Dynamics of Power Systems

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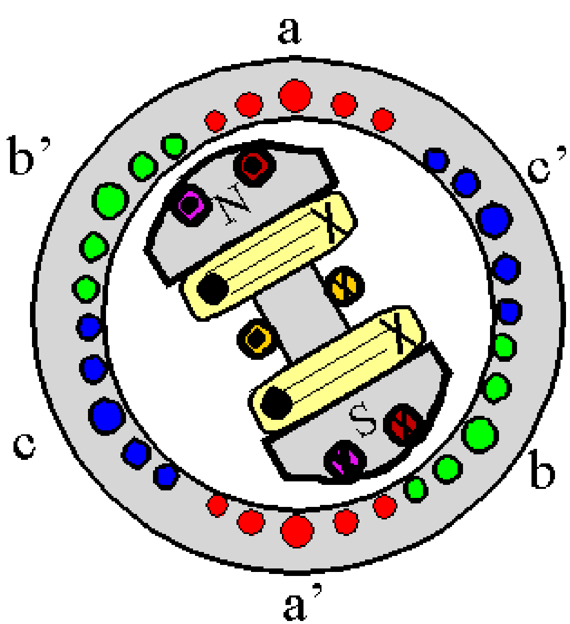
January, 2019

Outline

- Fundamentals of power system angle and voltage stability.
- Impact of loads on power system dynamics.
- Generator controls.
- Modeling.
- Trajectory sensitivity and approximation.

Synchronous machines

- Conventional generators are synchronous machines.
  - Rotor spins at synchronous speed.
  - Field winding on the rotor, stator windings deliver electrical power to the grid.



- Note that the dynamic behavior of wind generators (as seen from the grid) is dominated by control loops not the physics of the machines.

Machine dynamic models

- Dynamic models are well documented.
  – Electrical relationships are commonly modeled by a set of four differential equations.
  – Mechanical dynamics are modeled by the second-order differential equation:

$$J\frac{d^2\theta}{dt^2} = T_m - T_e$$

where

θ : angle (rad) of the rotor with respect to a stationary reference.

J : moment of inertia.

T_m : mechanical torque from the turbine.

T_e : electrical torque on the rotor.

Angle/frequency dynamics

- Through various approximations, the dynamic behavior of a synchronous machine can be written as the *swing equation*:

$$M\frac{d\omega}{dt} + D\omega = P_m - P_e$$

where

$\omega \equiv \frac{d\theta}{dt}$: deviation in angular velocity (frequency) from nominal.

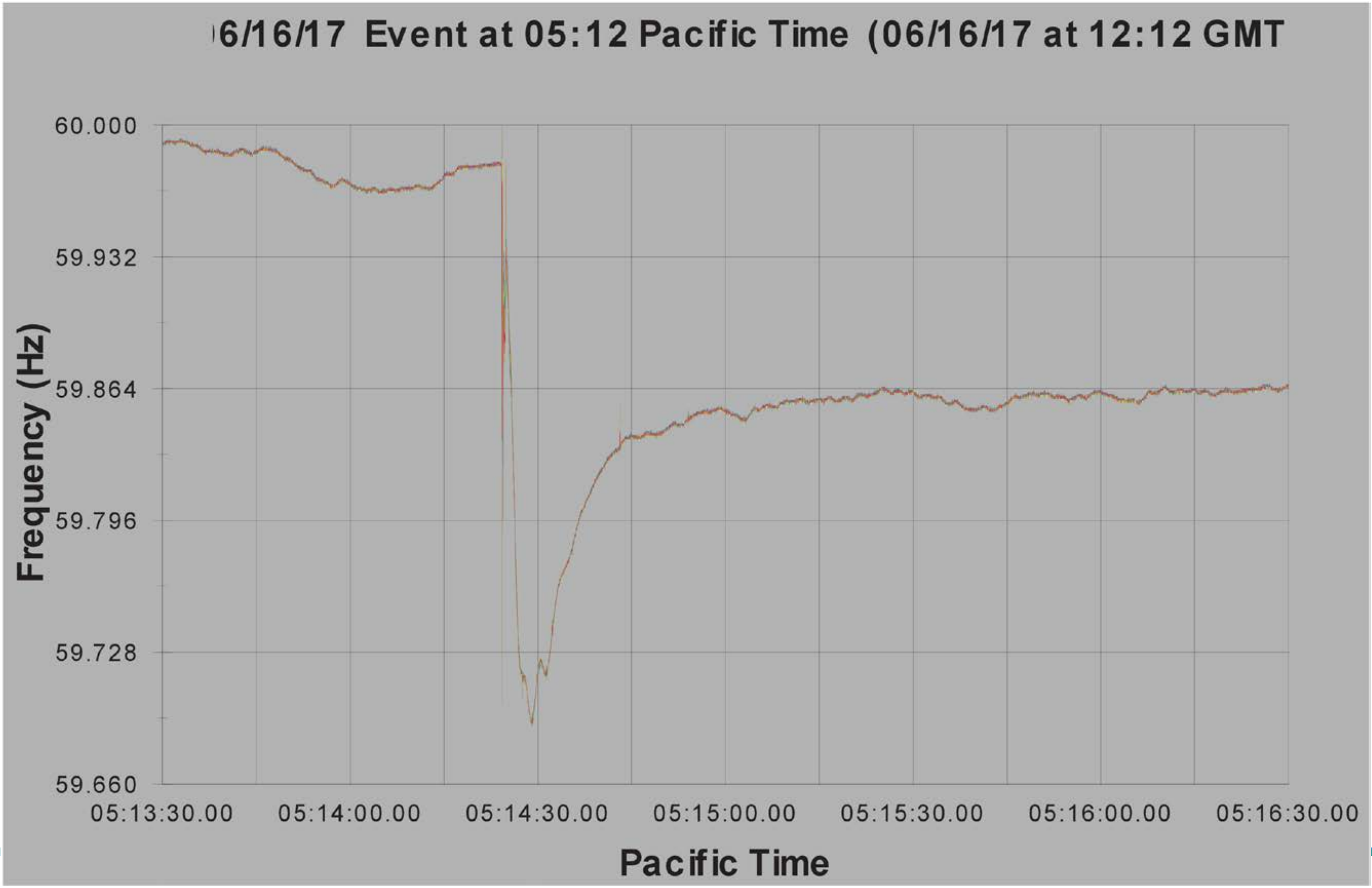
M : inertia.

D : damping, this is a fictitious term that may be added to represent a variety of damping sources, including control loops and loads. (It is zero in detailed modeling.)

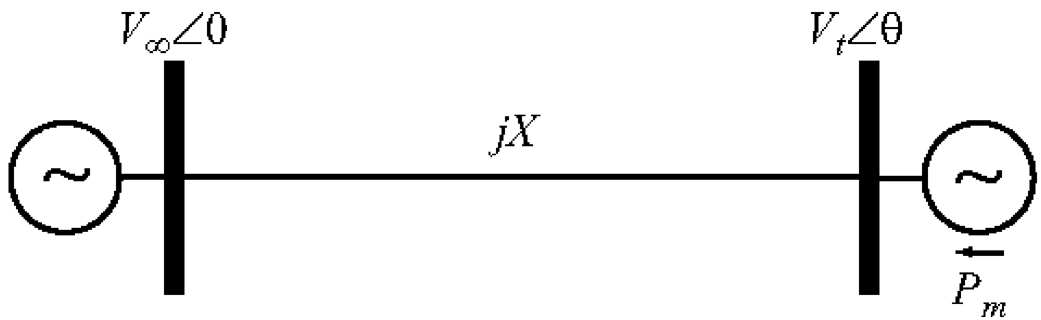
P_m, P_e : mechanical and electrical power.

System-wide frequency dynamics

- Response of frequency following generation tripping.



Single machine infinite bus system



- For a single machine infinite bus system, the swing equation becomes:

$$M\frac{d\omega}{dt} + D\omega = P_m - P_{max}\sin\theta$$

where $P_{max} = \dfrac{V_\infty V_t}{X}$.

- Dynamics are similar to a nonlinear pendulum.
- Equilibrium conditions, $\omega = 0$ and $P_m = P_{max}\sin\theta$.

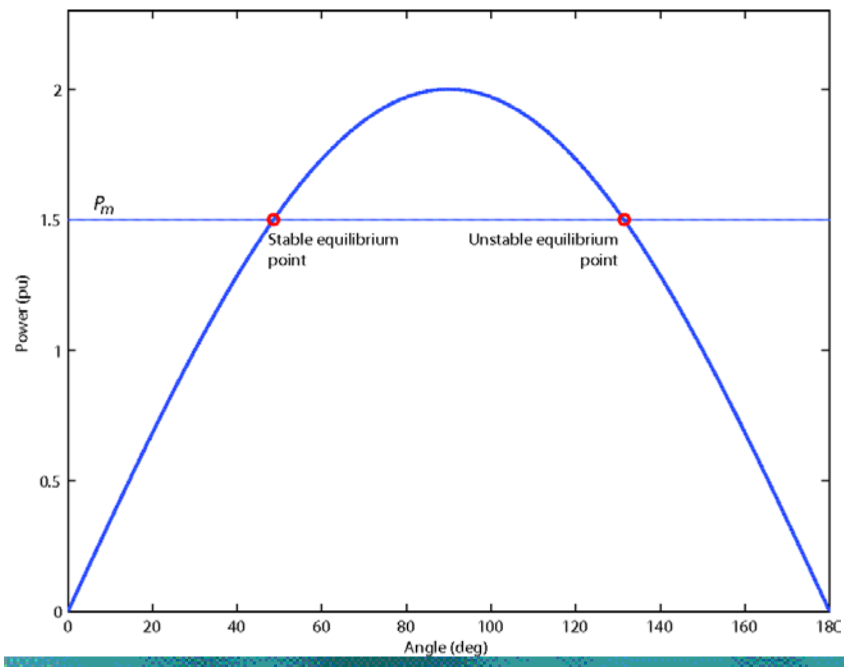
Region of attraction

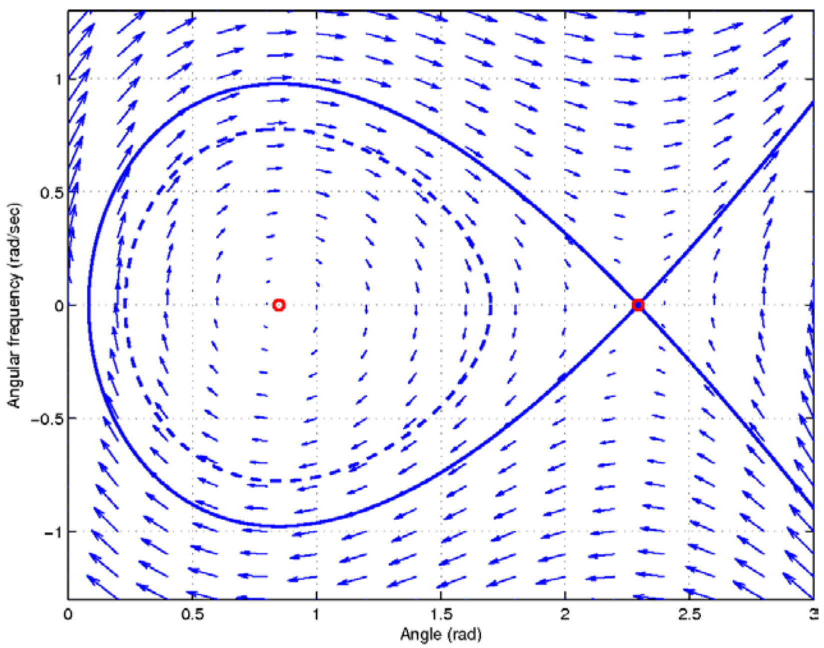
- The equilibrium equation has two solutions, θ_s and θ_u where:

  θ_s : stable equilibrium point.

  θ_u : unstable equilibrium point.

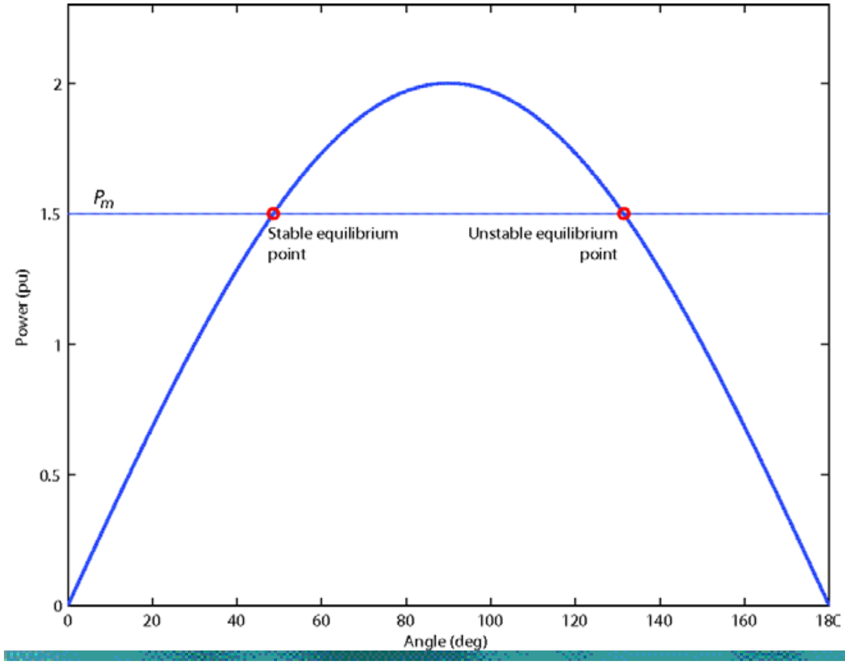
- Local stability properties are given by the eigenvalues of the linearized system at each equilibrium point.

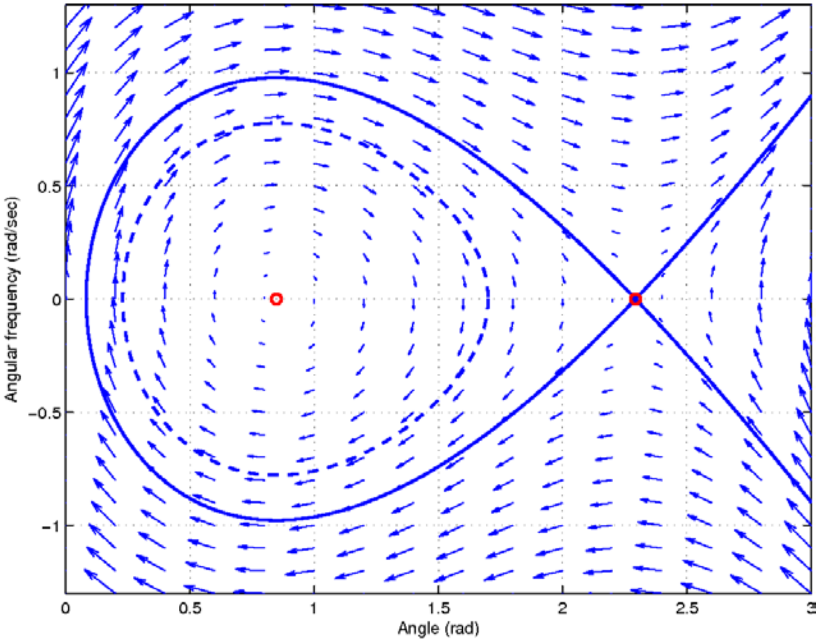




Region of attraction

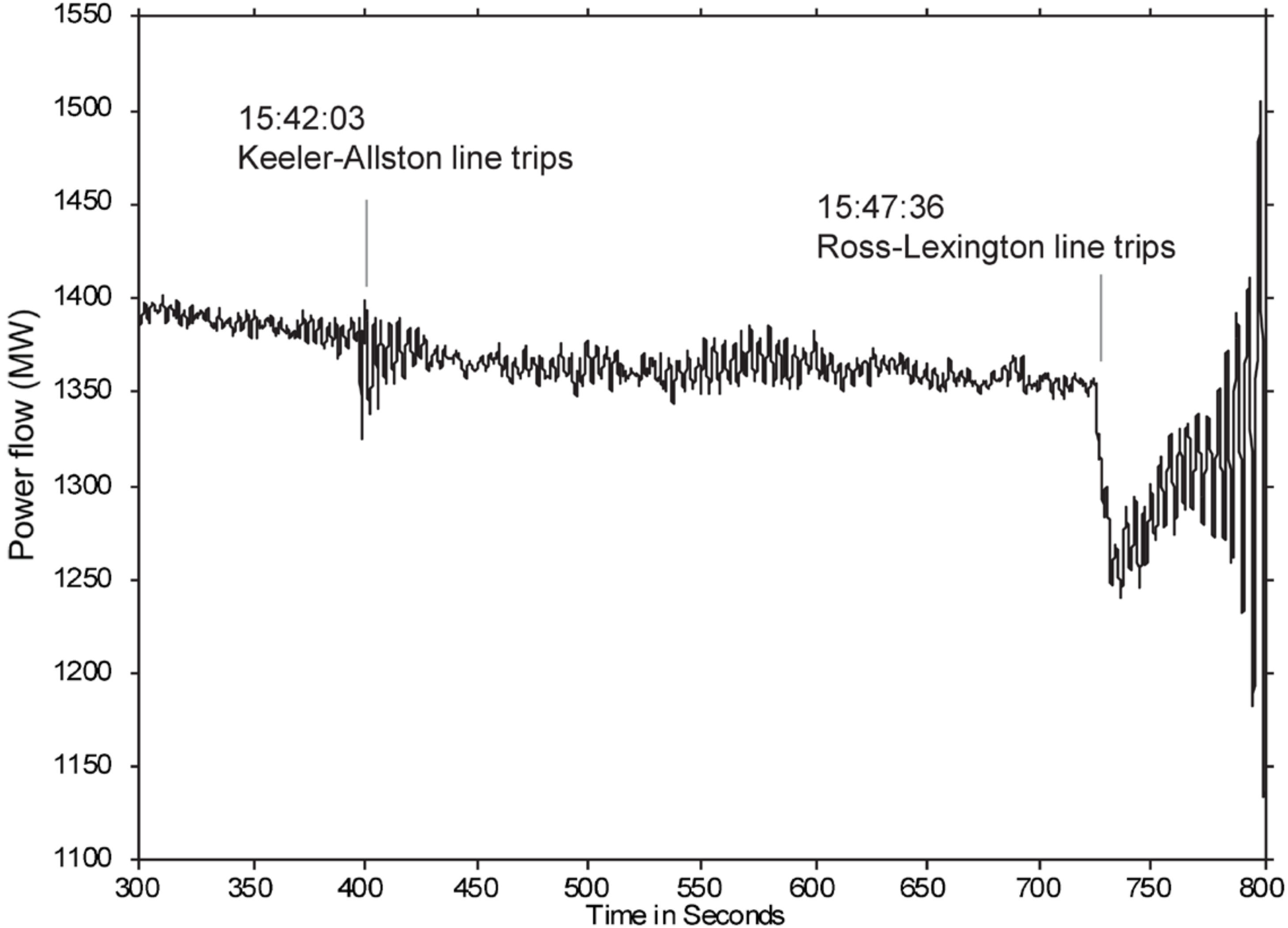
- As P_m increases, the separation between equilibria diminishes.
  - The region of attraction decreases as the loading increases.
  - Solutions coalesce when $P_m = P_{max}$. A bifurcation occurs.





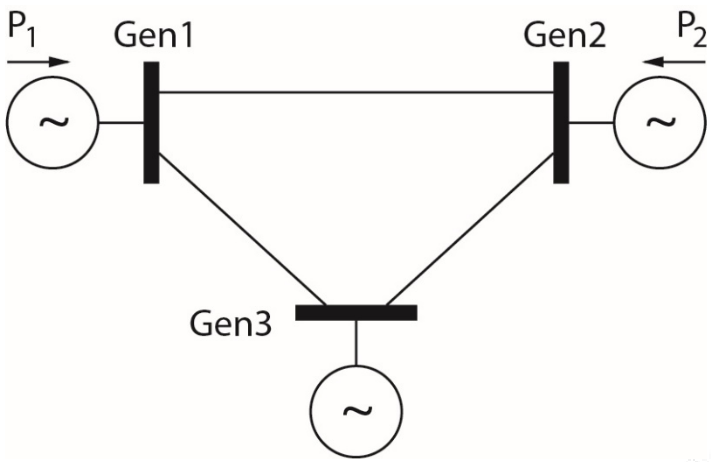
System damping

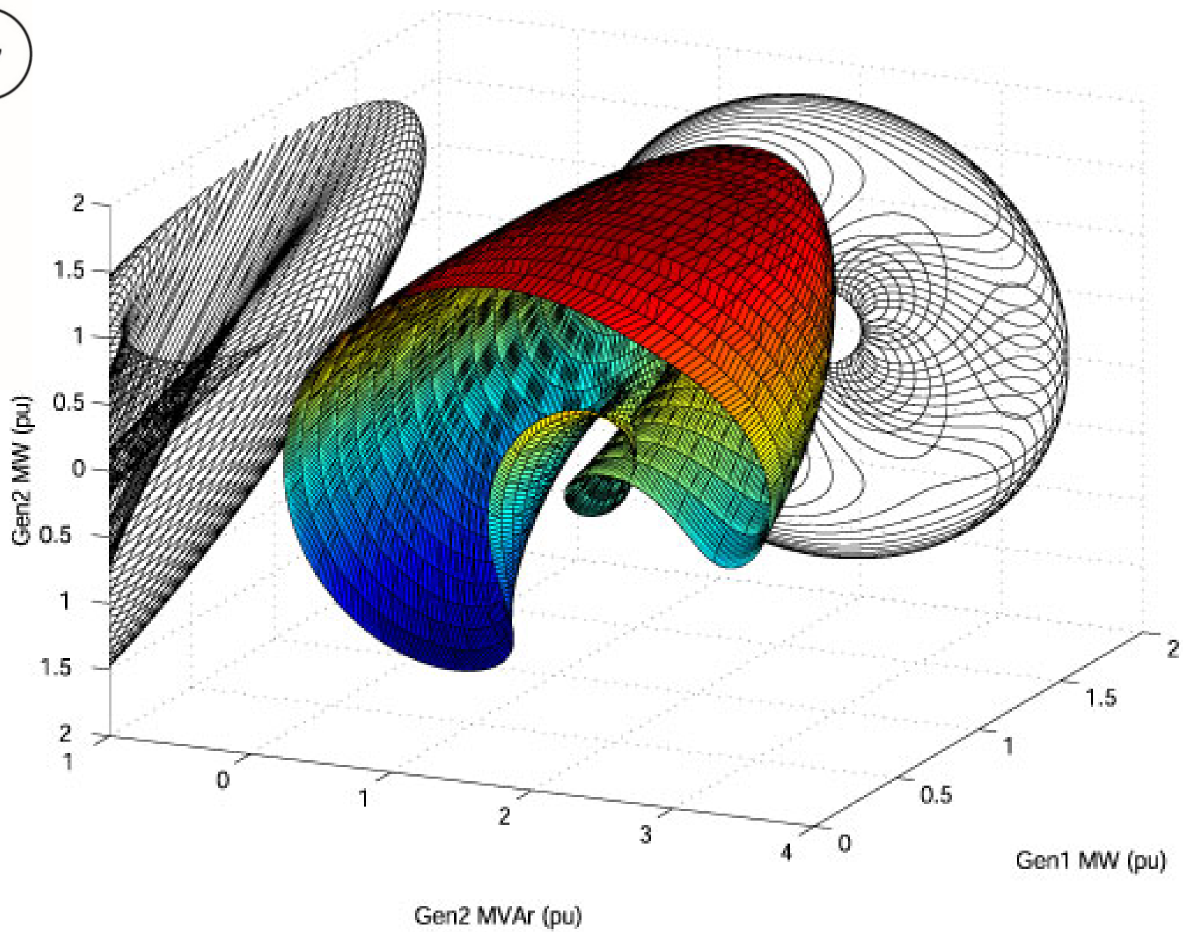
- Damping reduces as equilibria move closer.
  - In this case the system is progressive weakened by lines tripping.



Multiple equilibria

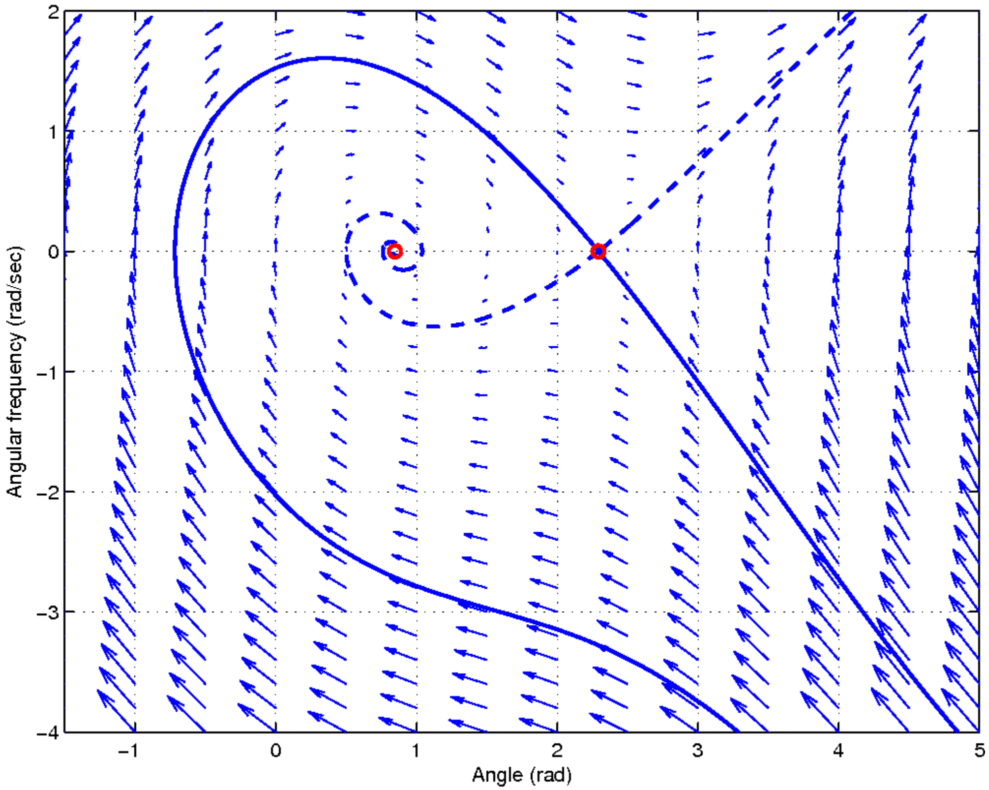
- Real power systems typically have many equilibria.





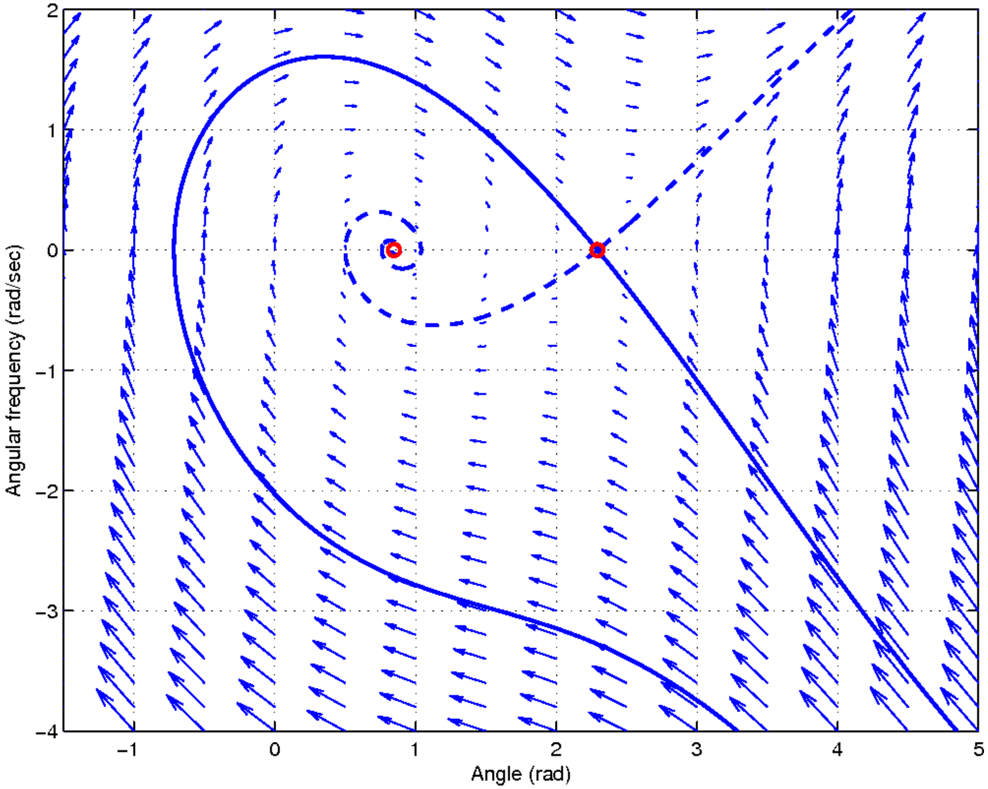
Large disturbance behavior

- A fault on the system, for example a lightning strike, will force the states away from the stable operating (equilibrium) point.
  - If the fault is sufficiently large, the disturbance will cause the trajectory to cross the boundary of the region of attraction, and stability will be lost.



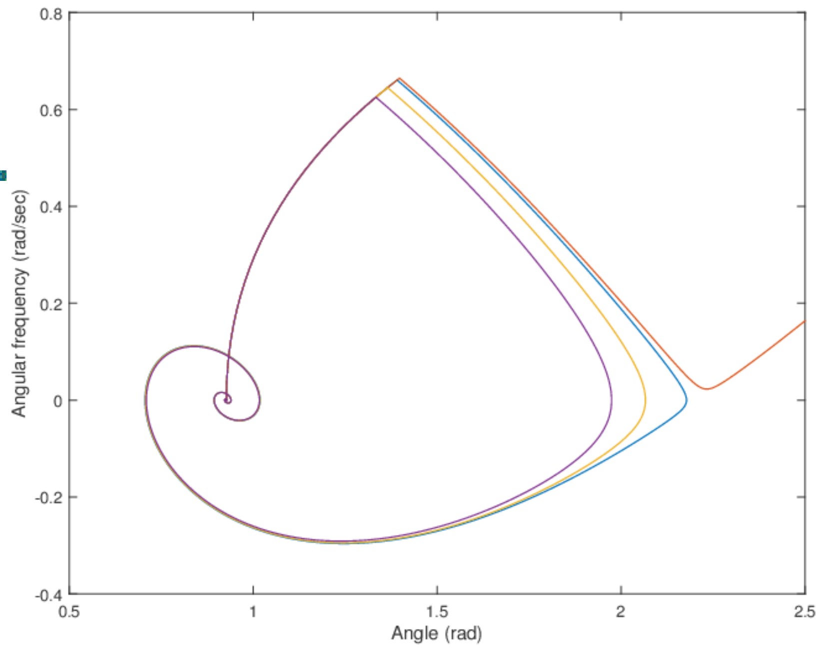
Critical clearing

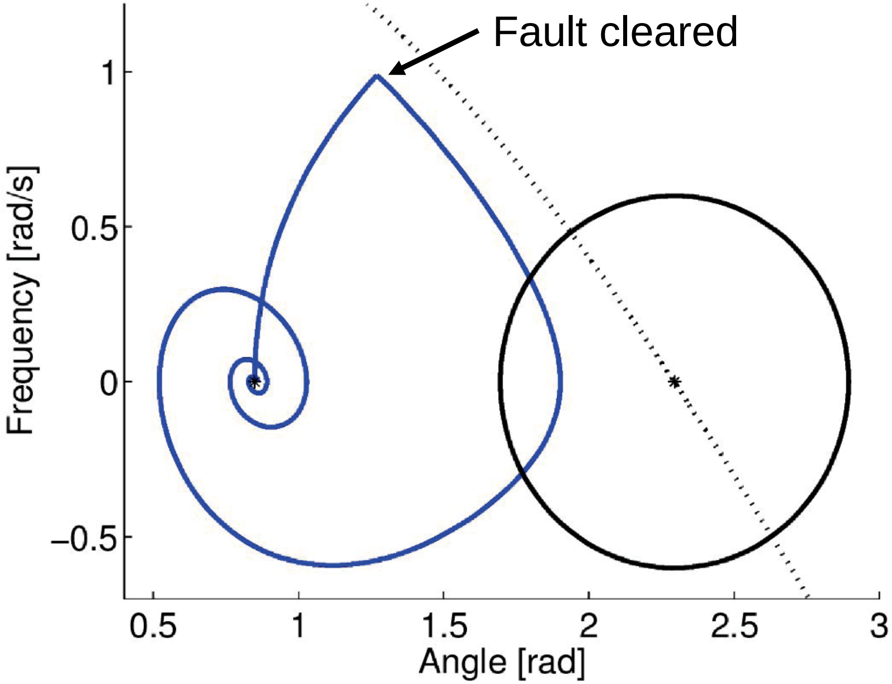
- Critical clearing refers to the (hypothetical) situation where the fault is removed when the state lies exactly on the stability boundary.
  - Conceptually, the resulting trajectory would run exactly to the unstable equilibrium point and stay there.
  - This is equivalent to bumping a pendulum so that it reaches equilibrium in the upright position.

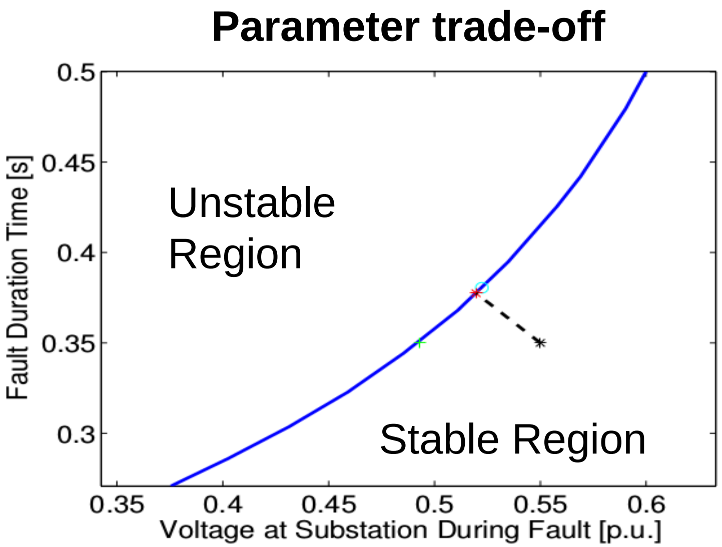


Forcing critical clearing

- Approximate a trajectory on the stability boundary by a trajectory that spends a long time near the unstable equilibrium point.

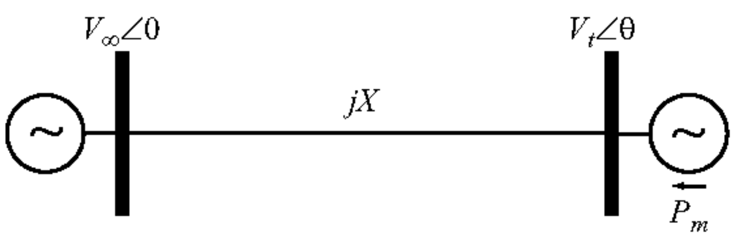


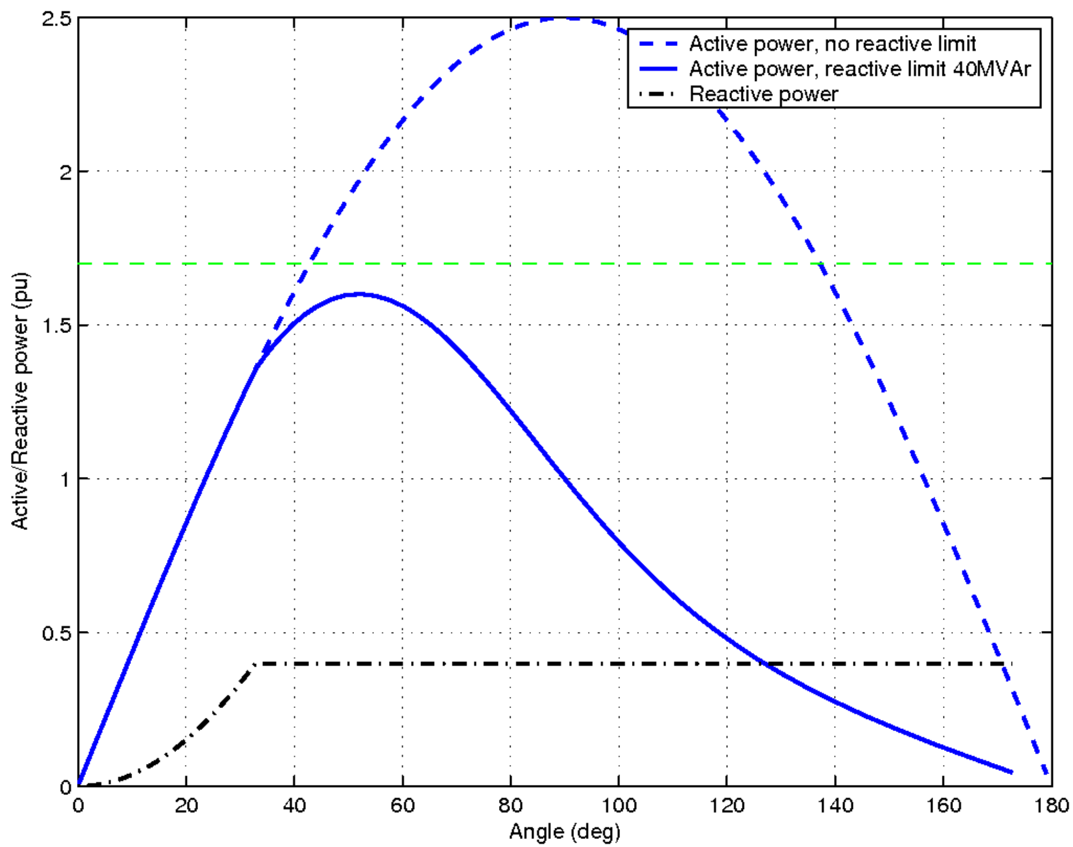




Voltage reduction

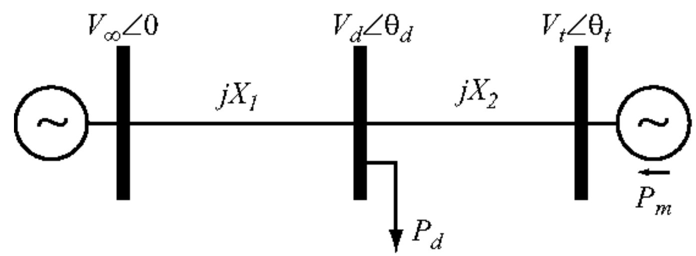
- The single machine infinite bus example assumes the generator maintains a constant terminal voltage.
  - The reactive power required to support the voltage is limited.
  - Upon encountering this limit, the over-excitation limiter will act to reduce the terminal voltage.



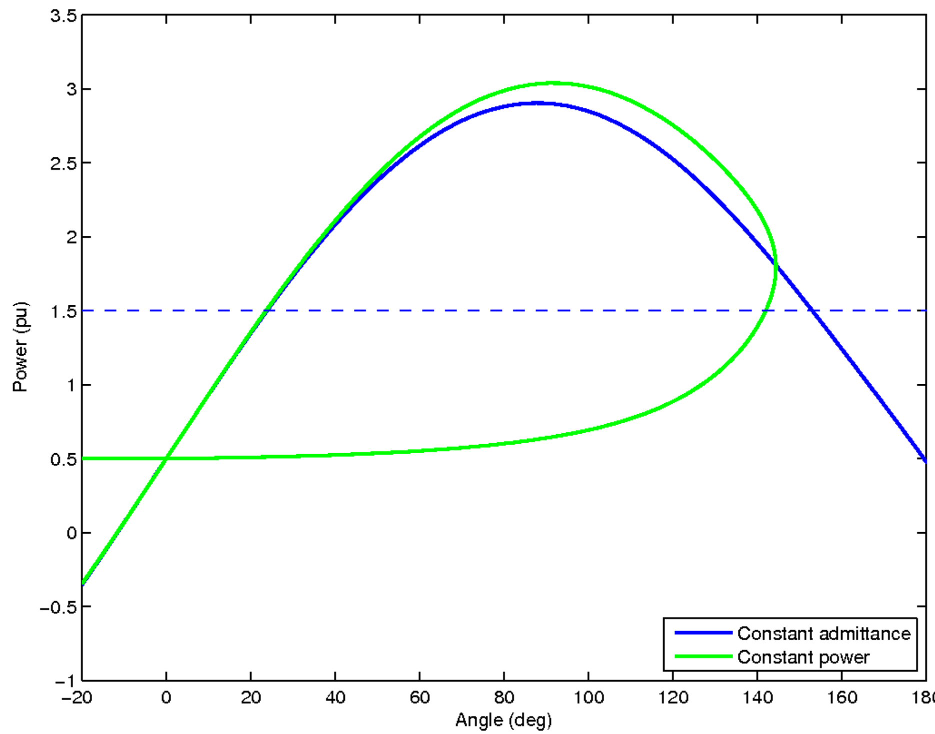


Effect of load

- Consider the effect of load behavior on stability.
- Two cases:
  - Constant admittance: $P_d = K_a V_d^2$
  - Constant power: $P_d = K_p$
- Notice the loss of structural stability as the voltage index changes.

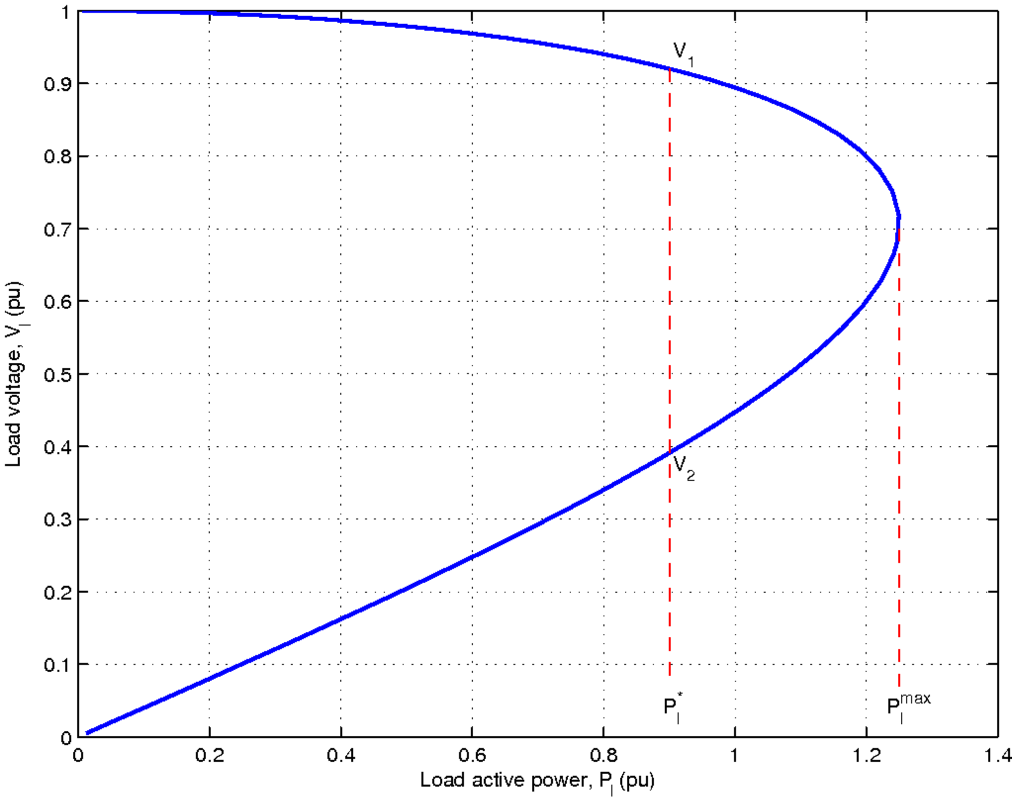


- Power electronic loads behave like constant power.
  - Bad for grid stability.
  - Examples: energy-efficient lighting, plug-in EVs.
  - Below a certain voltage, power electronics shut down.
  - This gives a fast transition from full power to zero.



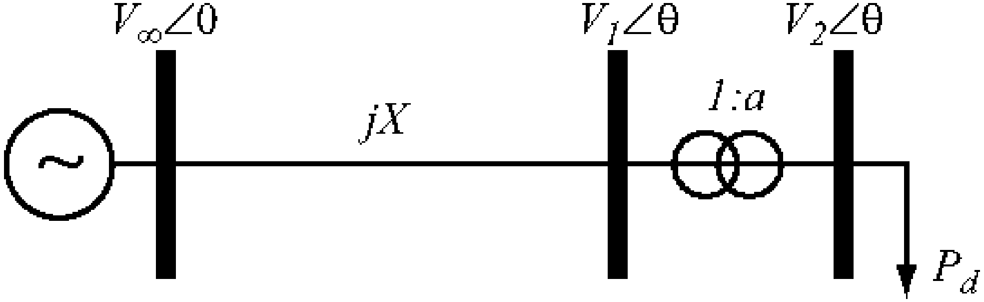
Voltage collapse

- Voltage collapse occurs when load-end dynamics attempt to restore power consumption beyond the capability of the supply system.
  - Power systems have a finite supply capability.
- For this example, two solutions exist for viable loads.
- Solutions coalesce at the load bifurcation point.
  - Known as the point of maximum loadability.

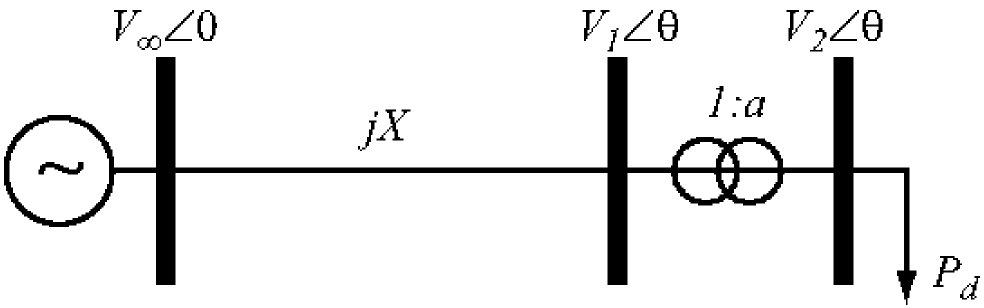


Load restoration dynamics

- Transformers are frequently used to regulate load-bus voltages.
- Sequence of events:
  - Line trips out, raising the network impedance.
  - Load-bus voltage drops, so transformer increases its tap ratio to try to restore the voltage.
  - Load is voltage dependent, so the initial voltage increase causes the load to increase.
  - The increasing load draws more current across the network, causing the voltage to drop further.



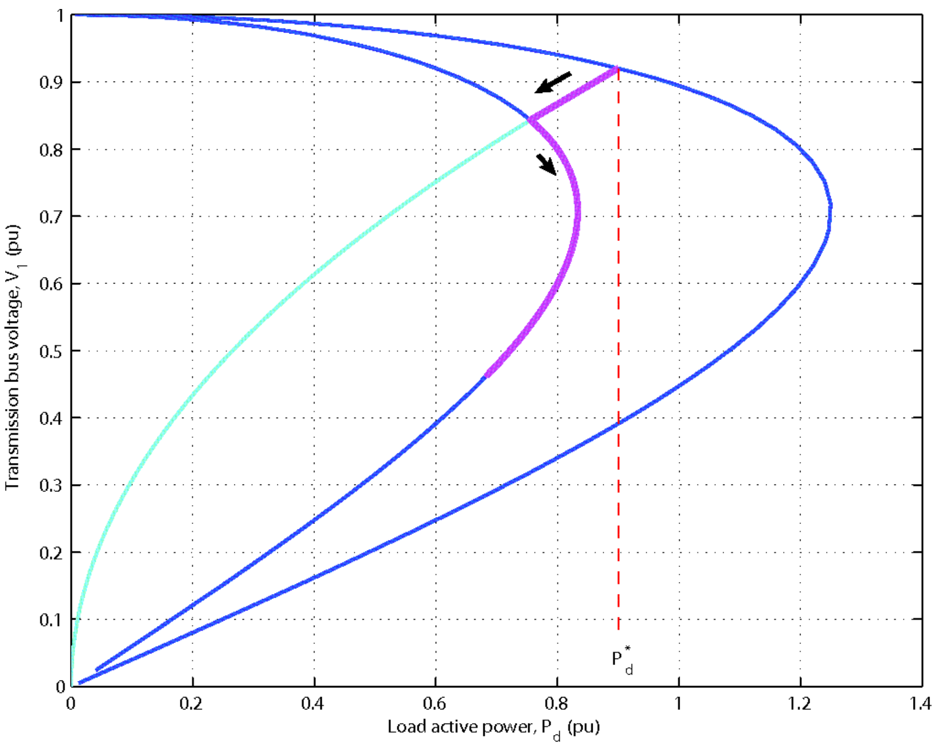
Load restoration dynamics

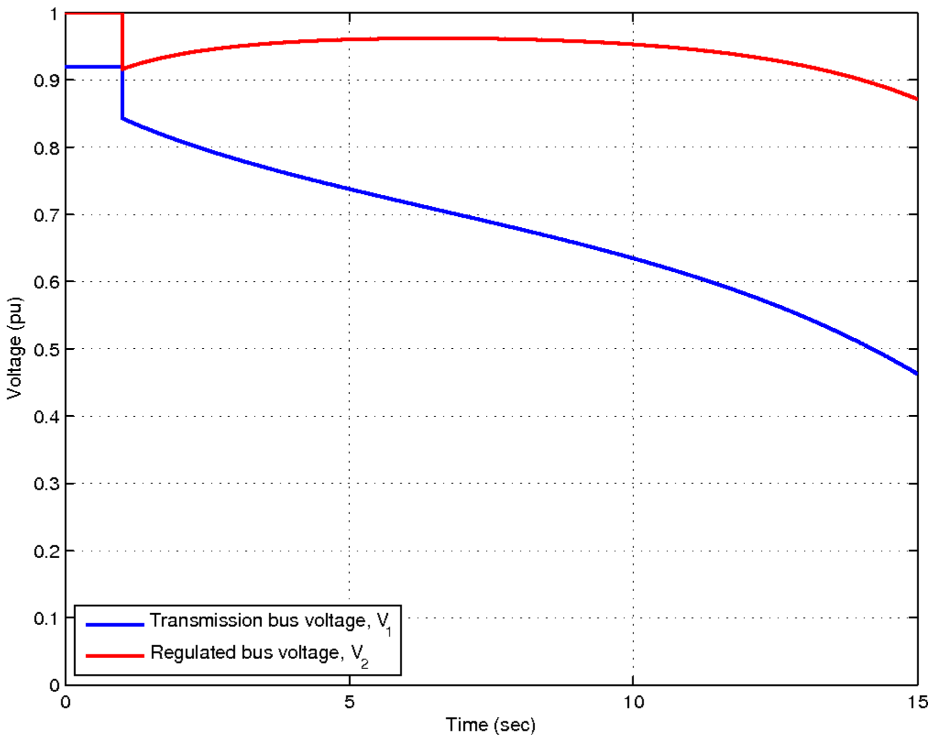


$$\frac{da}{dt} = \frac{1}{T}(V_{set} - V_2)$$

$$V_2 = aV_1$$

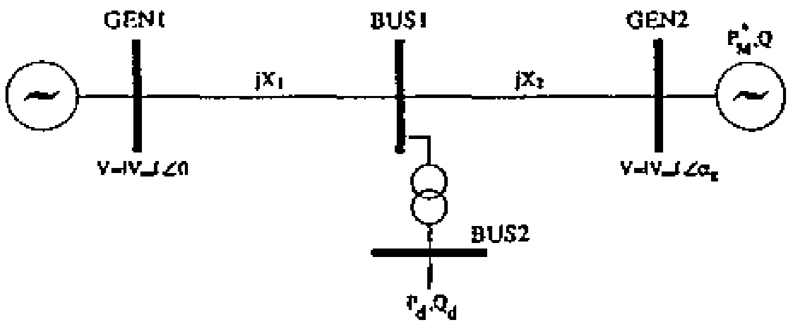
$$P_d = P_0 \left(\frac{V_2}{V_{set}}\right)^2$$

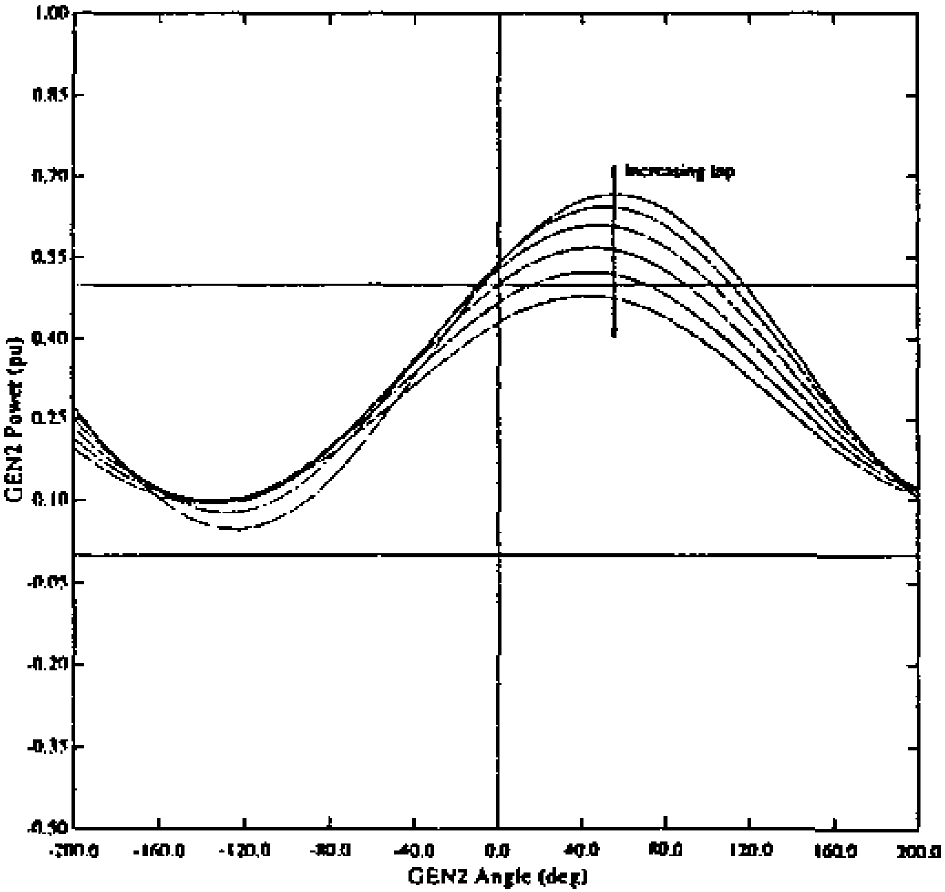




Voltage-angle interactions

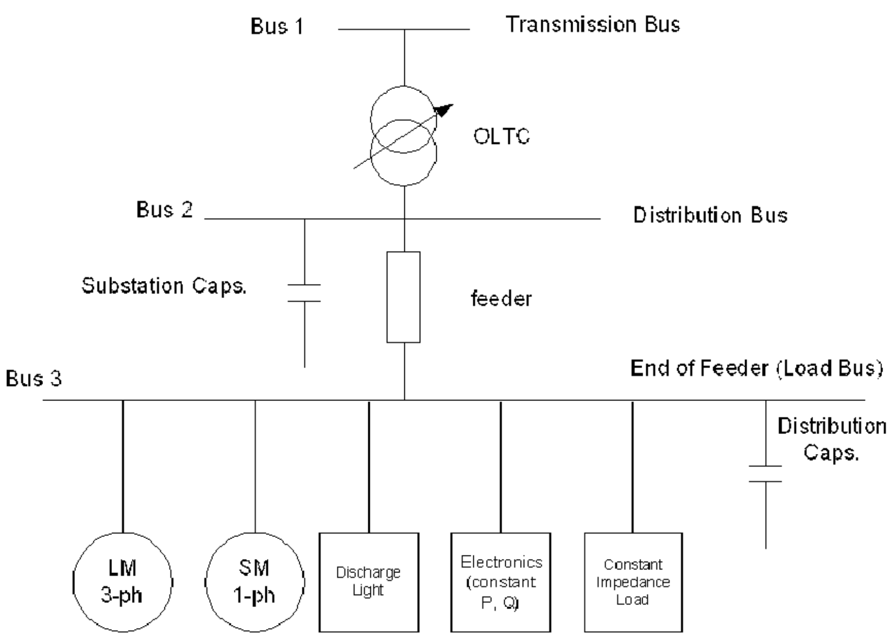
- Each time the transformer taps up to lift the voltage at the load bus, the transmission system is weakened a little more, until the generator loses synchronism.

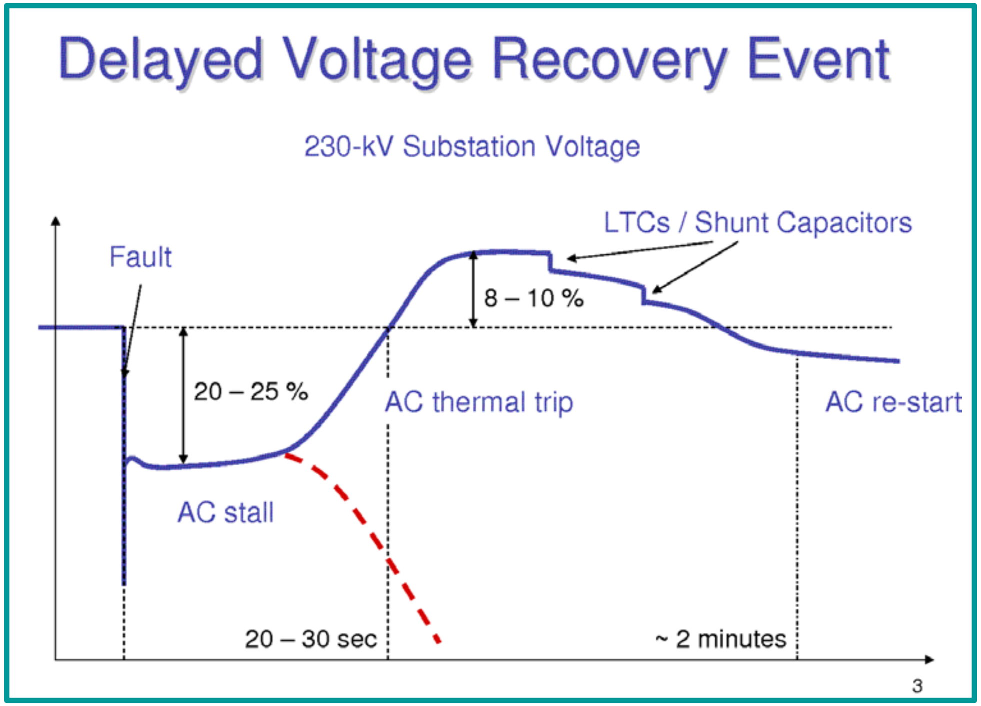




Load model

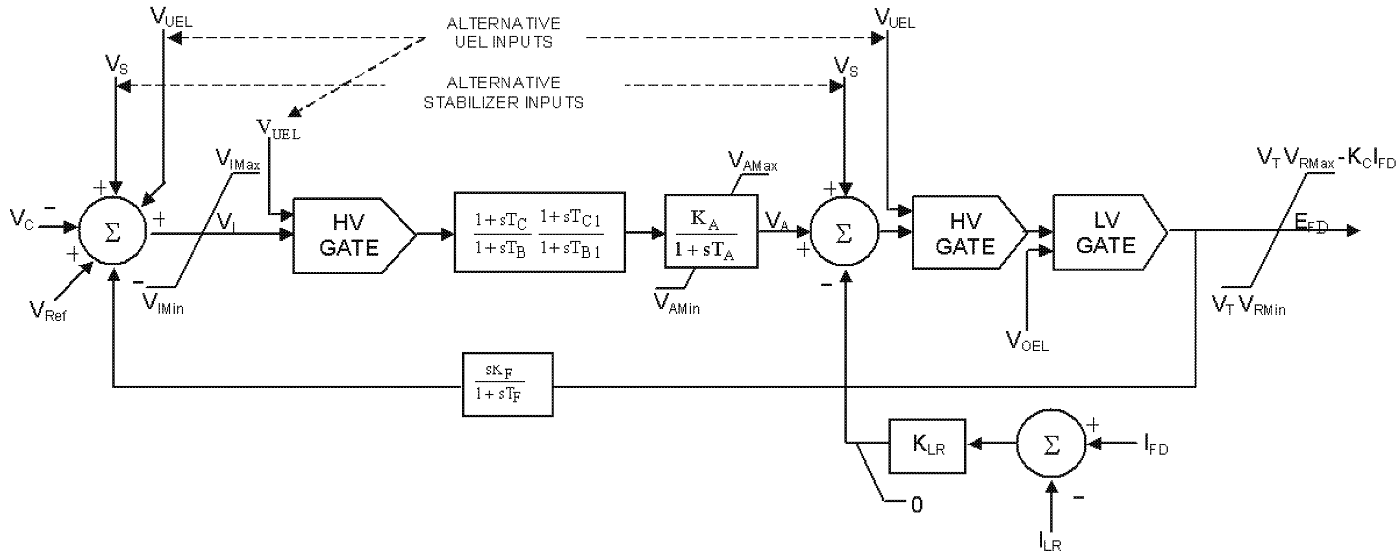
- Motivated by a desire to capture phenomena such as “fault induced delayed voltage recovery” (FIDVR).
- WECC load model:





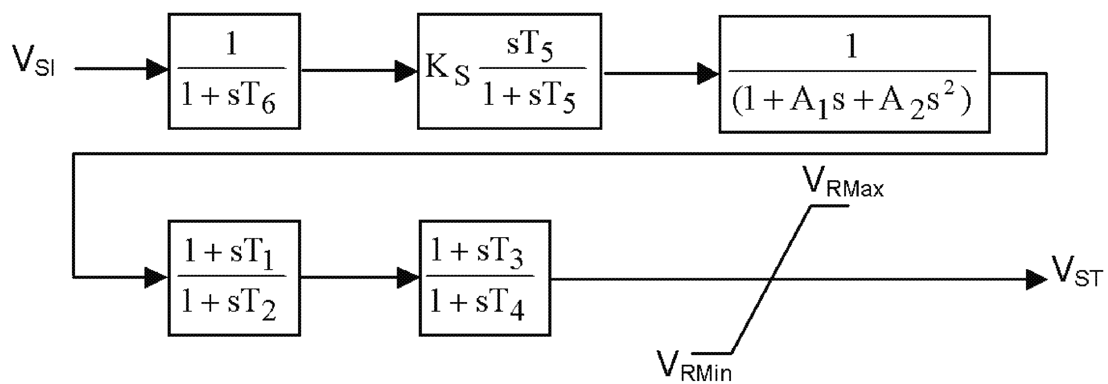
Generator voltage control

- Voltage control is achieved by the automatic voltage regulator (AVR).
  - Terminal voltage is measured and compared with a setpoint.
  - The voltage error is driven to zero by adjusting the field voltage.
- An increase in the field voltage will result in an increase in the terminal voltage and in the reactive power produced by the generator.
- If field voltage becomes excessive, an over-excitation limiter will operate to reduce the field current.
  - The terminal voltage will subsequently fall.



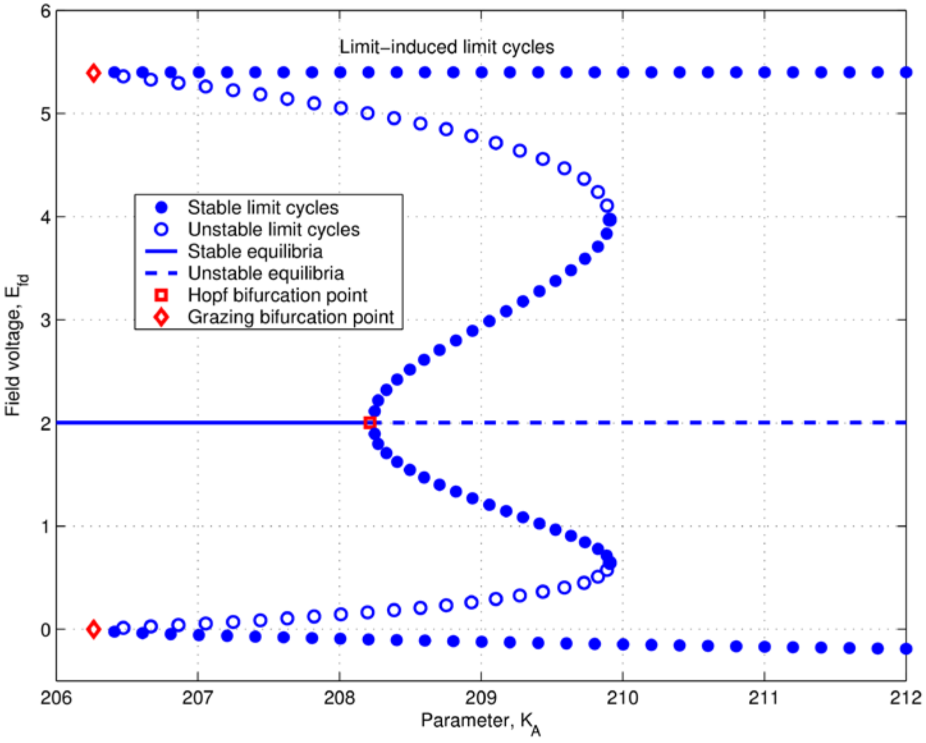
Power system stabilizers

- High-gain voltage control can destabilize angle dynamics.
- To compensate, many generators have a power system stabilizer (PSS) to improve damping.

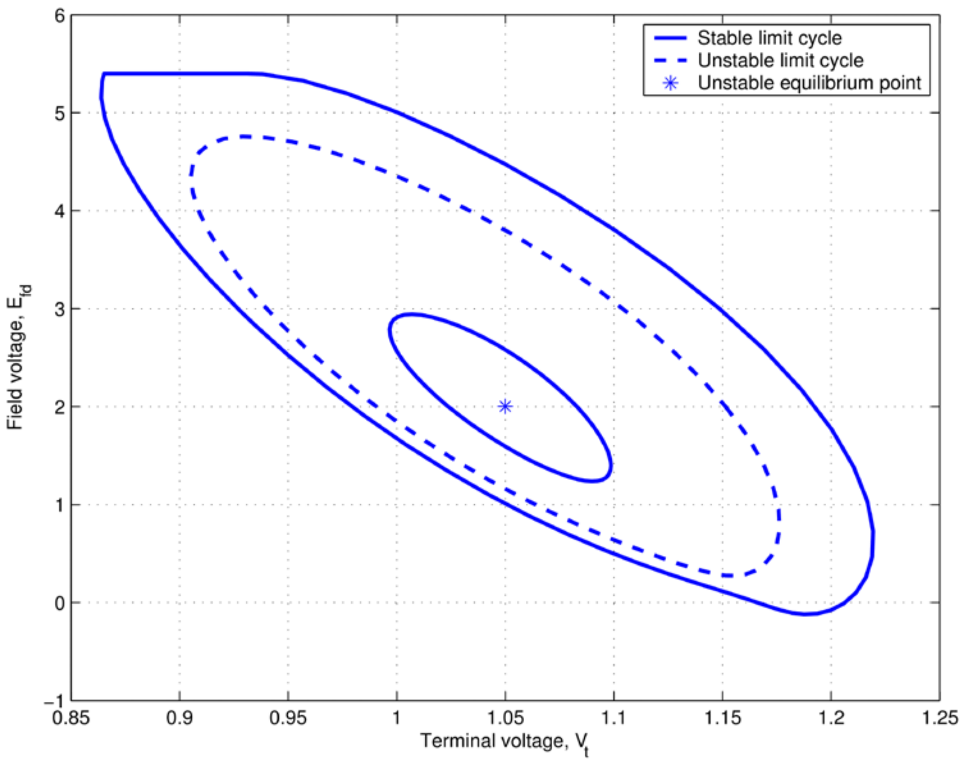


High-gain AVR instability

Bifurcation diagram as AVR gain K_A varies.

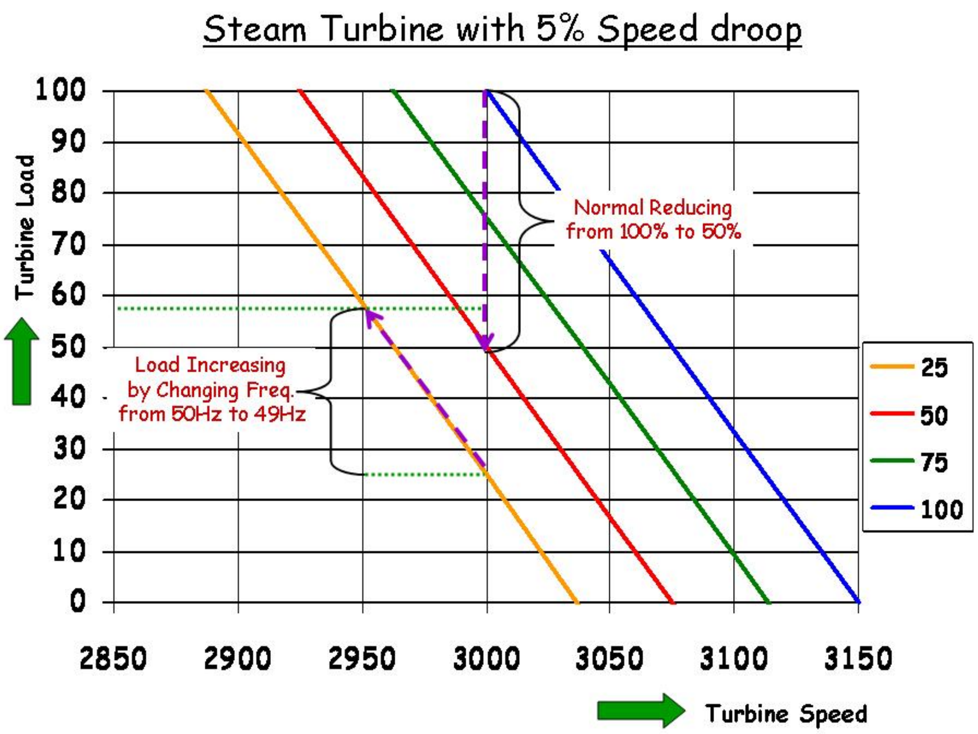


Co-existing limit cycles for $K_A = 209$.



Governor

- Active power regulation is achieved by a governor.
  - If frequency is less than desired, increase mechanical torque.
  - Decrease mechanical torque if frequency is high.
- For a steam plant, torque is controlled by adjusting the steam value, for a hydro unit control vanes regulate the flow of water delivered by the penstock.
- Frequency is a common signal seen by all generators.
  - If all generators tried to regulate frequency to its nominal setpoint, hunting would result.
  - This is overcome through the use of a droop characteristic.

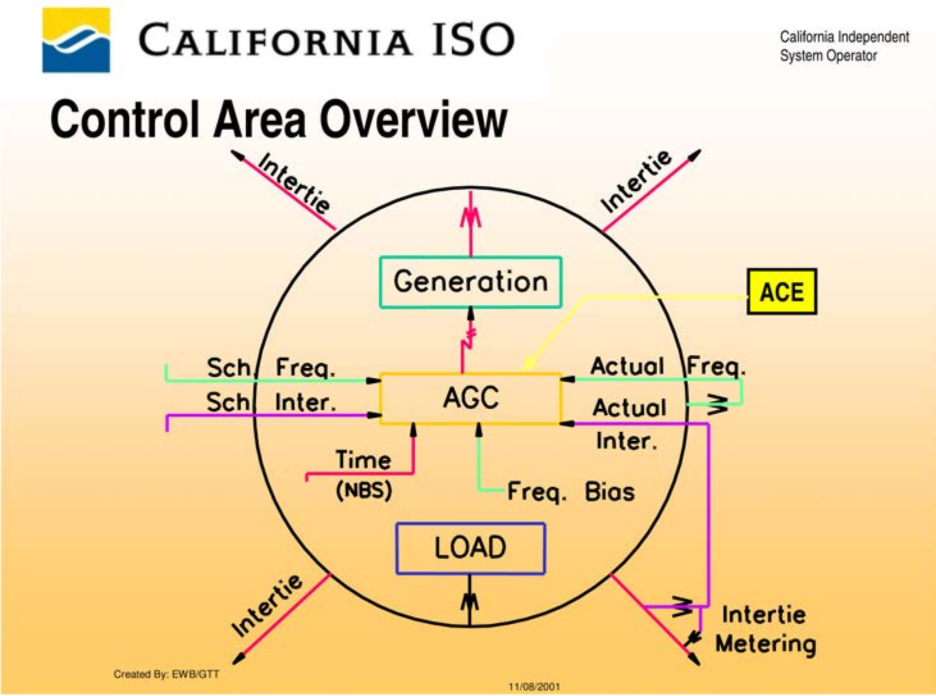


Automatic generation control (AGC)

- Based on a control area concept (now called a balancing authority.)
- Each balancing authority generates an “area control error” (ACE) signal,

$$ACE = -\Delta P_{net\ int} - B\Delta f$$

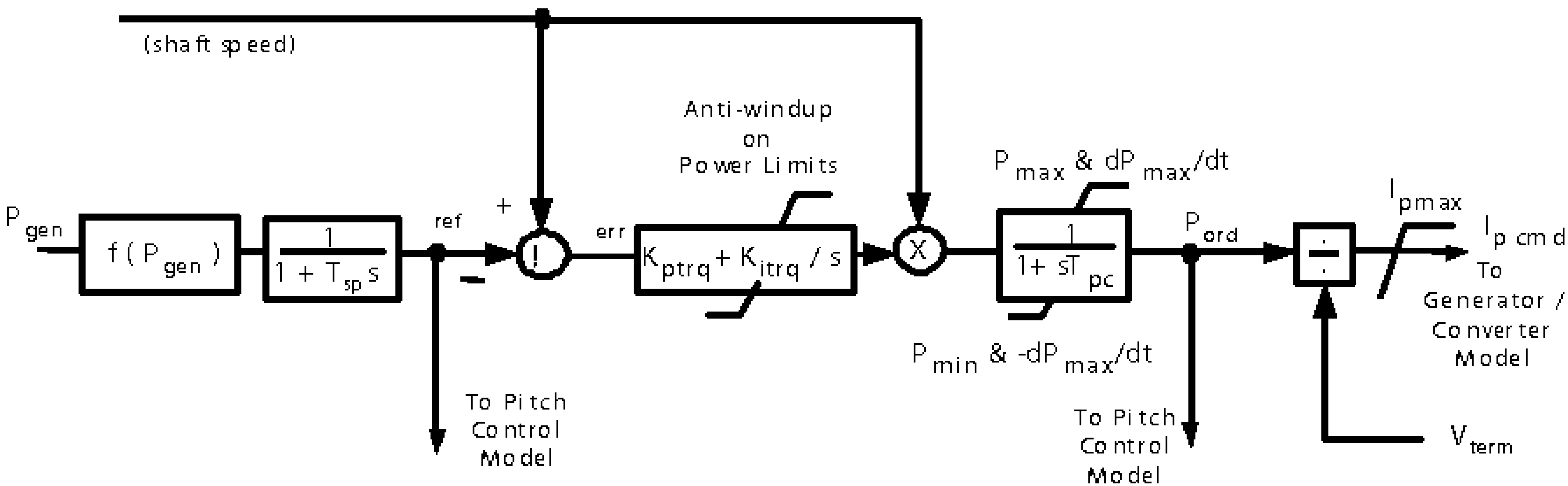
where B is the frequency bias factor.



- The ACE signal is used by AGC to adjust governor setpoints at participating generators.
  - This restores frequency and tie-line flows to their scheduled values.
  - Economic dispatch operates on a slower timescale to re-establish the most economic generation schedule.

Modeling continuous-discrete interactions

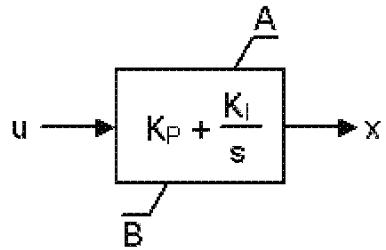
- Type-3 wind turbine converter control model:



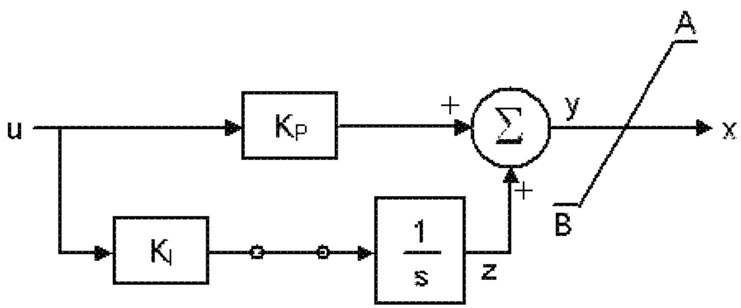
- Note the PI block with non-windup limits.
- The behavior of such a block is not well defined.
- IEEE Standard 421.5-2016 provides a definition for such a block.

PI block with non-windup limits

- According to the IEEE standard:

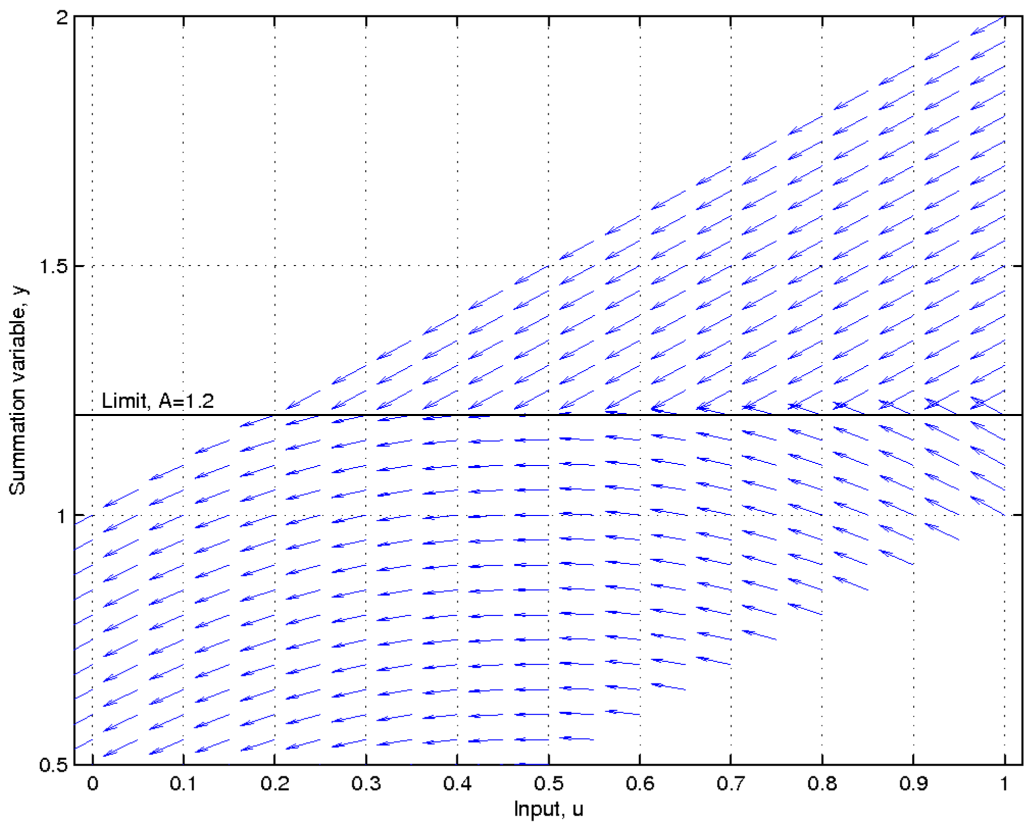


is modeled by:



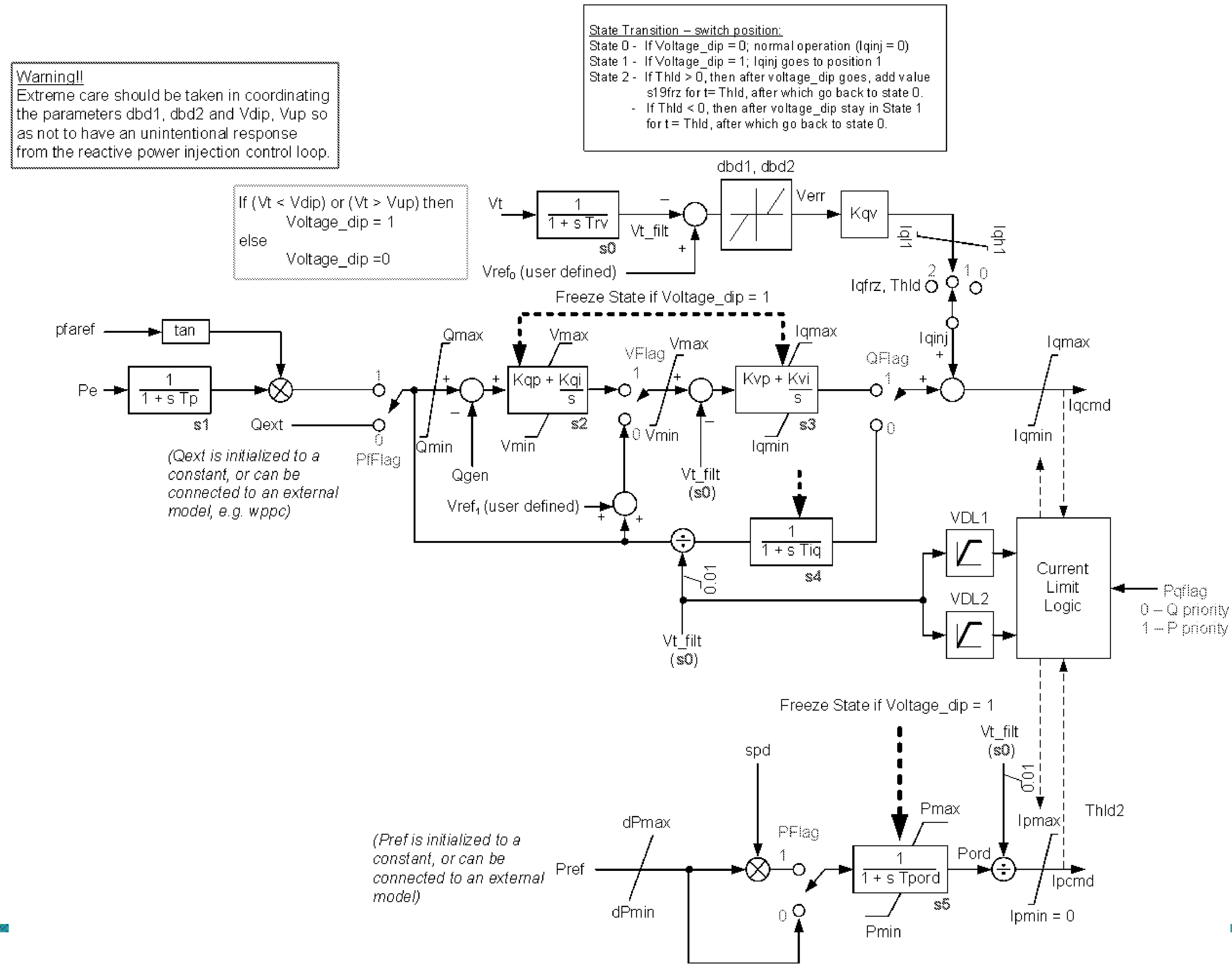
$$\text{If } y > A, \quad \text{then } x = A \text{ and } \frac{dz}{dt} = 0$$

$$\text{If } y < B, \quad \text{then } x = B \text{ and } \frac{dz}{dt} = 0.$$



- This model is prone to deadlock.
- Most commercial simulation programs don't recognize deadlock.

Latest model for type-3 wind turbines



Trajectory sensitivities

- Consider a trajectory (or flow) $x(t) = \phi(x_0, t)$ generated by simulation.
- Linearize the system around the *trajectory* rather than around the equilibrium point.

$$\begin{aligned}\Delta x(t) &= \frac{\partial \phi(x_0, t)}{\partial x_0} \Delta x_0 + \text{higher order terms} \\ &\approx \Phi(t) \Delta x_0\end{aligned}$$

- Trajectory sensitivities describe the change in the trajectory due to (small) changes in parameters and/or initial conditions.
  - Parameters incorporated via $\dot{\lambda} = 0, \qquad \lambda(0) = \lambda_0$
- Provides gradient information for iteratively solving inverse problems, such as parameter estimation.

Trajectory sensitivity evolution

- Along smooth sections of the trajectory:

System evolution

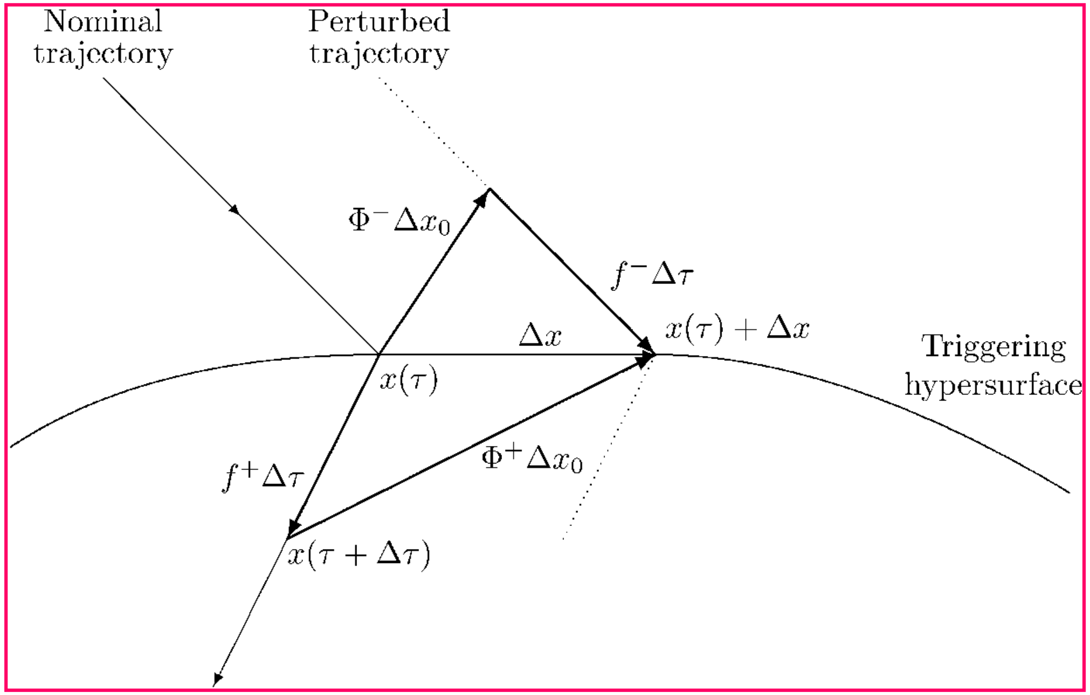
$$\dot{x} = f(x), \qquad x(0) = x_0$$

Sensitivity evolution

$$\dot{\Phi} = \left.\frac{\partial f}{\partial x}\right|_{x(t)} \Phi, \qquad \Phi(0) = I$$

At an event

$$\Phi(\tau^+) = \Phi(\tau^-) - \left(f^+ - f^-\right) \frac{\partial \tau}{\partial x_0}$$



Trajectory sensitivity computation

Implicit numerical integration allows efficient computation of trajectory sensitivities.

System evolution

$$\dot{x} = f(x)$$

Trapezoidal integration

$$x^{k+1} = x^k + \tfrac{h}{2}\Big(f(x^k) + f(x^{k+1})\Big)$$

Each integration timestep involves a Newton solution process.

- The Jacobian $\underbrace{\left(\frac{h}{2}Df - I\right)}$ must be formed and factored.

Sensitivity evolution

$$\dot{\Phi} = Df(x(t))\Phi$$

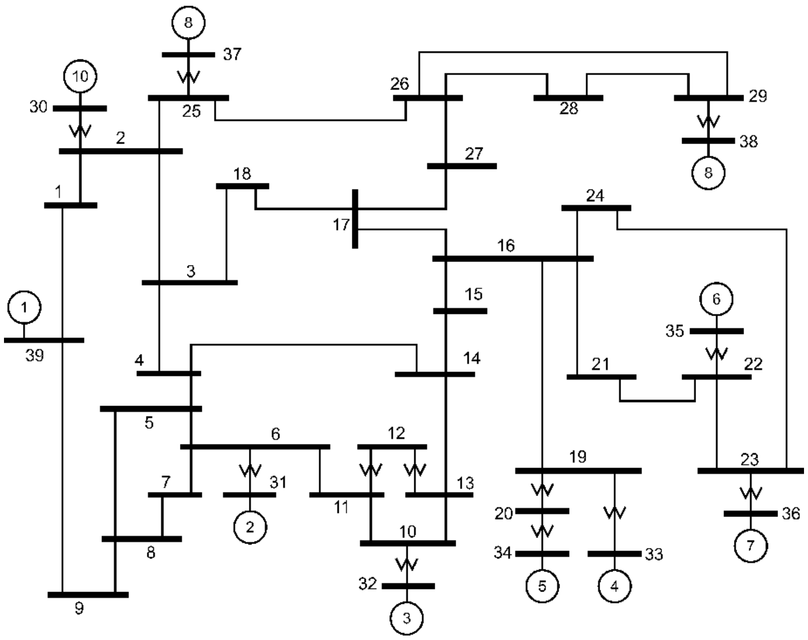
Trapezoidal integration

$$\Phi^{k+1} = \Phi^k + \tfrac{h}{2}\Big(Df(x^k)\Phi^k + Df(x^{k+1})\Phi^{k+1}\Big)$$

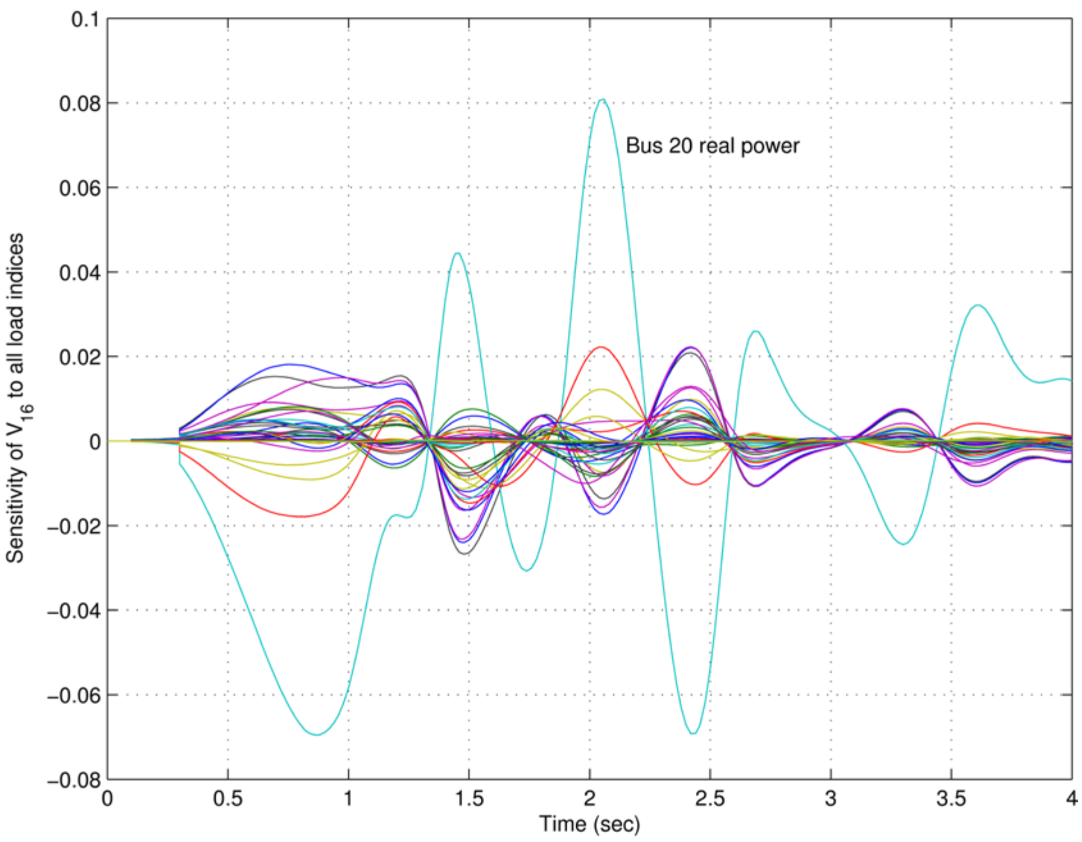
$$\Rightarrow \underbrace{\left(\frac{h}{2}Df(x^{k+1}) - I\right)}_{\boxed{\text{Already factored}}}\Phi^{k+1} = -\Big(\tfrac{h}{2}Df(x^k) + I\Big)\Phi^k$$

Parameter ranking example

IEEE 39 bus system



Sensitivity of V_{16} to load parameters



Trajectory approximation

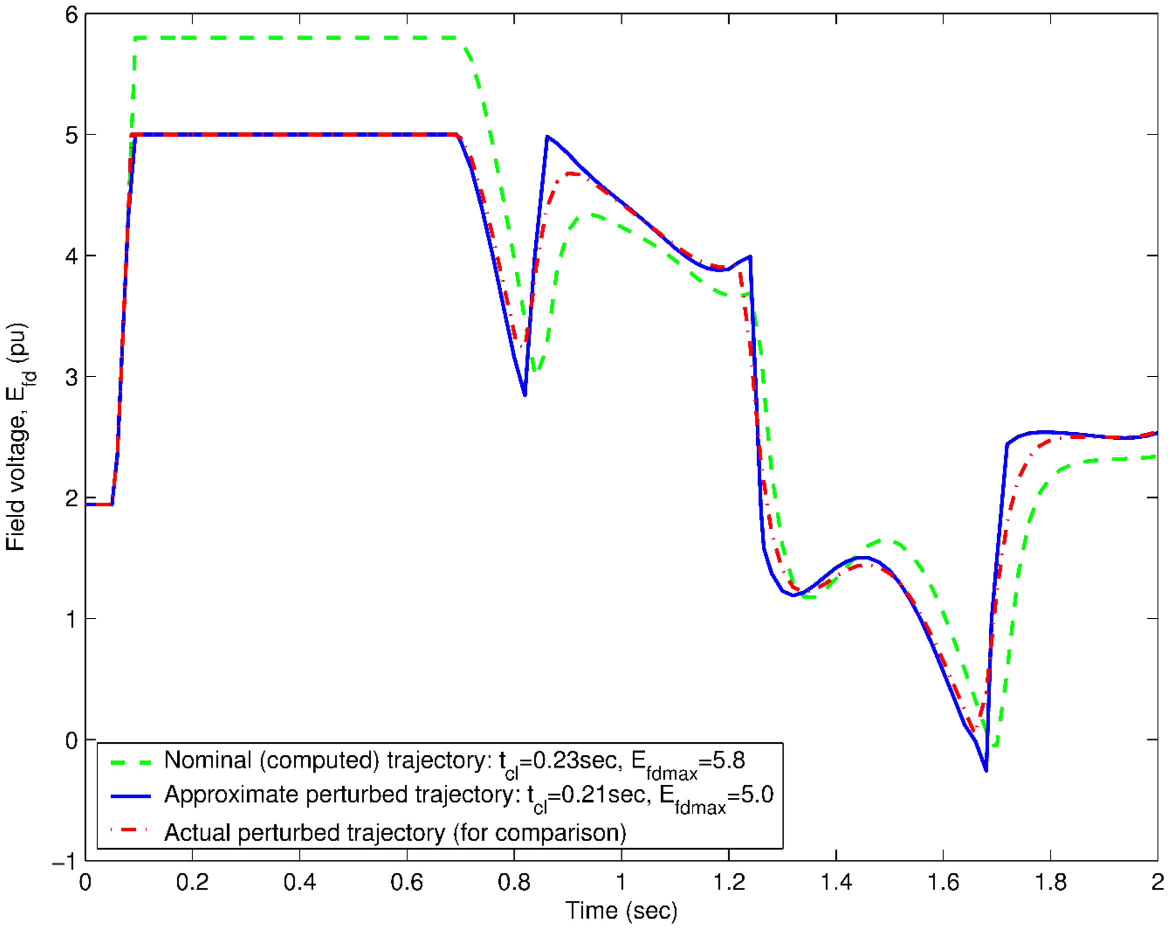
- Neglecting higher order terms of the Taylor series:

$$\phi(x_0 + \Delta x_0, t) \approx \phi(x_0, t) + \Phi(x_0, t)\Delta x_0$$

- Affine structure.

Example:

Generator field voltage response to a fault.



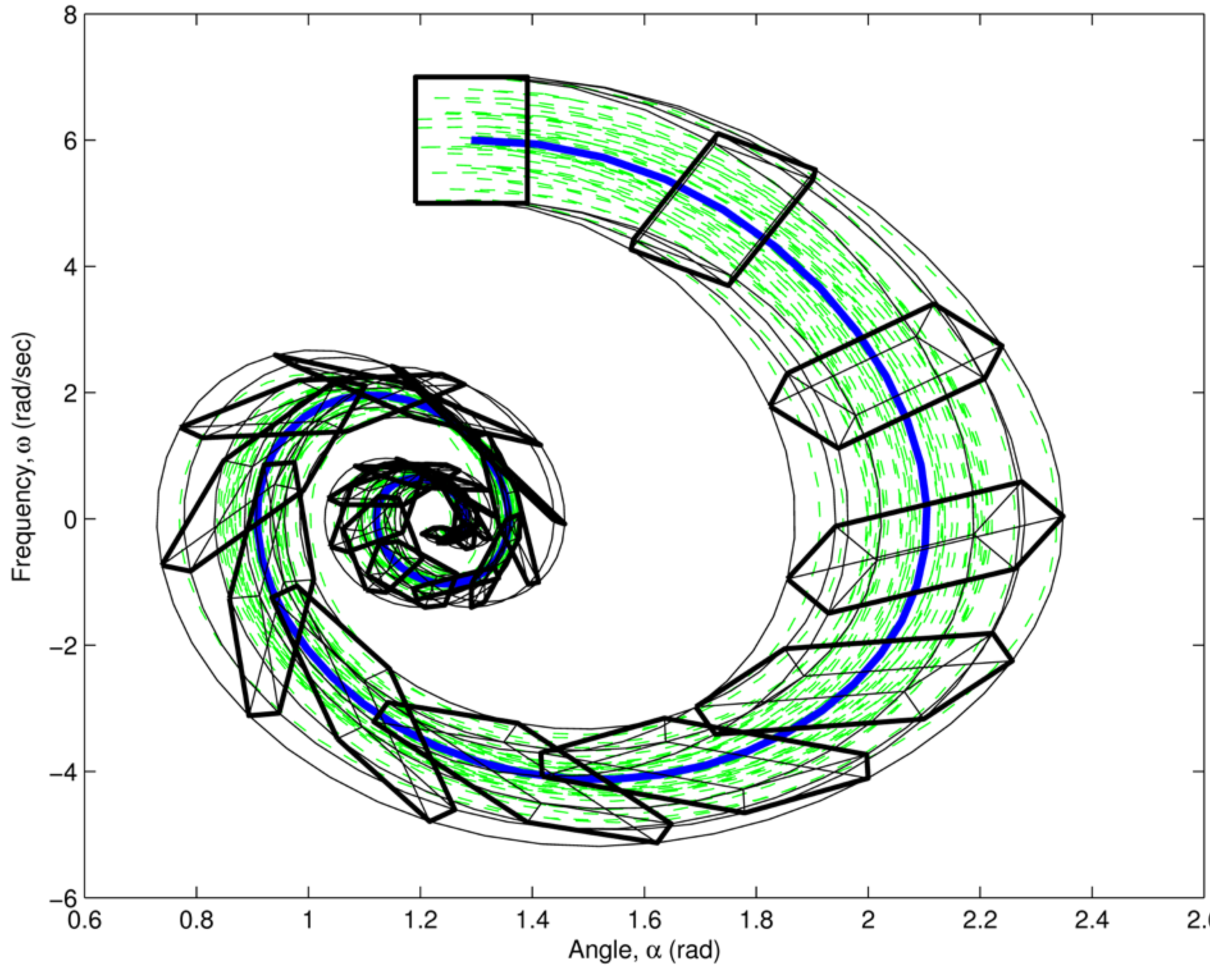
Parameter uncertainty

Worst-case analysis: Assume parameter uncertainty is uniformly distributed over an orthotope $\mathcal{B}$ (multi-dimensional rectangle.)

Assume all trajectories emanating from $x_0 + \mathcal{B}$ have the same order of events.

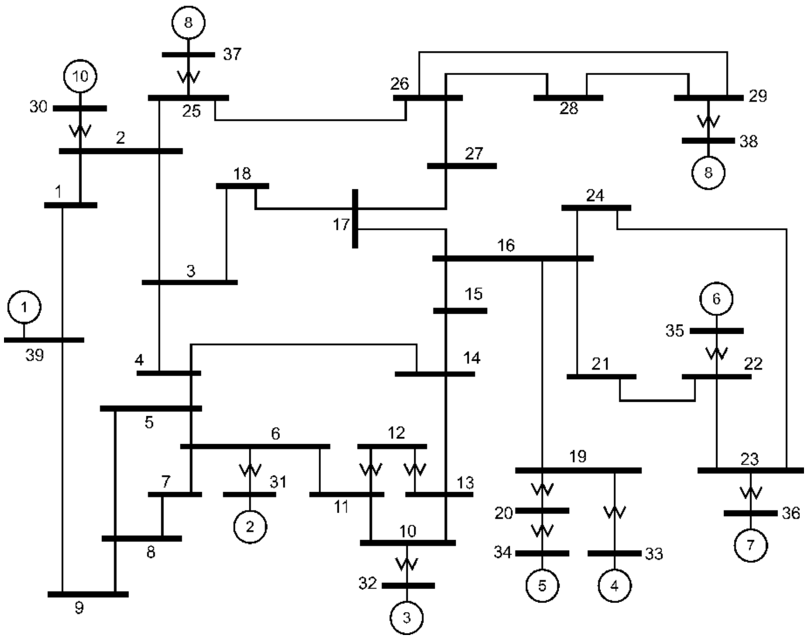
Propagation of uncertainty is described (approximately) by the time-varying parallelotope

$$\mathcal{P}(t) = \phi(x_0, t) + \Phi(x_0, t)\mathcal{B}$$



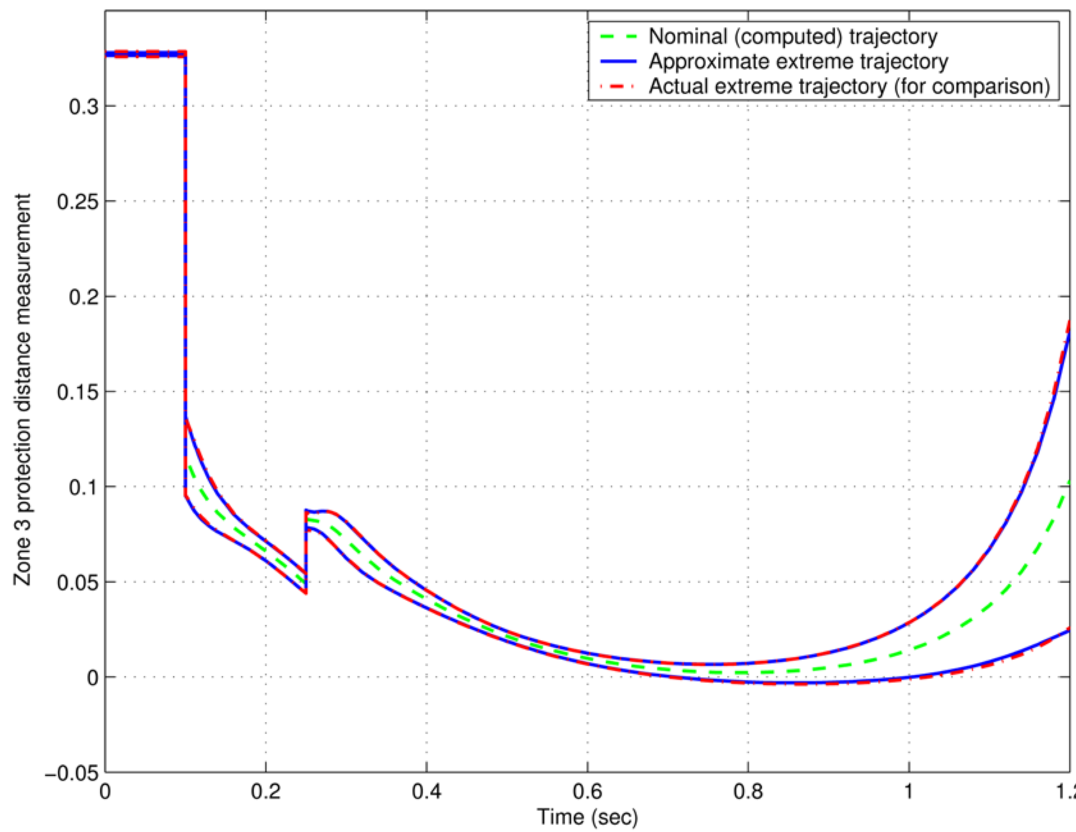
Example – worst case analysis

Uncertainty: $0.3 \leq \nu_{23}, \nu_{24} \leq 0.7$



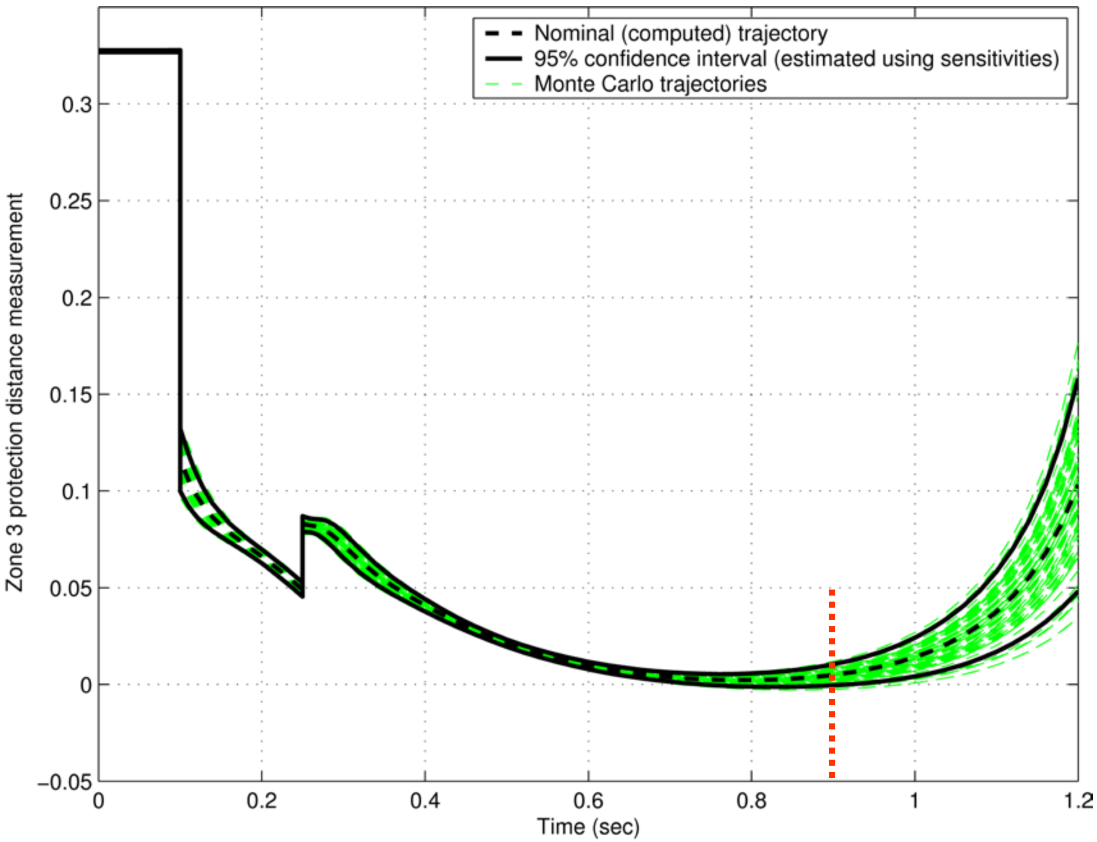
Protection signal

- Zero crossing indicates protection trip.

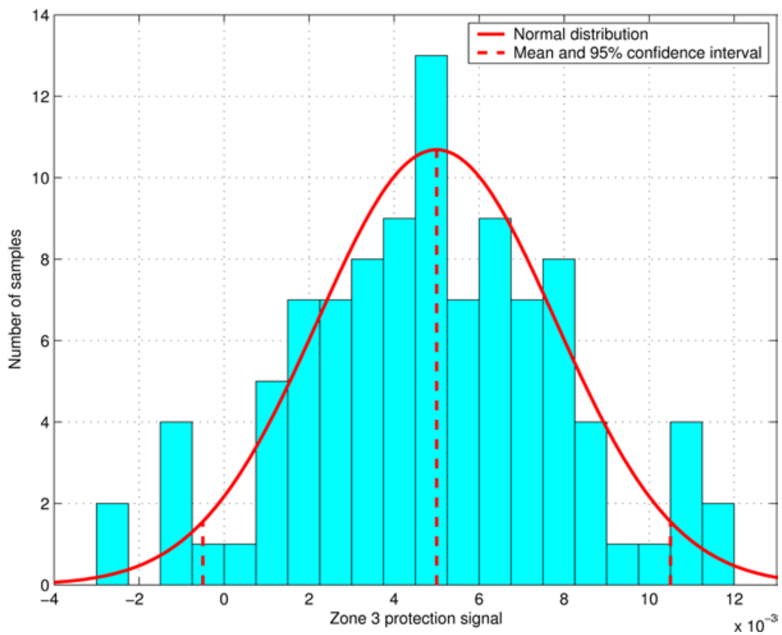


Example – probabilistic assessment

Uncertainty: $E[\nu_{23}] = E[\nu_{24}] = 0.5,\ \mathrm{Var}[\nu_{23}] = \mathrm{Var}[\nu_{24}] = 0.01$



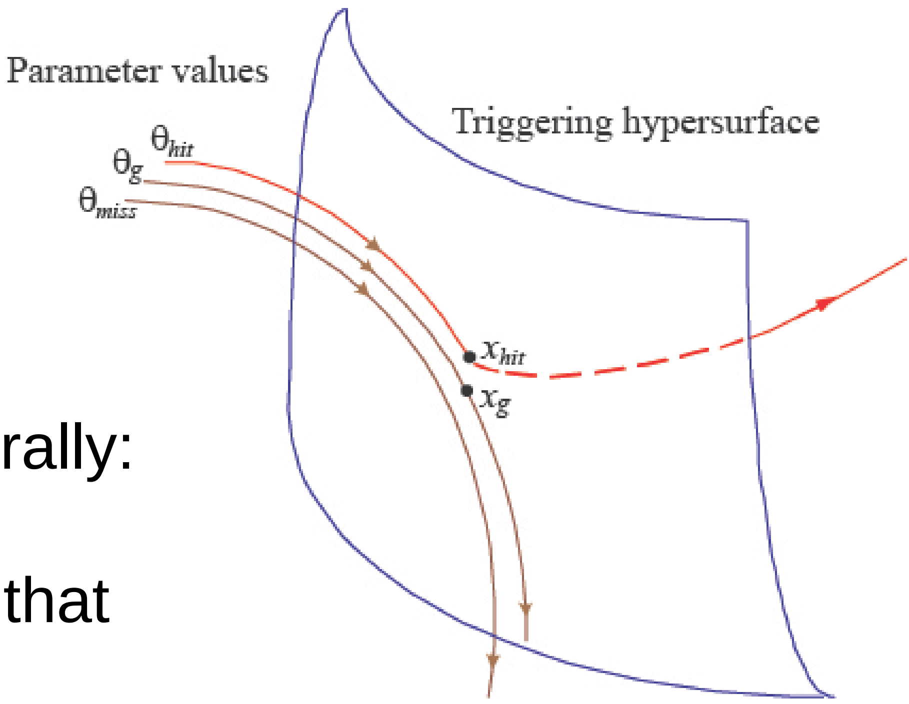
Signal distribution at 0.9 sec.



Grazing formulation for reachability

- At a grazing point the trajectory has a tangential encounter with the target hypersurface: $b(x) = 0$
- Tangency implies: $\nabla b^\top f(x) = 0$
- Grazing points are described by:

$$\begin{aligned} F_{g1}(x_g, \theta, t_g) &:= \phi(x_0(\theta), t_g) - x_g &= 0 \\ F_{g2}(x_g) &:= b(x_g) &= 0 \\ F_{g3}(x_g) &:= \nabla b(x_g)^\top f(x_g) &= 0 \end{aligned}$$

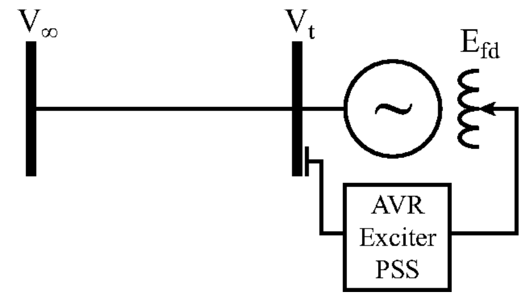


where initial conditions are parameterized by θ .

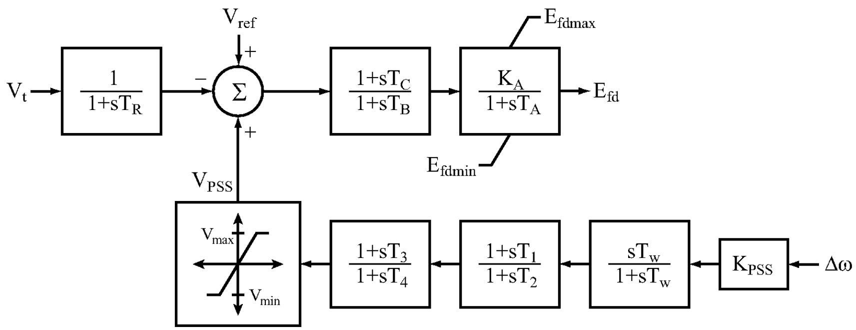
- This formulation extends naturally:
  - Continuation.
  - Closest set of parameters that induce grazing.

Example

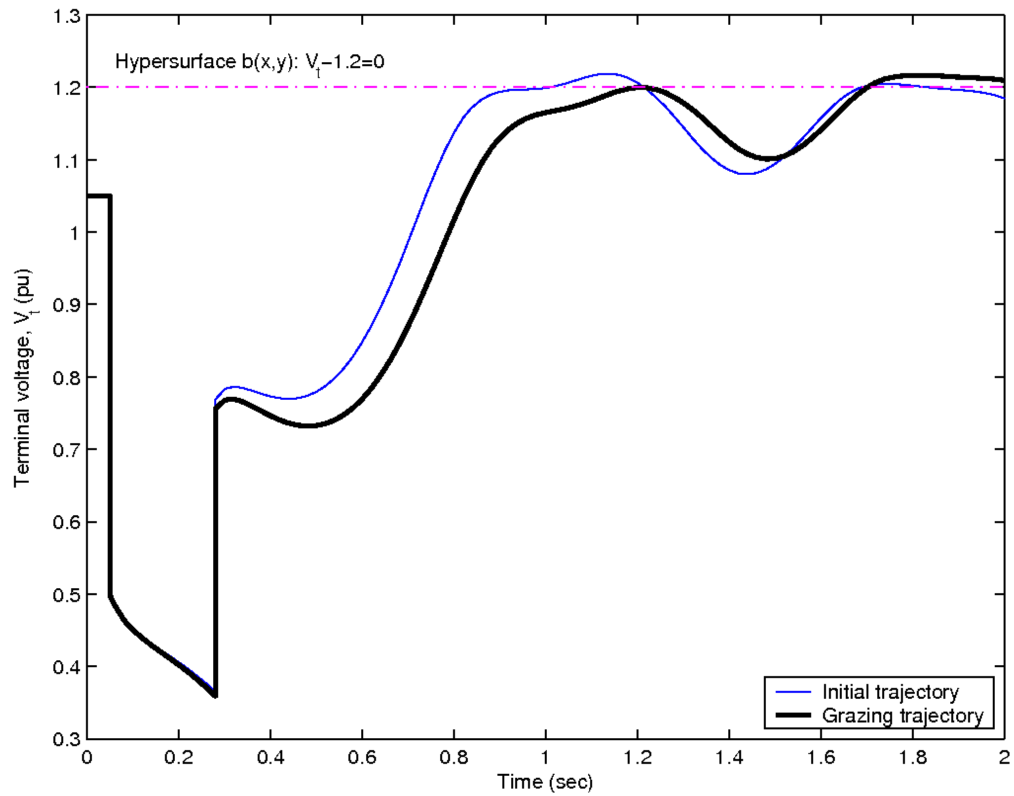
- Single machine infinite bus system:



- Generator AVR/PSS:



- Determine $E_{fd,max}$ so that generator terminal voltage does not (initially) rise above 1.2 pu.



Conclusions

- Power systems are nonlinear, non-smooth, differential-algebraic systems.
  – Hybrid dynamical systems.
- A variety of controls, from local to wide-area, are used to ensure reliable, robust behavior.
- Care must be taken in modeling and simulation.
- Variability inherent in renewable generation:
  – Challenge existing control structures.
  – Require more exhaustive investigation of dynamic behavior.