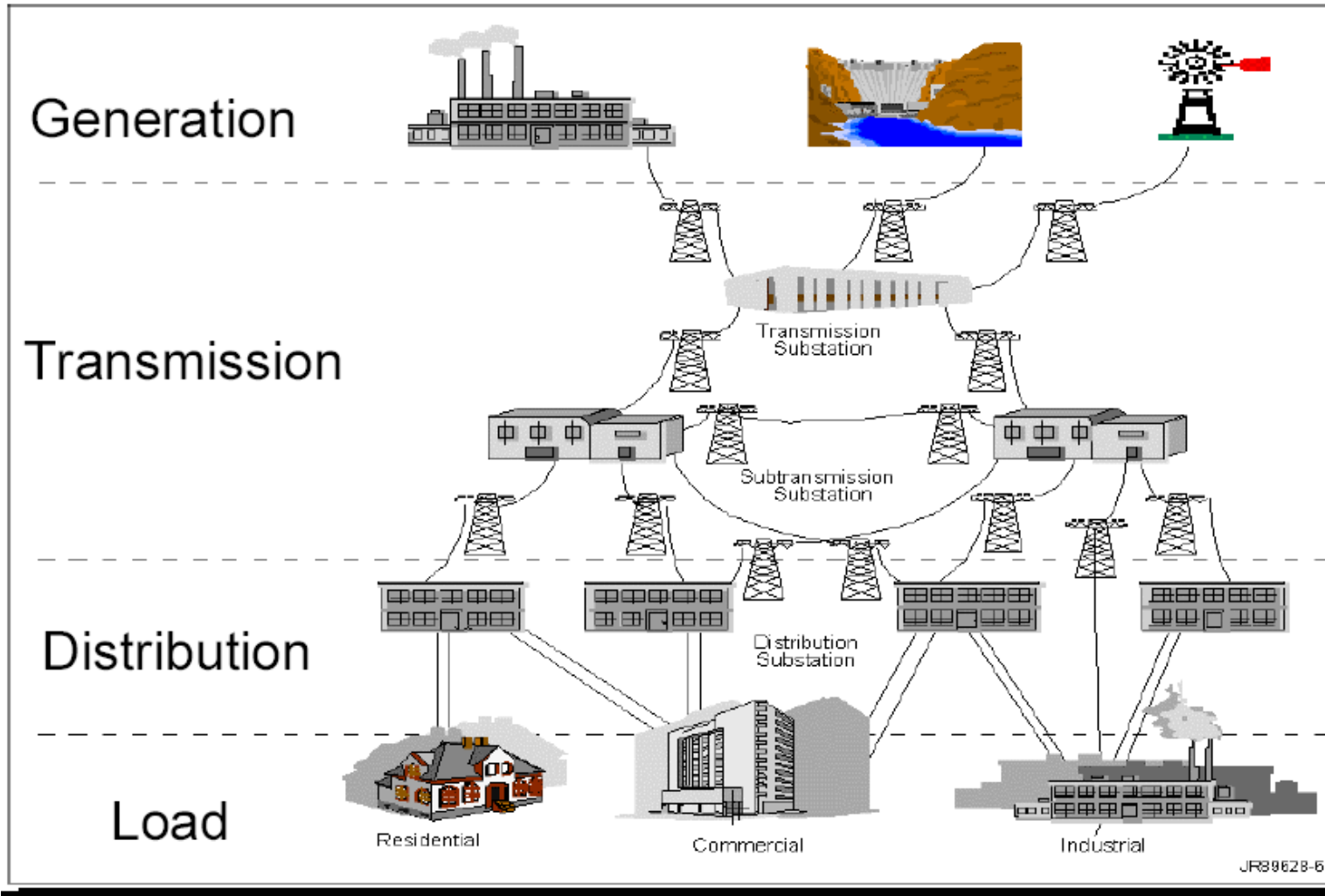
We've come a long ways since 1996 towards improved simulations. Still, a finding from the 2011 Blackout is the simulations didn't match the actual system response and need to be improved.

Electric Grid Overview



- Generation – source of electric energy
 - coal had provided over half of the U.S. electric energy, but now natural gas leads, with renewable sources rapidly growing
- Load – consumes electric energy
 - consumers are in complete control of the switch; utilities must supply enough power to meet load
- Transmission and Distribution – the wires that carry the power from generation to load
 - Operating at voltages up to 765 kV (kilovolt), with 500 kV, 345 kV and 230 kV common

Major Power Grid Components

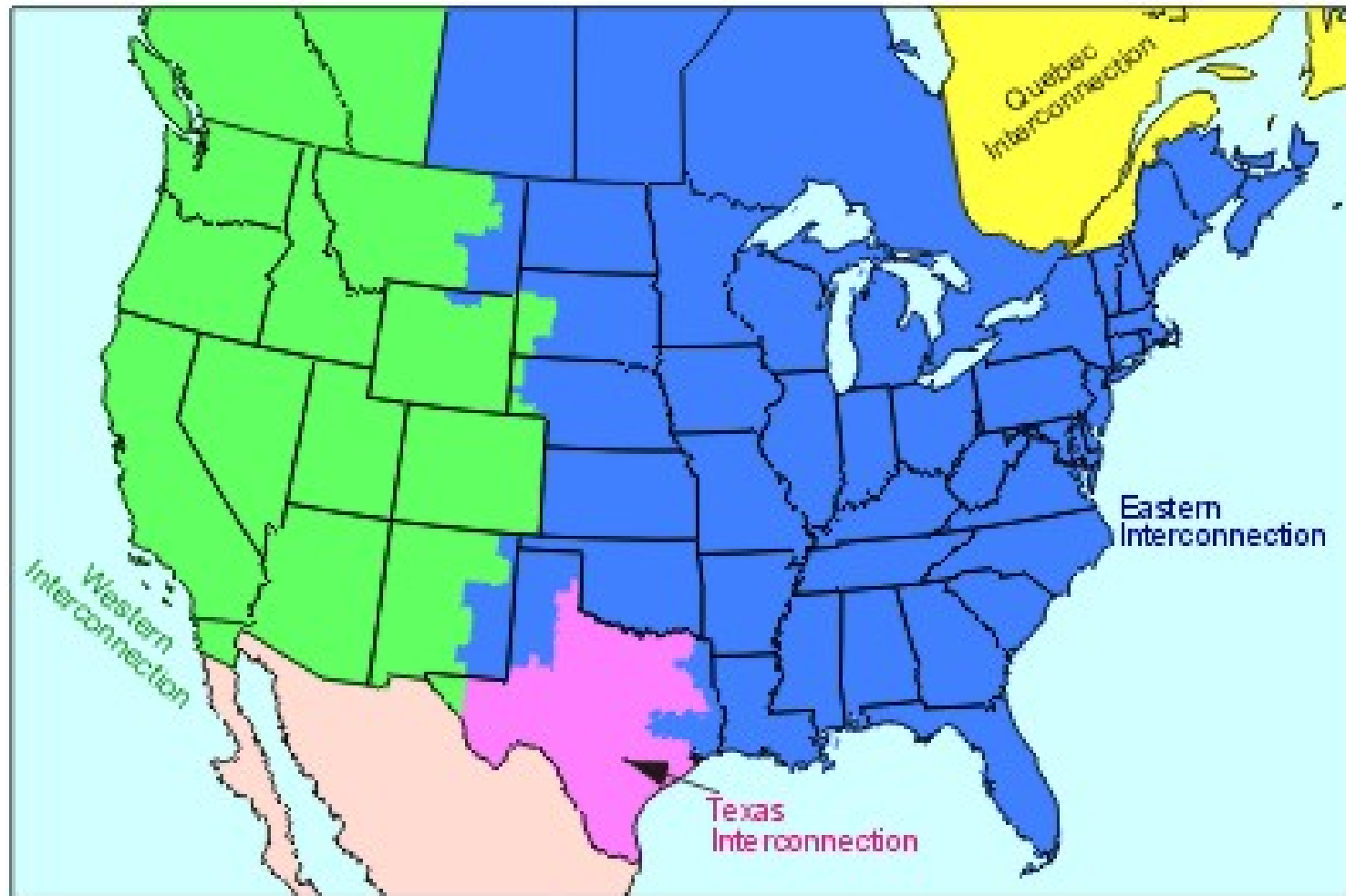


Synchronous Electric Grids



- Much of the electricity in the developed world is supplied by large-scale, 60 or 50 Hz synchronous electric grids
 - Such grids can provide improved reliability, larger electricity markets and often economics of scale
 - However, they add planning complexities
 - Power can be transferred between synchronous grids by first converting it to dc, with HVDC lines one example
- Islands, and other parts of the world are supplied by smaller electric grids

North America Interconnections



Three-Phase Systems



- Essentially all large-scale electric grids are three-phase
 - Three wires, with the same voltage magnitude and a phase shift of 120 degrees
- Usually the high voltage electric grid is “balanced,”
 - This means that it can be very well modeled as an equivalent single-phase system
 - The three-phase lines are often shown with a single line, what is known as a one-line



Components Join Together at a Bus



Challenge: Power System Time Frames

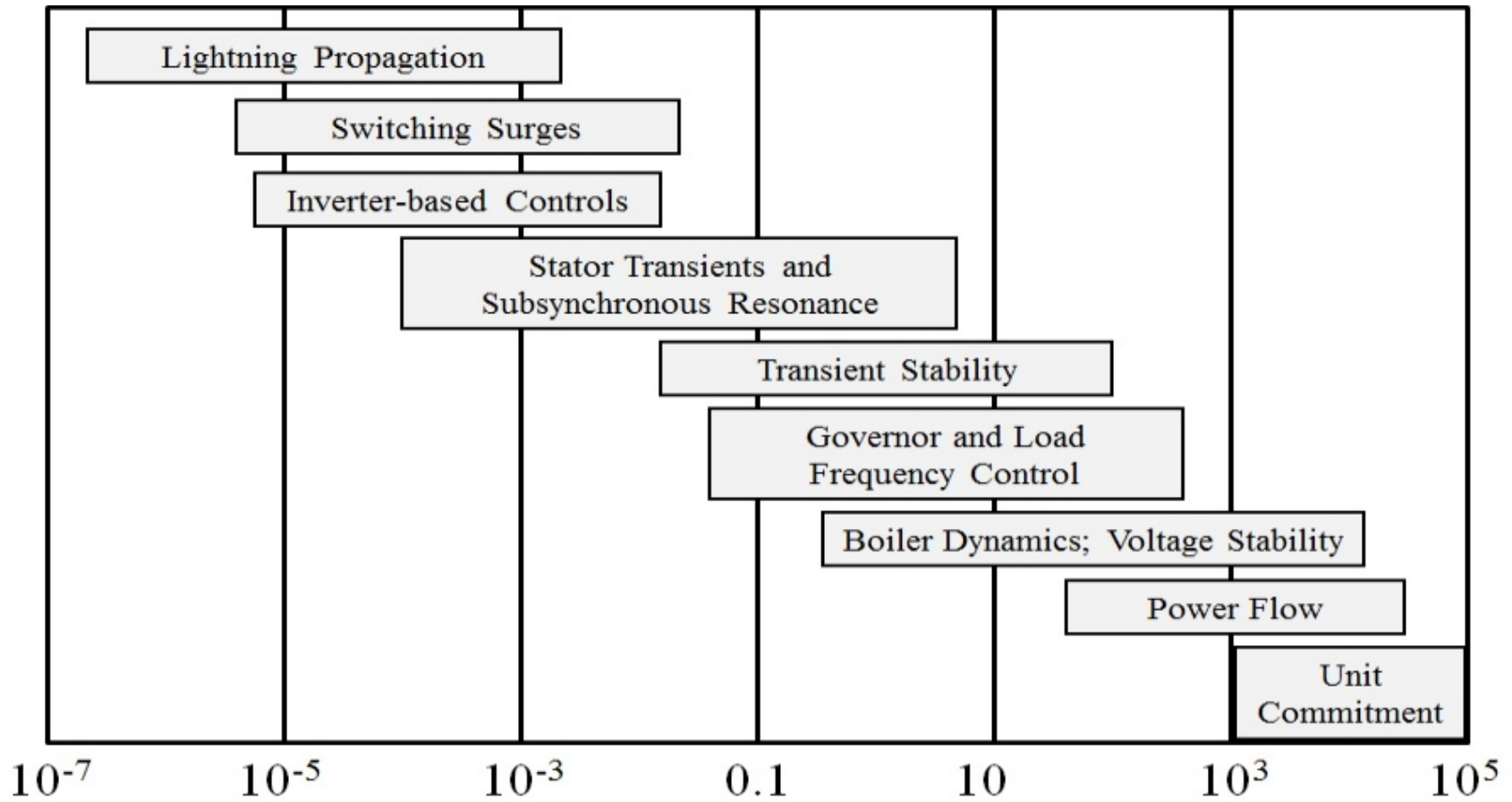


Image source: P.W. Sauer, M.A. Pai, Power System Dynamics and Stability, 1997, Fig 1.2, modified

Models and Their Parameters



- Models approximate the generic behavior of an object (e.g, a resistor with $V = RI$)
- The model's parameters describe the behavior of a particular object
- Models and parameters can be tightly coupled
 - The parameters for a particular model might have been derived from actual results on the object of interest, with the parameters tuned to match
 - For example, the resistance of an aluminum conductor is dependent on temperature and frequency, which might not be included in its model

Models and Their Parameters



- Changing the model (even correcting an "incorrect" simulation implementation) can result in unexpected results!
- Using a more detailed simulation approach, without changing the model, can also result in incorrect results
 - More detailed models are not necessarily more accurate
- Not all parameters are created equal, and don't need equal accuracy

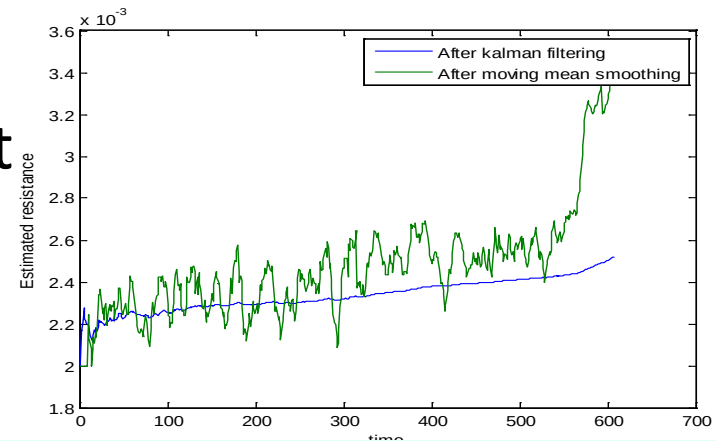


Image shows estimated line resistance variation (time in seconds)

Static versus Dynamic Analysis



- Statics versus dynamics analysis appears in many fields
- An equilibrium point is a point at which the system model is not changing
 - Real systems are always changing, but over the time period of interest an unchanging system can be a useful approximation
- Static analysis looks at how the equilibrium points change to a change in the model
 - Power flow is a power system example

Static versus Dynamic Analysis



- Dynamic analysis looks at how the system responds over time when it is perturbed away from an equilibrium point
 - Power system example is transient stability
- Key analysis question in setting up and solving models is knowing the time frame of interest
- Values that change slowly (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)

Static versus Dynamic Analysis



- 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
- In the power flow the control response of the human operator is considered a fast control whereas in dynamic analysis it is either slow or needs to be considered

Planning Model Components for Static Analysis

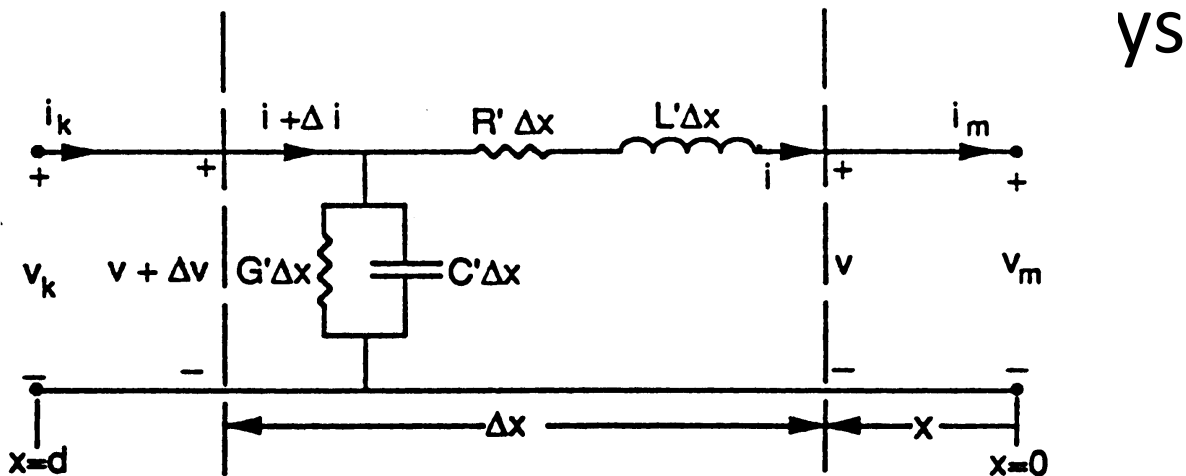


- The next few slides introduce the common models of the major electric grid components used for the dynamic analysis considered here
 - Transmission Lines
 - Transformers
 - Generators
 - Loads
- Remainder of this section then explains the process of assembling models of large-scale electric grids for dynamic studies

Incremental Transmission Line Modeling



- On a very short time-scale (micro-seconds), a full incremental transmission line model



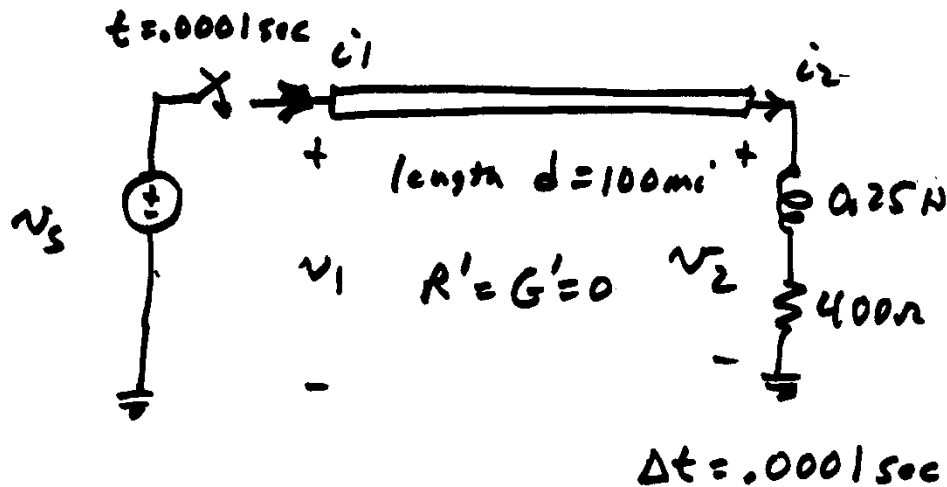
$$\Delta v = R' \Delta x i + L' \Delta x \frac{\partial i}{\partial t}$$

$$\Delta i = G' \Delta x (v + \Delta v) + C' \Delta x \frac{\partial}{\partial t} (v + \Delta v)$$

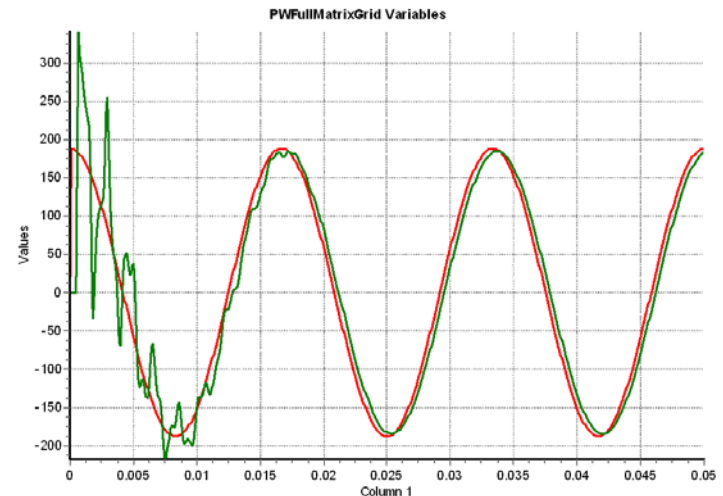
Fast Simulation Example



- Example shows a detailed (100 μ sec time step) of closing a transmission line with a 60 Hz source and a RL load)



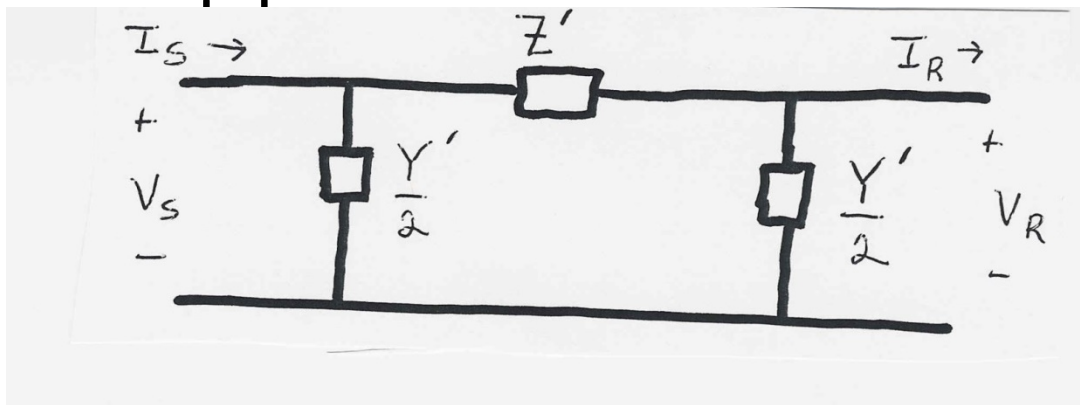
Red is the v_s end, green the v_2 end



Lumped Parameter Transmission Line Models



- For the longer time frame considered here (microseconds and up) transmission lines can be modeled using a lumped parameter p



- This model is only valid for transmission lines with symmetric tower configurations or if one assumes uniformly transposed lines

Symmetric Line Spacing – 69 kV

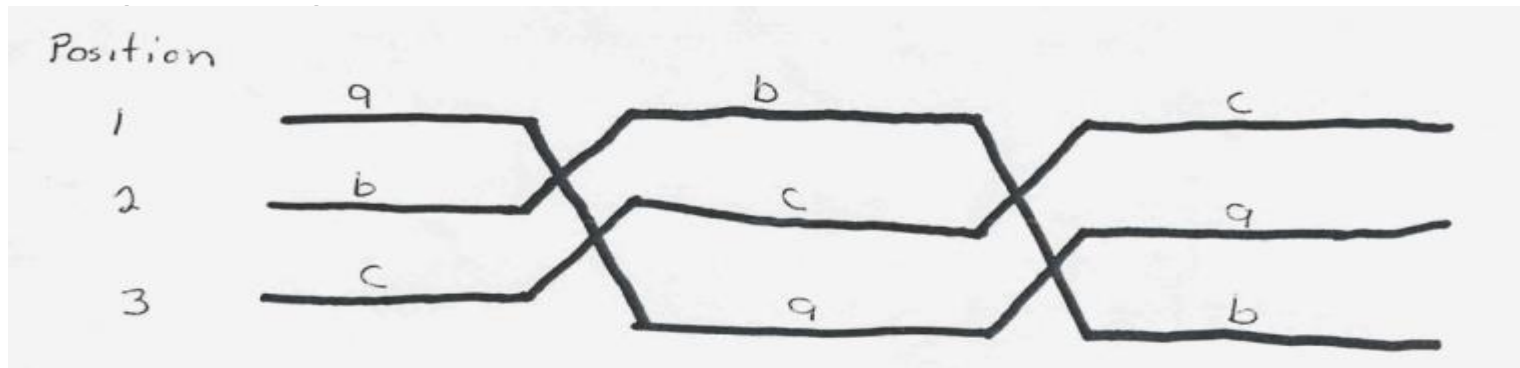


09/12/2004

Unsymmetric Lines and Transposition



- To keep system balanced, over the length of a transmission line the conductors are rotated so each phase occupies each position on tower for an equal distance.



Per Phase Analysis of Three-Phase

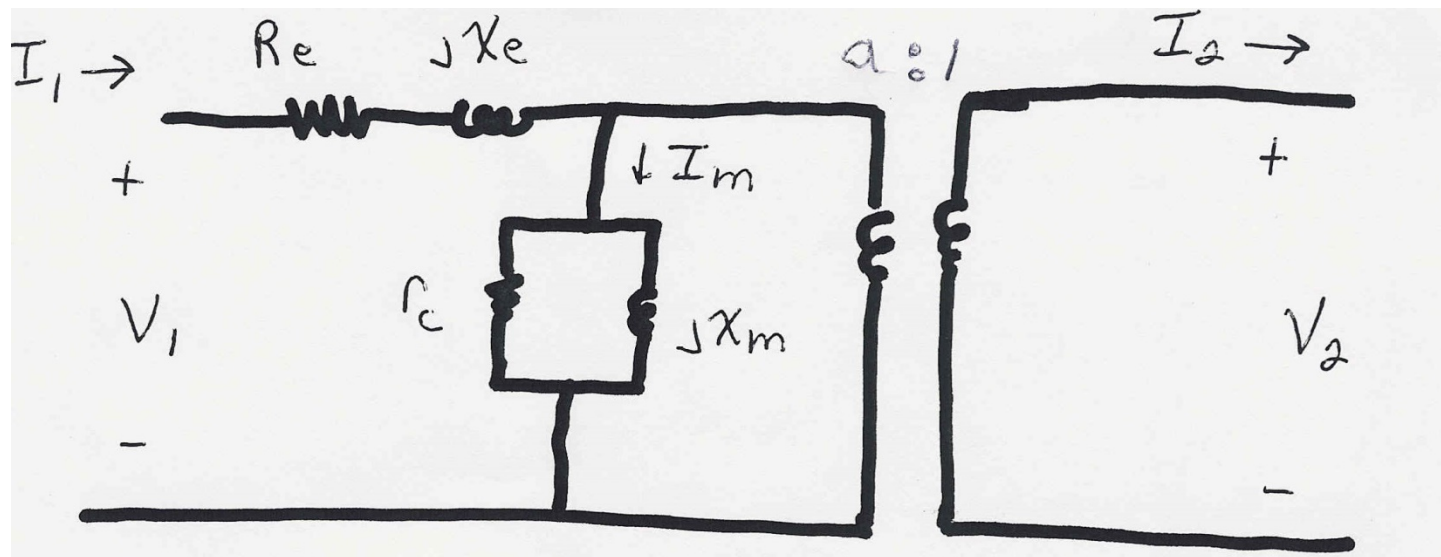


- Large-scale electrical systems are almost exclusively three-phase. Common analysis tools, such as power flow and transient stability, often assume balanced operation
- Balanced three-phase systems could be modeled with a per phase approach
 - Balanced Three-Phase Theorem: If a three-phase system is balanced, all loads and sources are Y-connected, and there is no mutual inductance between the phases then
 - All neutrals at the same potential
 - Phases are completely decoupled

Transformer Models



- Transformer per phase equivalent model (assuming we neglect any Y-D shift)



The turns ratio, a , can be a key control value. This is potentially a complex number (e.g., with a phase shifting transformer)

When Transformers Go Bad!



mer_failure

Per Unit Calculations



- A key problem in analyzing power systems is the large number of transformers.
 - It would be very difficult to continually have to refer 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

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

Generator Models



- Engineering models depend upon application
- Generators are often synchronous machines
- For generators we will use two different models:
 - a steady-state model, treating the generator as a constant power source operating at either a fixed voltage magnitude or fixed reactive power output; this model will be used for power flow and economic analysis
 - a much more detailed model when we consider dynamics later in this course

Load Models



- Ultimate goal is to supply loads with electricity at constant frequency and voltage
- Electrical characteristics of individual loads matter, but usually they can only be estimated
 - actual loads are constantly changing, consisting of a large number of individual devices
 - only limited network observability of load characteristics
- Aggregate models are typically used for analysis
- Two common models
 - constant power: $S_i = P_i + jQ_i$
 - constant impedance: $S_i = |V|^2 / Z_i$

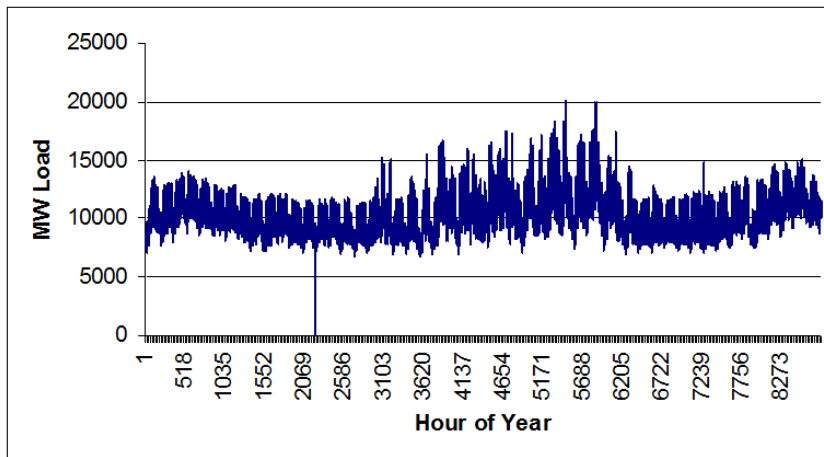
The ZIP model combines constant impedance, current and power (P)

Load Variation

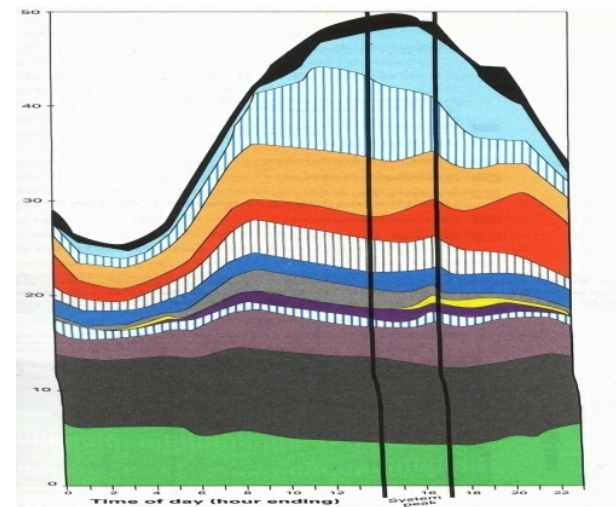


- A challenge is the load is constantly changing, both in magnitude and in composition
- The growth in distributed energy resources (e.g., PV) in the distribution is making it more challenging to forecast load

Yearly variation for a utility



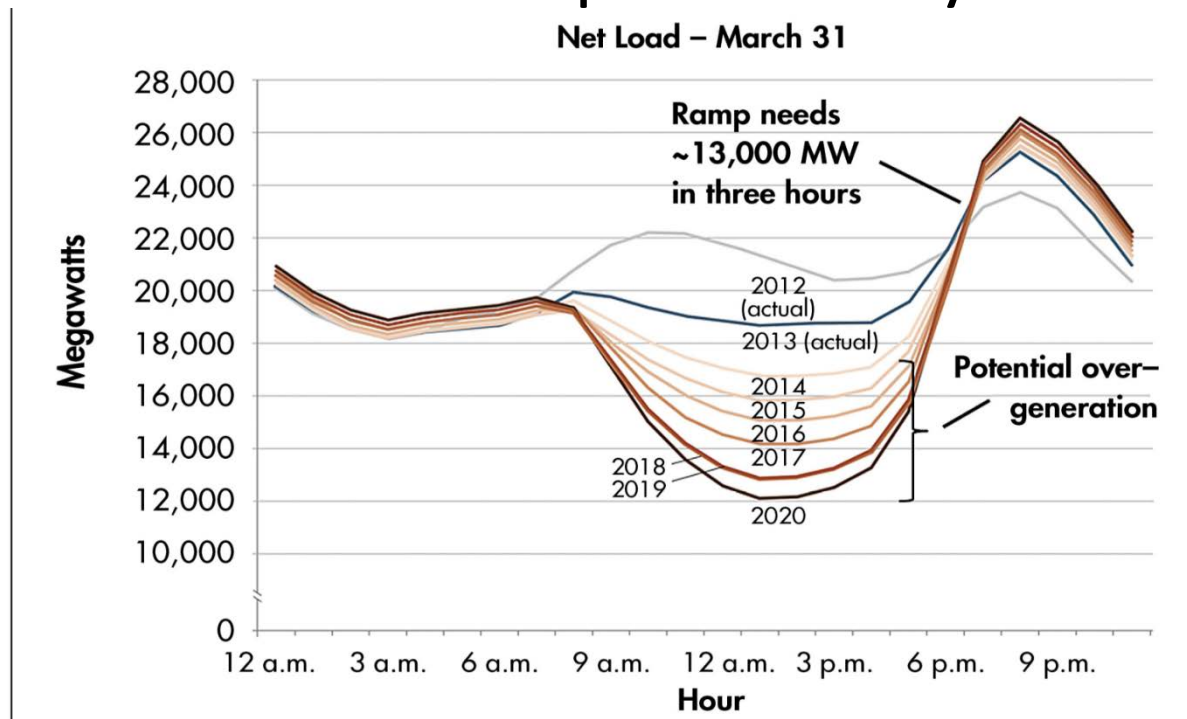
24 Hour Load Variation at a single bus



The Duck Curve



- The duck curve, which was created by the California ISO in 2012, shows how growing solar could impact their system load



The loss of solar in the late afternoon leads to a need to rapidly increase other types of generation.

Image Source: The California ISO

Symmetric Components



- Much of power system dynamic analysis is done assuming the system is operated balanced, three-phase
- However, we need to briefly consider unbalanced system operation, which certainly can occur during faults
 - The most common fault is a single line-to-ground (SLG) fault, whereas three-phase faults are uncommon
- Such systems can be analyzed using symmetrical components

Symmetric Components



- The key idea of symmetrical component analysis is to decompose the system into three sequence networks. The networks are then coupled only at the point of the unbalance (i.e., the fault)
- The three sequence networks are known as the
 - positive sequence (this is the one for balanced systems)
 - negative sequence
 - zero sequence
- Presented in paper by Charles .L Fortescue in 1918 (most important 20th century power paper)

Heydt, G. T.; Venkata, S. S.; Balijepalli, N. (October 24, 2000). ["High Impact Papers in Power Engineering, 1900-1999"](#) *Proceedings 2000 North American Power Symposium, vol. 1, October 2000*. North American Power Symposium (NAPS). Waterloo, Ontario.

Positive, Negative and Zero Sequence Sets



- The positive sequence sets have three phase currents/voltages with equal magnitude, with phase b lagging phase a by 120° , and phase c lagging phase b by 120°
- The negative sequence sets have three phase currents/voltages with equal magnitude, with phase b **leading** phase a by 120° , and phase c **leading** phase b by 120°
- Zero sequence sets have three values with equal magnitude and angle

Symmetrical Component Conversion



- Voltages and currents can be easily transformed between their phase and sequence values

Define the symmetrical components transformation matrix

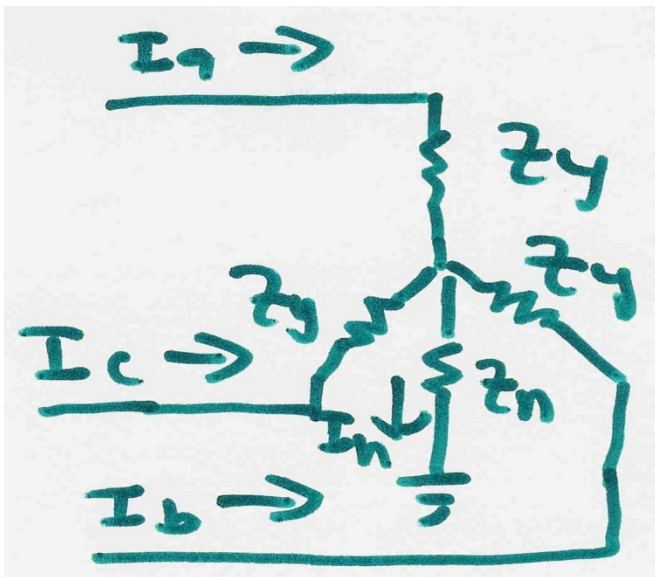
$$\mathbf{A} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix}$$

$$\text{Then } \mathbf{I} = \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \mathbf{A} \begin{bmatrix} I_a^0 \\ I_a^+ \\ I_a^- \end{bmatrix} = \mathbf{A} \begin{bmatrix} I^0 \\ I^+ \\ I^- \end{bmatrix} = \mathbf{A} \mathbf{I}_s$$

Symmetrical Components to Decouple Unbalanced Networks



- Consider the following wye-connected



$$I_n = I_a + I_b + I_c$$

$$V_{ag} = I_a Z_y + I_n Z_n$$

$$V_{ag} = (Z_Y + Z_n)I_a + Z_n I_b + Z_n I_c$$

$$V_{bg} = Z_n I_a + (Z_Y + Z_n)I_b + Z_n I_c$$

$$V_{cg} = Z_n I_a + Z_n I_b + (Z_Y + Z_n)I_c$$

$$\begin{bmatrix} V_{ag} \\ V_{bg} \\ V_{cg} \end{bmatrix} = \begin{bmatrix} Z_y + Z_n & Z_n & Z_n \\ Z_n & Z_y + Z_n & Z_n \\ Z_n & Z_n & Z_y + Z_n \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

Symmetrical Components to Decouple Unbalanced Networks



$$\begin{bmatrix} V_{ag} \\ V_{bg} \\ V_{cg} \end{bmatrix} = \begin{bmatrix} Z_y + Z_n & Z_n & Z_n \\ Z_n & Z_y + Z_n & Z_n \\ Z_n & Z_n & Z_y + Z_n \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

$$\mathbf{V} = \mathbf{Z} \mathbf{I} \quad \mathbf{V} = \mathbf{A} \mathbf{V}_s \quad \mathbf{I} = \mathbf{A} \mathbf{I}_s$$

$$\mathbf{A} \mathbf{V}_s = \mathbf{Z} \mathbf{A} \mathbf{I}_s \rightarrow \mathbf{V}_s = \mathbf{A}^{-1} \mathbf{Z} \mathbf{A} \mathbf{I}_s$$

$$\mathbf{A}^{-1} \mathbf{Z} \mathbf{A} = \begin{bmatrix} Z_y + 3Z_n & 0 & 0 \\ 0 & Z_y & 0 \\ 0 & 0 & Z_y \end{bmatrix}$$

Use of Symmetrical Components



- Sequence models can be derived for lines, transformers, generators and loads
- During normal operation only the positive sequence network is excited
- The sequence networks get coupled because of the unbalances caused by faults
- Usually we only analyze the positive sequence network; unbalanced faults can be modeled by compensated positive sequence values

Power Flow and Dynamics

Introduction



- We now have the necessary models to start to develop the power system analysis tools
- The most common power system analysis tool is the power flow (also known as the load flow)
 - Power flow tells how the power flows in a network
 - Also used to calculate all bus voltages and all currents
 - Power flow is a steady-state analysis tool
- Due to constant power models the power flow is a nonlinear analysis technique
- Power flow is used to initialize dynamic simulations

Newton-Raphson Power Flow Algorithm



- Most common technique for solving the power flow problem is to use the Newton-Raphson algorithm
- Key idea behind Newton-Raphson is to use sequential linearization

General form of problem: Find an $\mathbf{x}$ such that

$$\mathbf{f}(\hat{\mathbf{x}}) = 0$$

- In the power flow $\mathbf{f}$ is the power balance equations and $\mathbf{x}$ is the voltage angles and magnitudes

Power Balance Equations at Bus i



$$\begin{aligned} S_i &= P_i + jQ_i = V_i \sum_{k=1}^n Y_{ik}^* V_k^* = \sum_{k=1}^n |V_i| |V_k| e^{j\theta_{ik}} (G_{ik} - jB_{ik}) \\ &= \sum_{k=1}^n |V_i| |V_k| (\cos \theta_{ik} + j \sin \theta_{ik}) (G_{ik} - jB_{ik}) \end{aligned}$$

Resolving into the real and imaginary parts

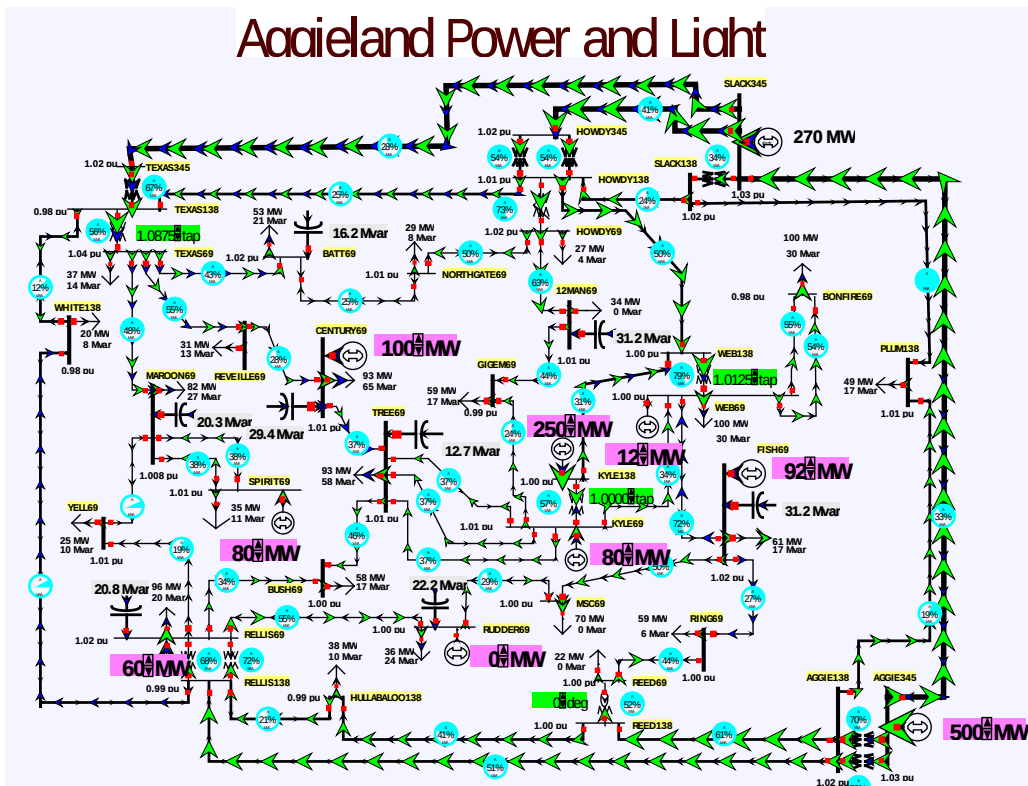
$$P_i = \sum_{k=1}^n |V_i| |V_k| (G_{ik} \cos \theta_{ik} + B_{ik} \sin \theta_{ik}) = P_{Gi} - P_{Di}$$

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

Hands-On: Power Flow Solution



- Power flow concepts will be illustrated in a PowerWorld Simulator using a 37 bus grid



PowerFlow

Left-click on the red circuit breaker symbols to see the impact of opening and closing devices

Slack (or Reference) Bus



- In the power flow we can not arbitrarily specify S at all buses because total generation must equal total load + total losses
- We also need an angle reference bus
- To solve these problems we define one bus as the "slack" bus. This bus has a fixed voltage magnitude and angle, and a varying real/reactive power injection.
- The slack bus will not be needed in dynamic simulations though we will still need an angle reference

Three Traditional Types of Power Flow Buses



- There are three traditional types of power flow buses
 - Load (PQ) at which P/Q are fixed; iteration solves for voltage magnitude and angle.
 - Slack at which the voltage magnitude and angle are fixed; iteration solves for P/Q injections
 - Generator (PV) at which P and $|V|$ are fixed; iteration solves for voltage angle and Q injection
- In dynamic simulations there will no longer be slack and PV buses

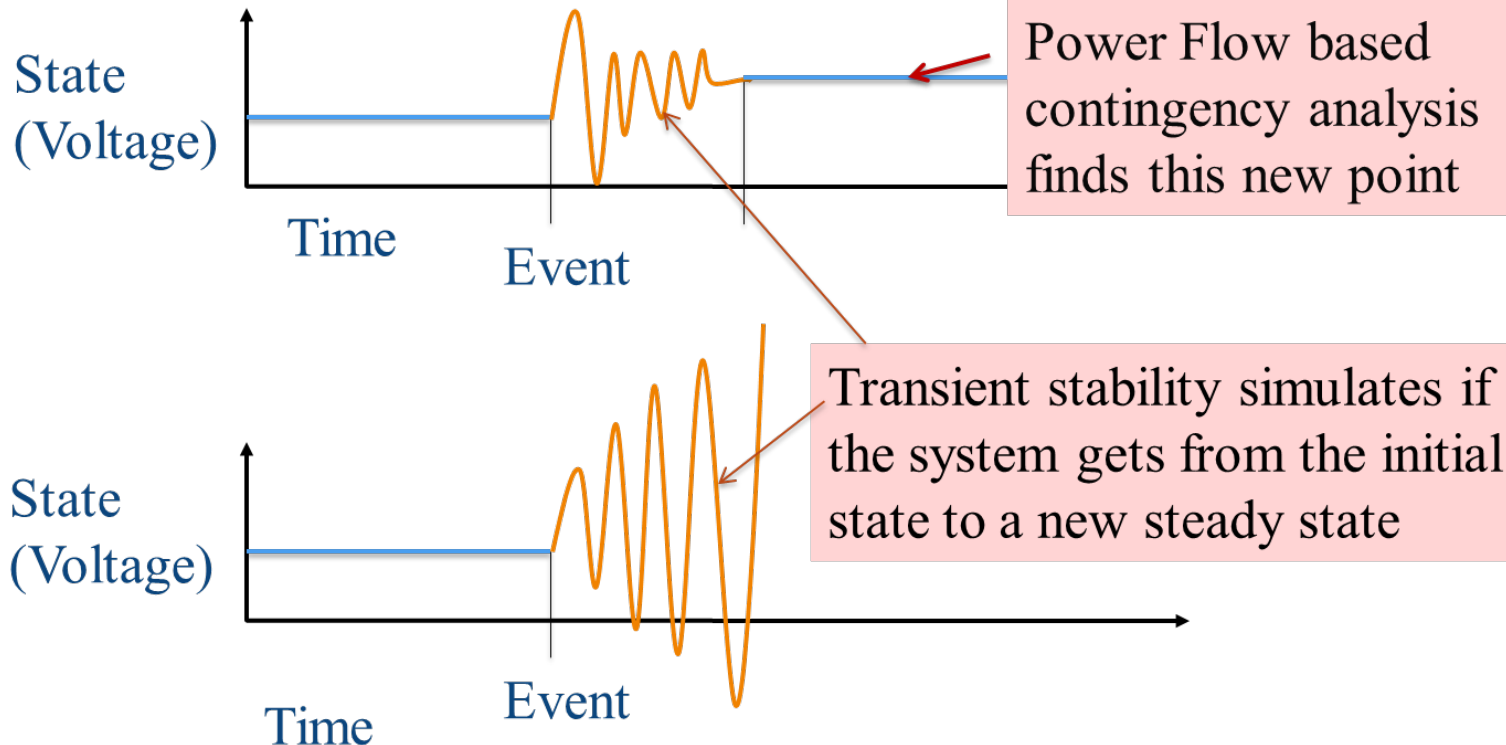
- Note that the change of 40 MW of generation at Rudder69 is totally absorbed by the slack bus



Power Flow and Dynamics



- Power flow characterizes the equilibrium points



Power Flow and Dynamics

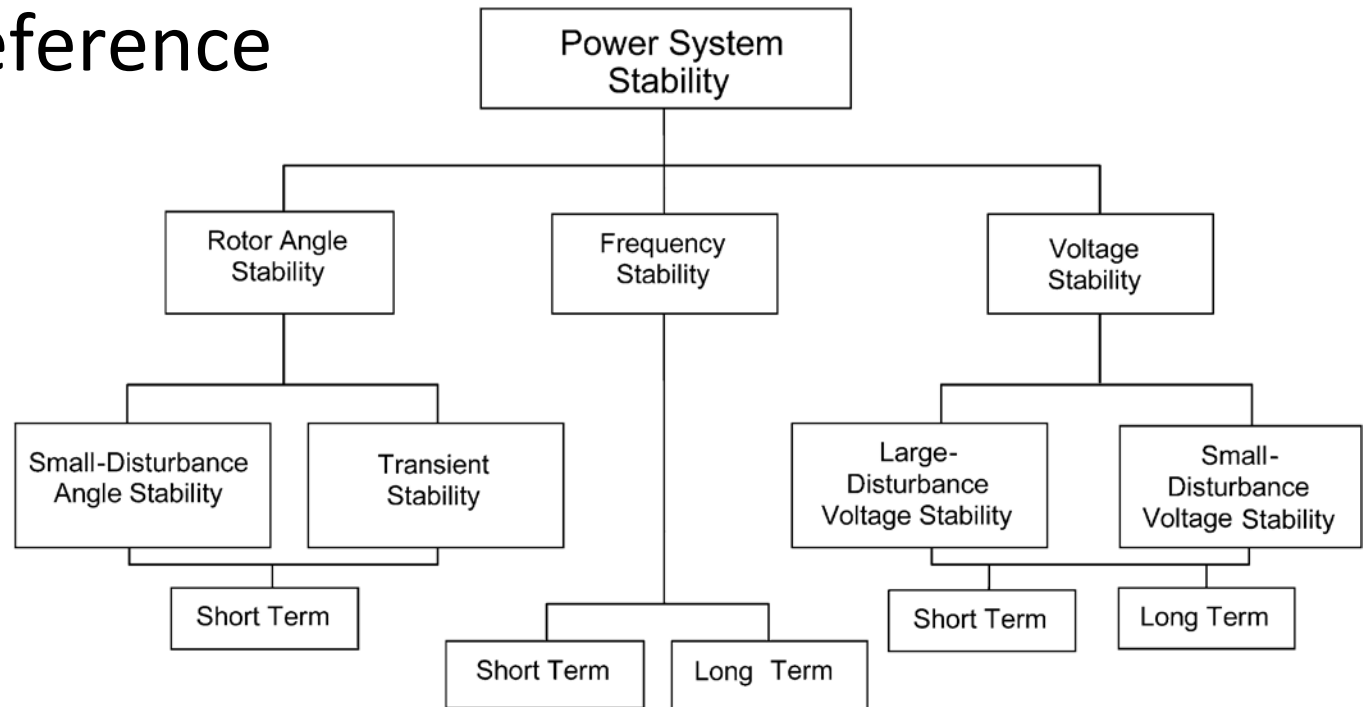


- Power flow determines quasi-steady state solution and provides the dynamics initial conditions
- Transient stability is used to determine whether following a contingency the power system returns to a steady-state operating point
 - Goal is to solve a set of differential and algebraic equations, $\frac{dx}{dt} = f(x,y)$, $g(x,y) = 0$
 - Starts in steady-state; hopefully returns to steady-state.
 - Models reflect the transient stability time frame (up to dozens of seconds), with some values assumed to be slow enough to hold constant while others are still fast enough to treat as algebraic

Power System Stability Terms



- Terms continue to evolve, but a good reference is [1]; image shows Figure 1 from this reference



[1] IEEE/CIGRE Joint Task Force on Stability Terms and Definitions, “Definitions and Classification of Power System Stability,” *IEEE Transactions Power Systems*, May 2004, pp.

1387-1401

First Example Case



- Open the previous 37 bus power flow case
- Add a dynamic generator model to an existing power flow case by:
 - In run mode, right-click on the generator symbol for bus Kyle138 (number 53), then select “Generator Information Dialog” from the local menu
 - This displays the Generator Information Dialog, select the “Stability” tab to view the transient stability models; none are initially defined.
 - Select the “Machine models” tab to enter a dynamic machine model for the generator. Click “Insert” to enter a machine model. From the Model Type list select GENCLS, which represents a simple “Classical” machine model. Use the default values.

Adding a Machine Model



Generator Information for Present

Bus Number: 53 Find By Number
Bus Name: KYLE138 Find By Name
ID: 1 Find ...
Area Name: 1 (1)
Labels: no labels
Generator MVA Base: 300.00
Fuel Type: Unknown
Unit Type: UN (Unknown)

Status:
☐ Open
☒ Closed

Energized:
☐ NO (Offline)
☒ YES (Online)

Power and Voltage Control Costs OPF Faults Owners, Area, etc. Custom Stability

Machine Models Exciters Governors Stabilizers Other Models Step-up Transformer Terminal and State

Insert Delete Gen MVA Base: 300.0 Show Block Diagram Create VCurve

Type: Active - GENCLS ☒ Active (only one may be active) Set to Defaults

Parameters
PU values shown/entered using device base of 300.0 MVA

H	3.00000
D	0.00000
Ra	0.00000
Xdp	0.20000
RComp	0.00000
XComp	0.00000

OK Save Save to Aux Cancel Help Print

The GENCLS model represents the machine dynamics as a fixed voltage magnitude behind a transient impedance $R_a + jX_{dp}$.

Press “Ok” when done to save the data and close the dialog

Transient Stability Form Overview



- Most of the PowerWorld Simulator dynamics functionality is accessed using the **Transient Stability Analysis** form. To view this form, from the ribbon select **Add Ons, Transient Stability**
- Key pages for quick start examples (listed under “Select Step”)
 - **Simulation:** Used for specifying the starting and ending time for the simulation, the time step, defining the transient stability fault (contingency) events, and running the simulation
 - **Options:** Various options associated with transient stability
 - **Result Storage:** Used to specify the fields to save and where
 - **Plots:** Used to plot results
 - **Results:** Used to view the results (actual numbers, not plots)

Transient Stability Overview Form



Transient Stability Analysis

Simulation Status: Not Initialized

Run Transient Stability | Pause | Abort | Restore Reference | For Contingency: Find | Sprit69 | Add... | Delete... | Rename... | Clone Contingency...

Select Step

- Simulation
 - Control
 - Definitions
 - Violations
- Options
- Result Storage
- Plots
- Results from RAM
- Transient Limit Monitors
- States/Manual Control
- Validation
- SMIB Eigenvalues
- Modal Analysis
- Dynamic Simulator Options

Process Contingencies

☒ One Contingency at a time

☐ Multiple Contingencies

Simulation

Control | Definitions | Violations

Simulation Time Values

Start Time (seconds): 0.000

End Time (seconds): 10.000

Time Step (cycles): 0.500

Specify Time Step in

☐ Seconds

☒ Cycles

Categories: Change...

Summary Results

	Generation	Load
Tripped	0.00	0.00
Islanded	0.00	0.00

Transient Contingency Elements

Insert | Clear All | Insert Apply/Clear/Open | Time Shift (seconds): 0.000

	Object Pretty	Time (Cycles)	Time (Seconds)	Object	
1	Line SPIRIT69 FROM MAROON69 CKT 1	60.0	1.000000	Branch '37' '18' '1'	FAULT
2	Line SPIRIT69 FROM MAROON69 CKT 1	72.0	1.200000	Branch '37' '18' '1'	OPEN I

Transient Contingency Monitor Violations

Limit Monitor Name	Contingency Name
None	Defined

Save All Settings To | Load All Settings From | Show Transient Contour Toolbar | Auto Insert... | Critical Clearing Time Calculator... | Help | Close

Infinite Bus Modeling



- Before doing our first simulation, it is useful to discuss the concept of an infinite bus. An infinite bus is assumed to have a fixed voltage magnitude, angle and nominal frequency
 - In real systems infinite buses do not exist, but they can be a useful concept when learning about transient stability.
 - By default PowerWorld Simulator does NOT treat the slack bus as an infinite bus, but does provide this as an option.
 - For this first example we will use the option to treat the slack bus as an infinite bus. To do this select “Options” from the “Select Step” list. This displays the option page. Select the “Power System Model” tab, and then set Infinite Bus Modeling to “Model the power flow slack bus(es) as infinite buses” if it is not already set to do so.

Transient Stability Options Page



Options

Note: Changes made to option entries are saved immediately and will be applied during the next transient stability run.

General Power System Model Remedial Actions Result Options Generic Limit Monitors User Defined Models Distributed Computing Transfer to Power Flow

Common Load Modeling Compatibility Options

Power System Values

Nominal System Frequency (Hz) 60.000

Initial System Frequency (Hz) 60.000

☒ When Using Playin Models Set Initial Hz to First Value

System MVA Base 100.00

Network Equations Solution Options

Solution Tolerance (MVA) 0.10000

Maximum Iterations 25

Abort after number of failed solutions 10

Force Network Equation Update 0.00

☒ Use Voltage Extrapolation

Inner Loop Mismatch Scalar 1.0

Handling of Initial Limit Violations

☒ Modify Limits and Run

☐ Abort

☐ Run without Changing Limits

Integration Method

☒ Second Order Runge-Kutta

☐ Euler

Infinite Bus Modeling

☒ No infinite buses (recommended setting)

☐ Model power flow slack buses as infinite buses

Frequency Measurement Options

Bus Frequency Measurement Time Constant (Sec.) 0.020

Minimum PJ voltage for relay frequency measurement 0.300

☐ Calculate Bus ROCOF (Rate of Change of Freq)

☐ Use Parallel Code

Island Synchronization

Angle Options

☒ Set to Degree Value

☐ Set if > Degree Value

☐ No Change

Frequency Options

☐ Set to Hz Value

☐ Set if > Hz Value

☒ No Change

Degree Value 0.000 Hz Value 0.000

Geomagnetic Induced Current Options

Ignore GIC Effects (Option Set on GIC Form)

☐ Just Calculate GIC with No Network Solution

GIC XF Time Constant (Sec) 0.0

**Infinite Bus
Modeling**

Specifying the Contingency Event

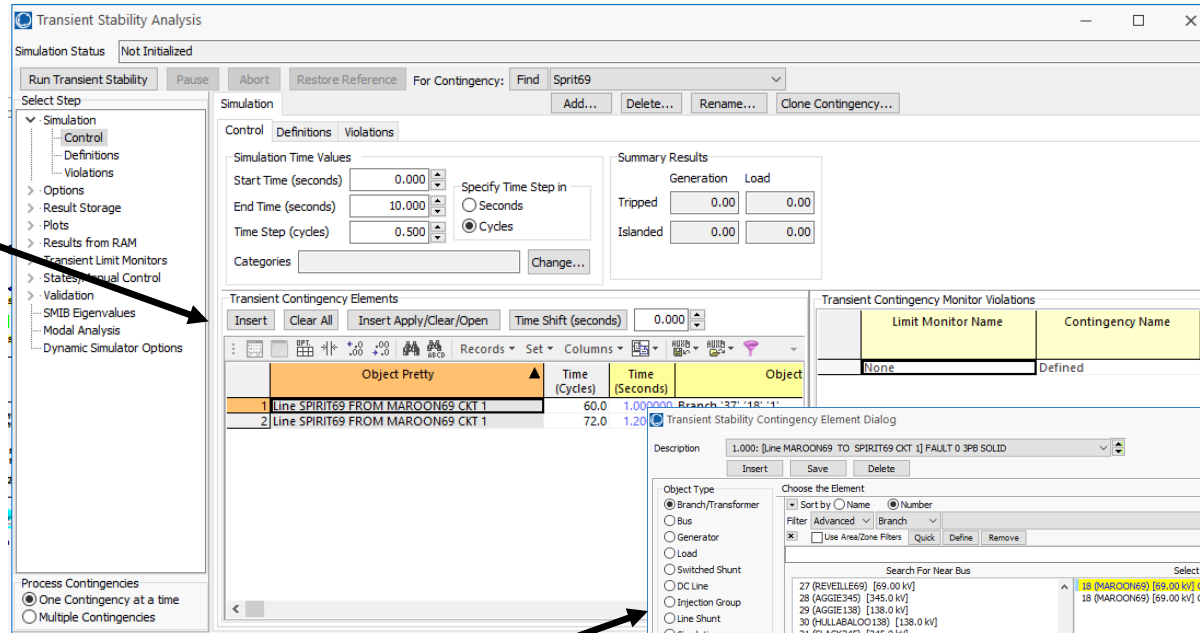


- To specify the contingency go back to the **Simulation** page and click on the **Insert Elements** button. This displays the **Transient Stability Contingency Element Dialog**, which is used to specify the events that occur during the study.
- Usually start at time > 0 to showcase runs flat
- The initial event is a fault on the line between buses 17 and 18, cleared after 0.2 seconds by opening the line

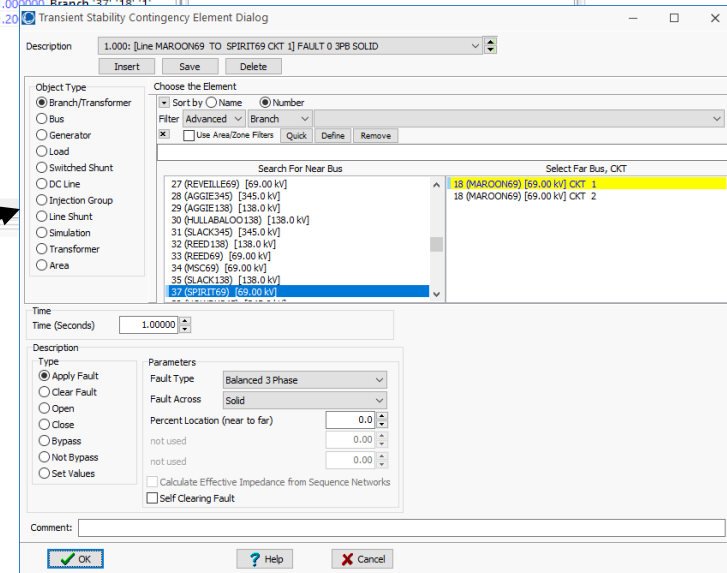
Inserting Transient Stability Contingency Elements



Click to
insert
new
elements



Dialog to specify
contingency
event details



Determining the Results to View



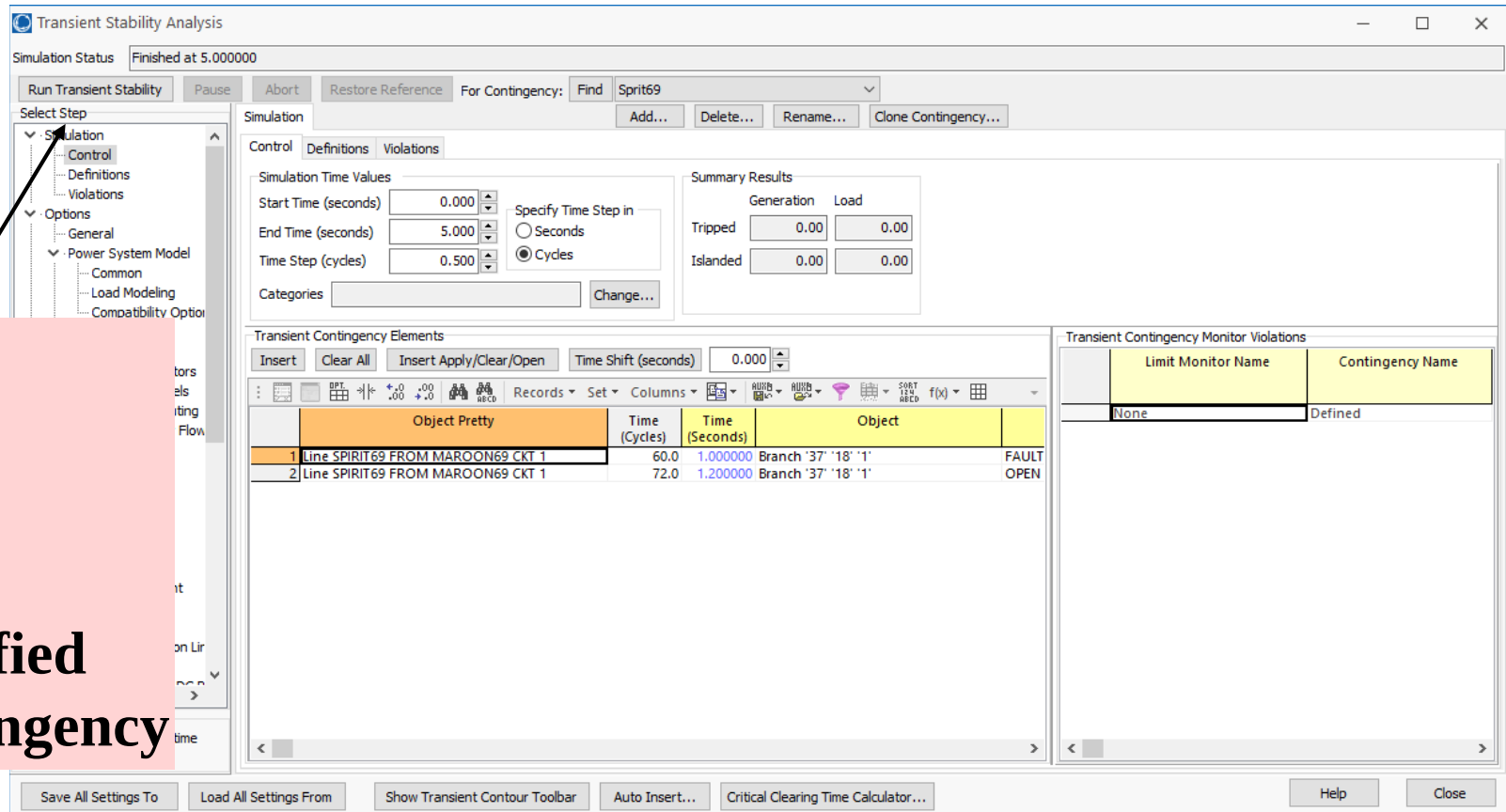
- For large cases, transient stability solutions can generate huge amounts of data. PowerWorld Simulator provides easy ways to choose which fields to save for later viewing. These choices can be made on the **Result Storage** page.
- For this example we'll save the generator 4 rotor angle, speed, MW terminal power and Mvar terminal power.
- From the **Result Storage** page, select the generator tab and double click on the specified fields to set their values to "Yes".

Saving Changes and Doing Simulation



- The last step before doing the run is to specify an ending time for the simulation, and a time step.
- Go to the **Simulation** page, verify that the end time is 5.0 sec. and the Time Step is 0.5 cycles
 - PowerWorld Simulator allows the time step to be specified in either seconds or cycles
- Before doing your first simulation, save all the changes made so far by using the main PowerWorld Simulator Ribbon, **select Save Case As AGL_Bus37_ReadyToRun**
- Click on **Run Transient Stability** to solve.

Doing The Run



Click
to
run
the
specified
contingency

Results: Time Values

Lots of options are available for showing and filtering the results.

Transient Stability Analysis

Simulation Status: Finished at 5.000000

Run Transient Stability | Pause | Abort | Restore Reference | For Contingency: Find | Sprit69

Select Step

- Simulation
 - Control
 - Definitions
 - Violations
- Options
 - General
 - Power System Model
 - Common
 - Load Modeling
 - Compatibility Option
 - Remedial Actions
 - Result Options
 - Generic Limit Monitors
 - User Defined Models
 - Distributed Computing
 - Transfer to Power Flow
- Result Storage
- Plots
- Results from RAM
 - Time Values
 - Generator
 - Bus
 - Load
 - Switched Shunt

Process Contingencies

☒ One Contingency at a time

☐ Multiple Contingencies

Results from RAM

Time Values | Minimum/Maximum Values | Summary | Events | Solution Details

Generator | Bus | Load | Switched Shunt | Branch | Transformer | DC Transmission Line | VSC DC Line | Mi

Column Order: Object then Field

Column Filtering: Filter | Modify...

☐ Use Area/Zone Filters

Choose Fields to Dis...

- ☒ Aero State
- ☒ AGC State
- ☒ Efd
- ☒ Exciter State
- ☒ Governor State
- ☒ I pu
- ☒ Ifd
- ☒ Machine State
- ☒ Mvar
- ☒ MW
- ☒ MW Accel

Check All | Uncheck All

	Time	Gen KYLE138 #1 Rotor Angle	Gen KYLE138 #1 MW	Gen KYLE138 #1 Mvar
1	0	-13.563	250	45
2	0.008333	-13.563	250	45
3	0.016667	-13.563	250	45
4	0.025	-13.563	250	45
5	0.033333	-13.563	250	45
6	0.041667	-13.563	250	45
7	0.05	-13.563	250	45
8	0.058333	-13.563	250	45
9	0.066667	-13.563	250	45
10	0.075	-13.563	250	45
11	0.083333	-13.563	250	45
12	0.091667	-13.563	250	45
13	0.1	-13.563	250	45
14	0.108333	-13.563	250	45
15	0.116667	-13.563	250	45
16	0.125	-13.563	250	45
17	0.133333	-13.563	250	45
18	0.141667	-13.563	250	45
19	0.15	-13.563	250	45
20	0.158333	-13.563	250	45
21	0.166667	-13.563	250	45

Load from Hard Drive File into RAM results specified by Store to RAM Options

Clear Time Values from RAM

Save All Settings To | Load All Settings From | Show Transient Contour Toolbar | Auto Insert... | Critical Clearing Time Calculator...

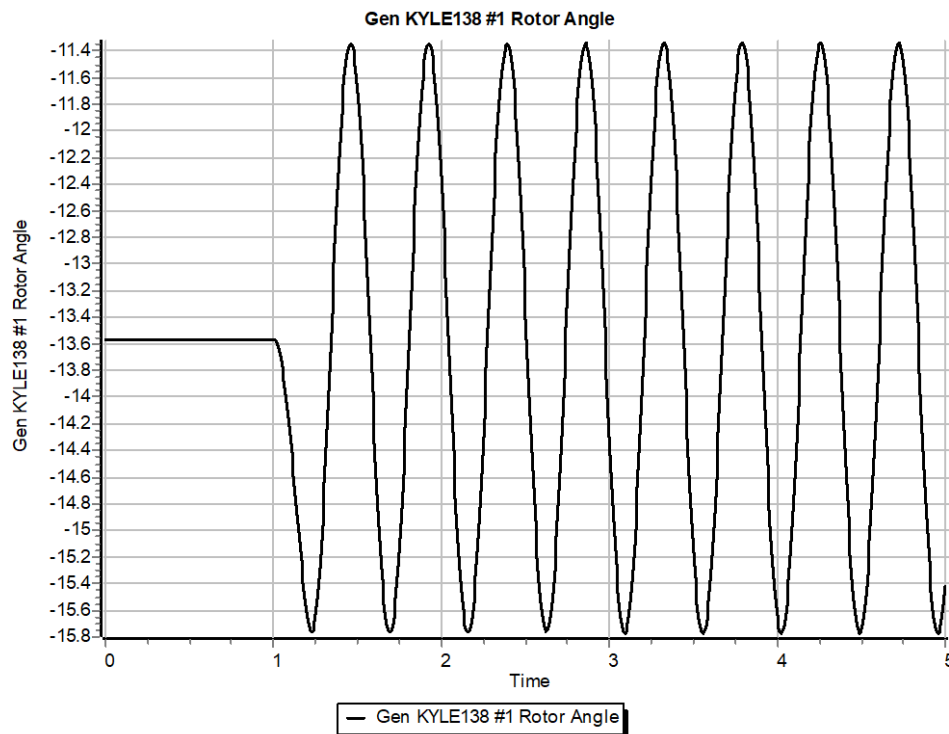
By default the results are shown for each time step. Results can be saved every “n” timesteps using an option on the Results Storage page

Quickly Plotting Results



- Time value results can be quickly plotted by using the standard case information display plotting capability.
 - Right-click on the desired column
 - Select **Plot Columns**
 - Use the **Column Plot Dialog** to customize the results.
 - Right-click on the plot to save, copy or print it.
- More comprehensive plotting capability is provided using the Transient Stability **Plots** page; this will be discussed later.

Generator Rotor Angle Column Plot



Notice that the result is undamped; damping is provided by damper windings

Starting the event at $t = 1.0$ seconds allows for verification of an initially stable operating point. The small angle oscillation indicates the system is stable, although undamped.

A More Realistic Generator Model



- The classical model is the simplest but also the hardest to justify
 - Had been widely used, but is now rapidly falling from use
- PowerWorld Simulator includes a number of much more realistic models that can be easily used
 - To replace the classical model with a detailed solid rotor, subtransient model, go to the **Generator Dialog, Machine Models**, click **Delete** to delete the existing model, select **Insert** to display the **Model Type Dialog** and select the GENROU model; accept the defaults.

GENROU Model



Generator Information for Present

Bus Number: 53 Find By Number

Bus Name: KYLE138 Find By Name

ID: 1 Find ...

Area Name: 1 (1)

Labels ...: no labels

Generator MVA Base: 300.00

Fuel Type: Unknown

Unit Type: UN (Unknown)

Status:
☐ Open
☒ Closed

Energized:
☐ NO (Offline)
☒ YES (Online)

Power and Voltage Control Costs OPF Faults Owners, Area, etc. Custom Stability

Machine Models Exciters Governors Stabilizers Other Models Step-up Transformer

Insert Delete Gen MVA Base: 300.0 Show Block Diagram

Type: Active - GENROU ☒ Active (only one may be active) Set to Defaults

Parameters
PU values shown/entered using device base of 300.0 MVA

H	3.00000	Xqp	0.50000	Tqopp	0.05000
D	0.00000	Xdpp	0.18000	S1	0.00000
Ra	0.00000	Xl	0.15000	S12	0.00000
Xd	2.10000	Tdop	7.00000	RComp	0.00000
Xq	0.50000	Tqop	0.75000	XComp	0.00000
Xdp	0.20000	Tdopp	0.04000		

OK Save Save to Aux Cancel Help

The GENROU model provides a good approximation for the behavior of a synchronous generator over the dynamics of interest during a transient stability study (up to about 10 Hz). It is used to represent a solid rotor machine with three damper windings.

Giving Every Generator a Model



- An easy method for giving every generator a GENROU model is to
 - Select **Add Ons, Stability Case Info, Models in Use**
 - Right-click on the GENROU Row and select **Show Dialog**
 - On the **Model Type GENROU Dialog** right-click in the Bus 53 row, and select **Copy/Paste/Send, Send All to Excel**
 - In Excel duplicate the row, adding entries for the other generators
 - Select all in Excel
 - Paste the data into the **Model Type GENROU Dialog**

Generator GENROU Data in Excel



This data is saved in the file AGL_Bus37_GENROU

AGL_Bus37_GENROU -

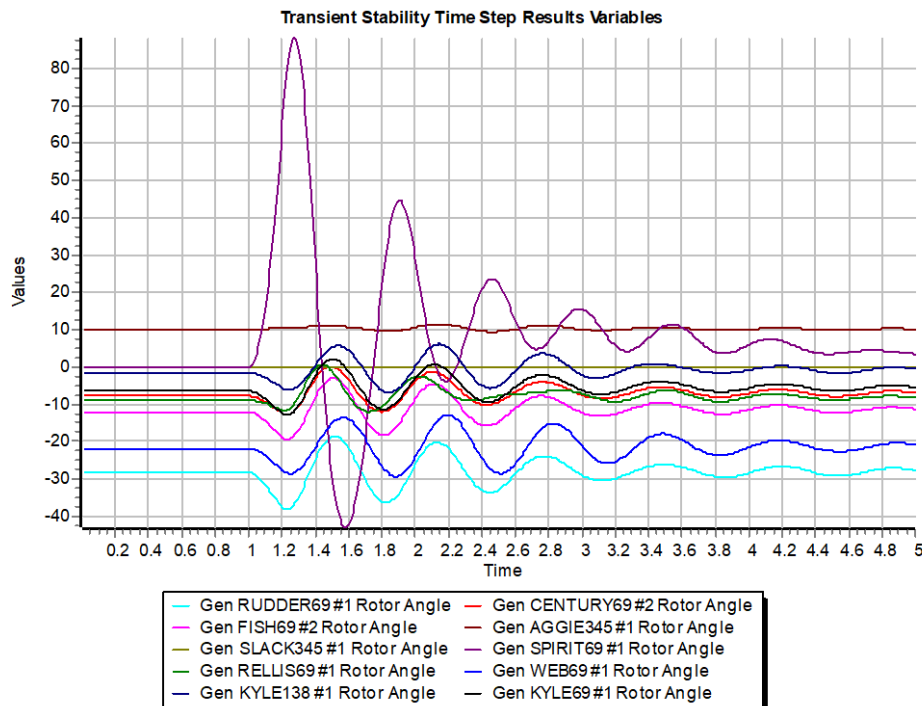
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	MachineModel_GENROU																			
2	Number	ID	H	D	Ra	Xd	Xq	Xdp	Xqp	Xdpp	Xl	Tdop	Tqop	Tdopp	Tqopp	S1	S12	RComp	XComp	
3	53	1	3	0	0	2.1	0.5	0.2	0.5	0.18	0.15	7	0.75	0.04	0.05	0	0	0	0	
4	14	1	3	0	0	2.1	0.5	0.2	0.5	0.18	0.15	7	0.75	0.04	0.05	0	0	0	0	
5	16	2	3	0	0	2.1	0.5	0.2	0.5	0.18	0.15	7	0.75	0.04	0.05	0	0	0	0	
6	20	2	3	0	0	2.1	0.5	0.2	0.5	0.18	0.15	7	0.75	0.04	0.05	0	0	0	0	
7	28	1	3	0	0	2.1	0.5	0.2	0.5	0.18	0.15	7	0.75	0.04	0.05	0	0	0	0	
8	31	1	3	0	0	2.1	0.5	0.2	0.5	0.18	0.15	7	0.75	0.04	0.05	0	0	0	0	
9	37	1	3	0	0	2.1	0.5	0.2	0.5	0.18	0.15	7	0.75	0.04	0.05	0	0	0	0	
10	44	1	3	0	0	2.1	0.5	0.2	0.5	0.18	0.15	7	0.75	0.04	0.05	0	0	0	0	
11	48	1	3	0	0	2.1	0.5	0.2	0.5	0.18	0.15	7	0.75	0.04	0.05	0	0	0	0	
12	54	1	3	0	0	2.1	0.5	0.2	0.5	0.18	0.15	7	0.75	0.04	0.05	0	0	0	0	
13																				
14																				

MachineModel_GENROU

Rerunning the Simulation



- On the **Results Storage, Generator** page select to save all the generator rotor angles, rerun the simulation, and plot all the rotor angles



This case is saved in the file AGL_Bus37_AllGENROU

Finally, Change the Fault Clearing Time



- To determine the time when a generator loses synchronism, increase the assumed fault clearing time

