Power Grid Dynamics and Control

Ian A. Hiskens

Vennema Professor of Engineering

Professor, Electrical Engineering and Computer Science

MichiganEngineering

Power Grids as Complex Networks

Santa Fe Institute

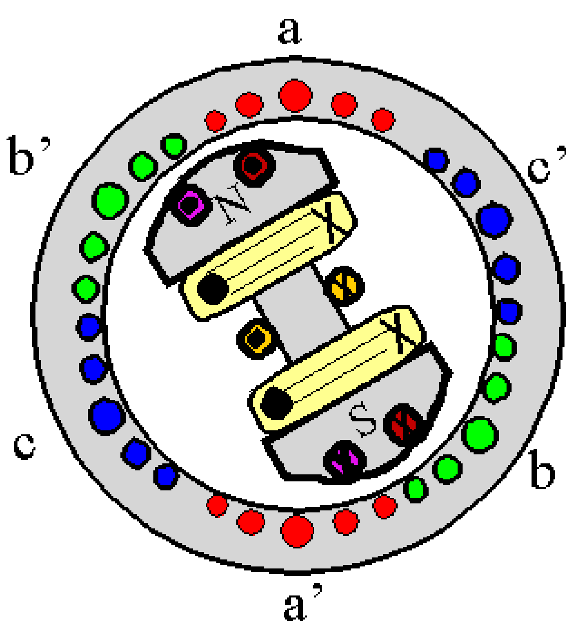
May 17, 2012

Outline

- Fundamentals of power system angle stability and voltage collapse.
- Impact of loads on power system dynamics, load modeling.
- Generator controls.
- Demand response: peak shaving, fully responsive load control.

Synchronous machines

- All large 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 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

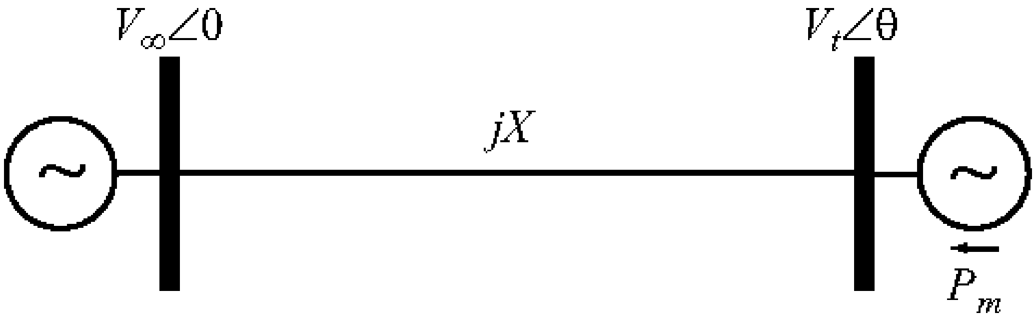
$\omega \equiv \frac{d\theta}{dt}$: deviation in angular velocity from nominal.

M : inertia constant.

D : damping constant, 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.

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 $P_m = P_{max}\sin\theta$.

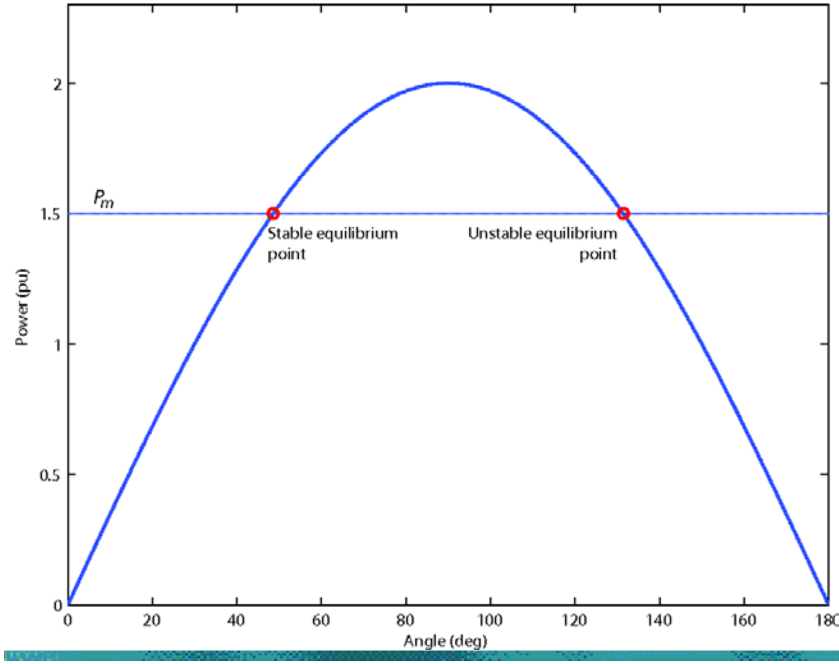
Region of attraction

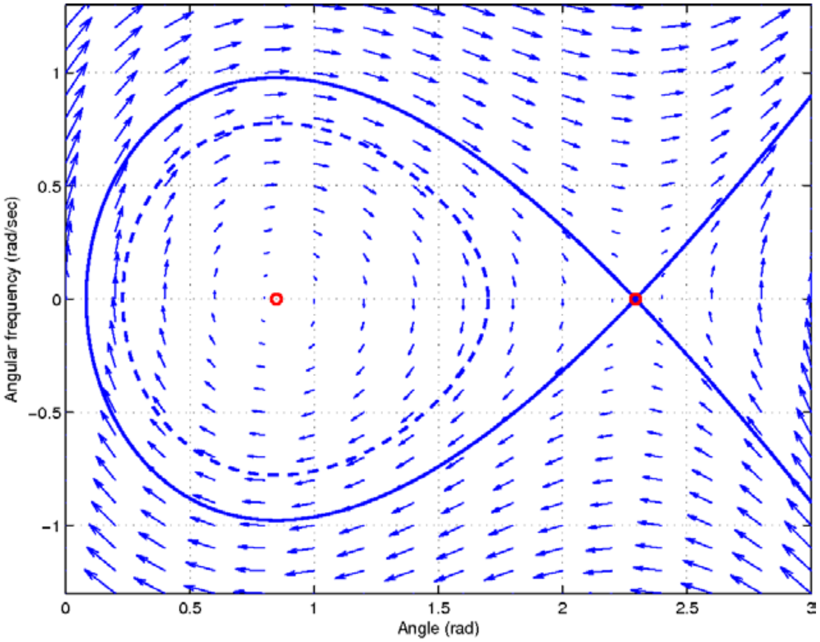
- The equilibrium equation has two solutions, θ_s and θ_u where

  θ_s : stable equilibrium point.

  θ_u : unstable equilibrium point.

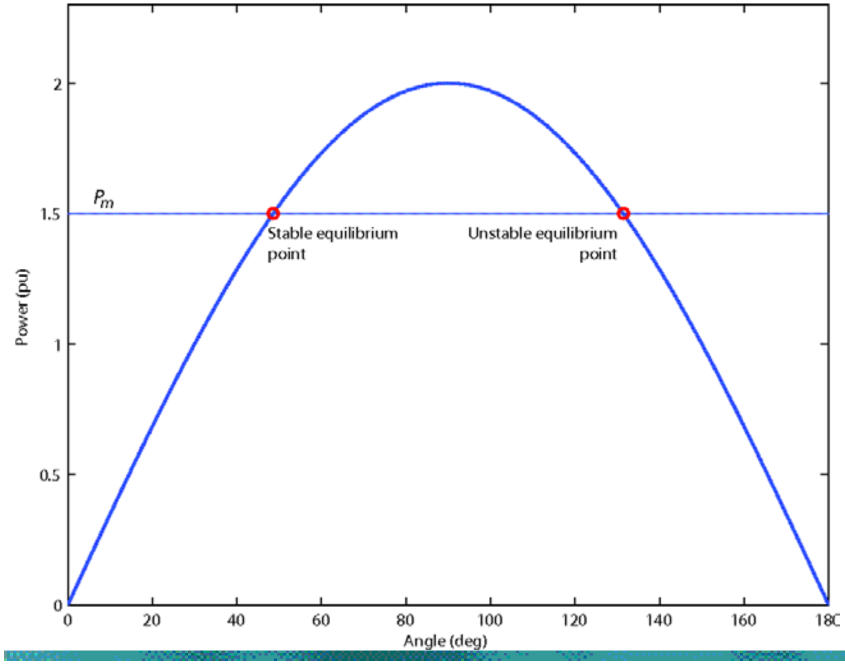
- Local stability properties are given by the eigenvalues of the linearized system at each equilibrium point.

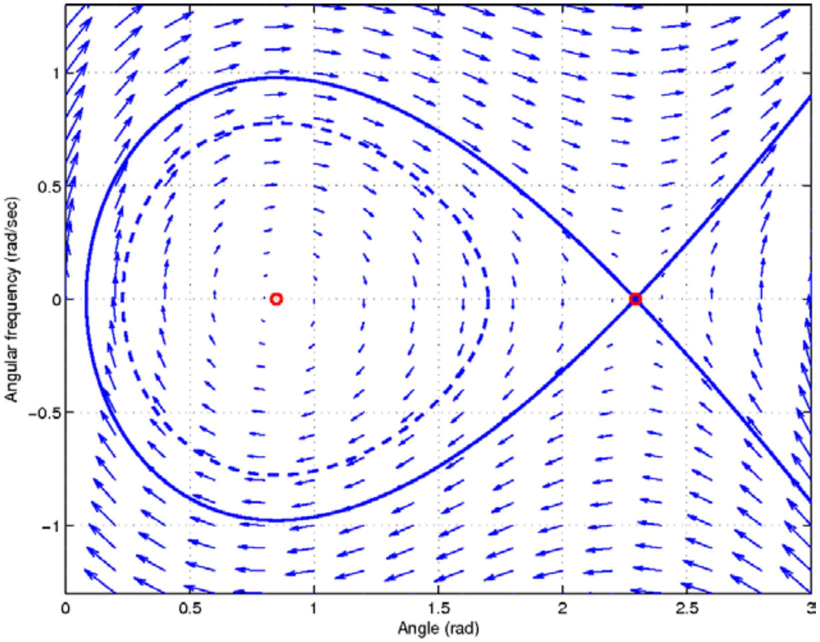




Region of attraction

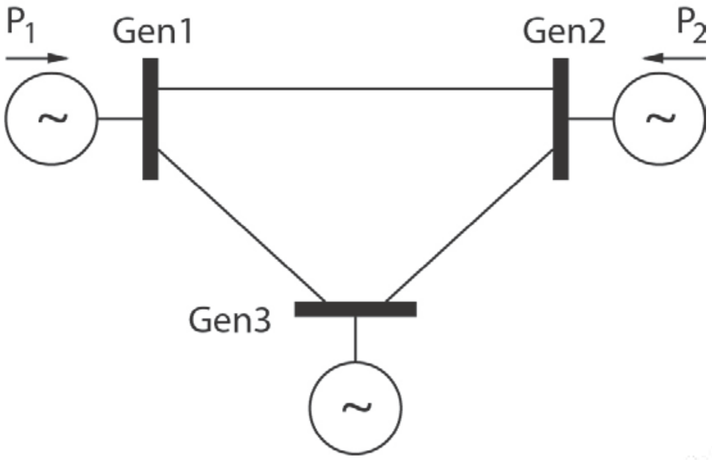
- As P_m increases, the separation between equilibria diminishes.
  - The region of attraction decreases as the loading increases.
  - Solutions coalesce when $P_m = P_{max}$. A bifurcation occurs.

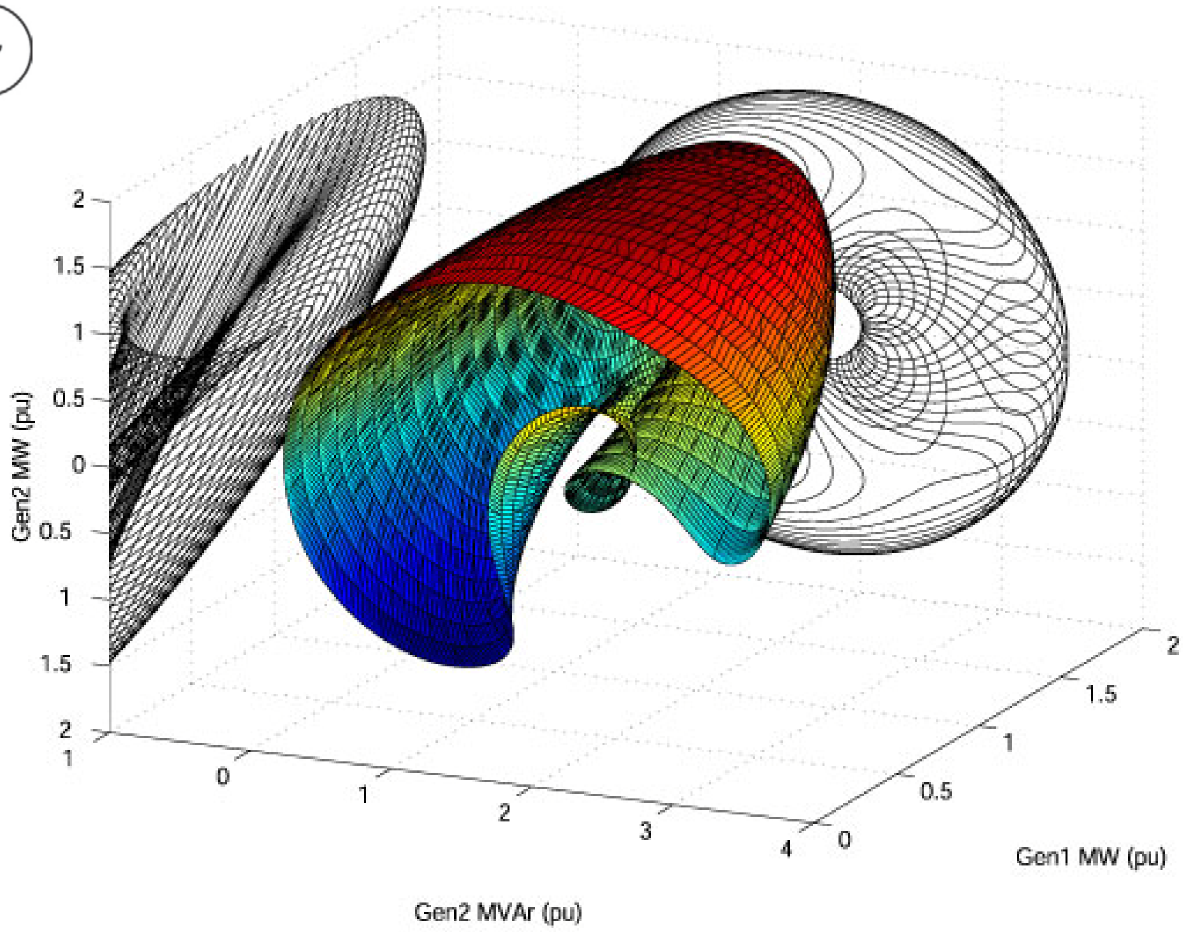




Multiple equilibria

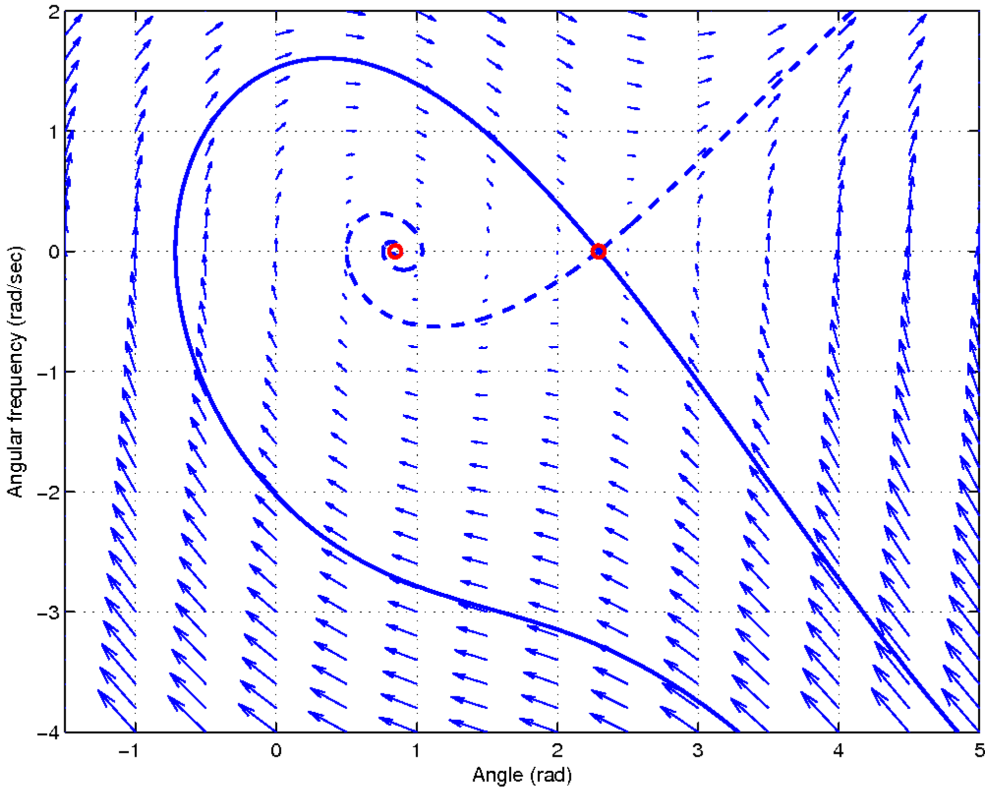
- Real power systems typically have many equilibria.





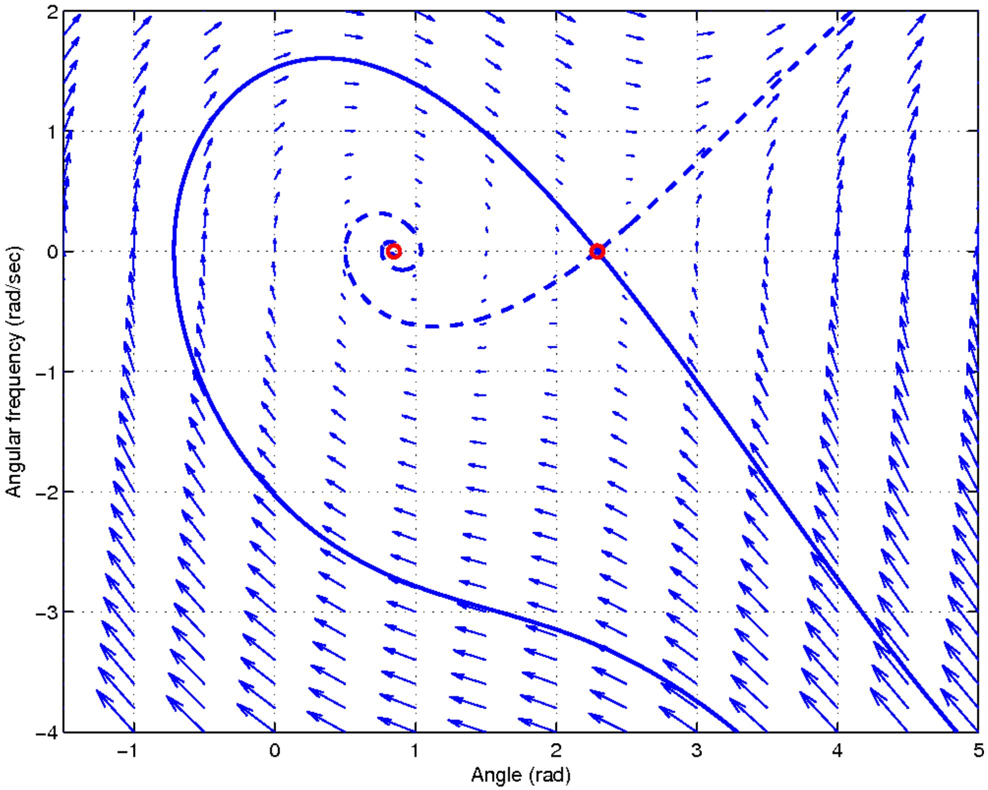
Large disturbance behavior

- 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.



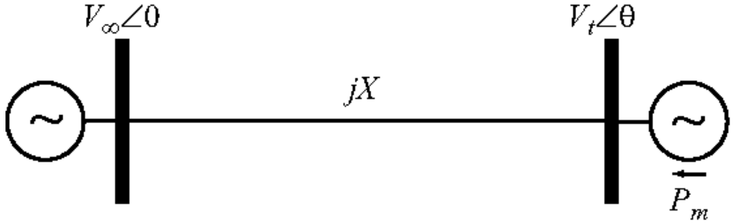
Critical clearing

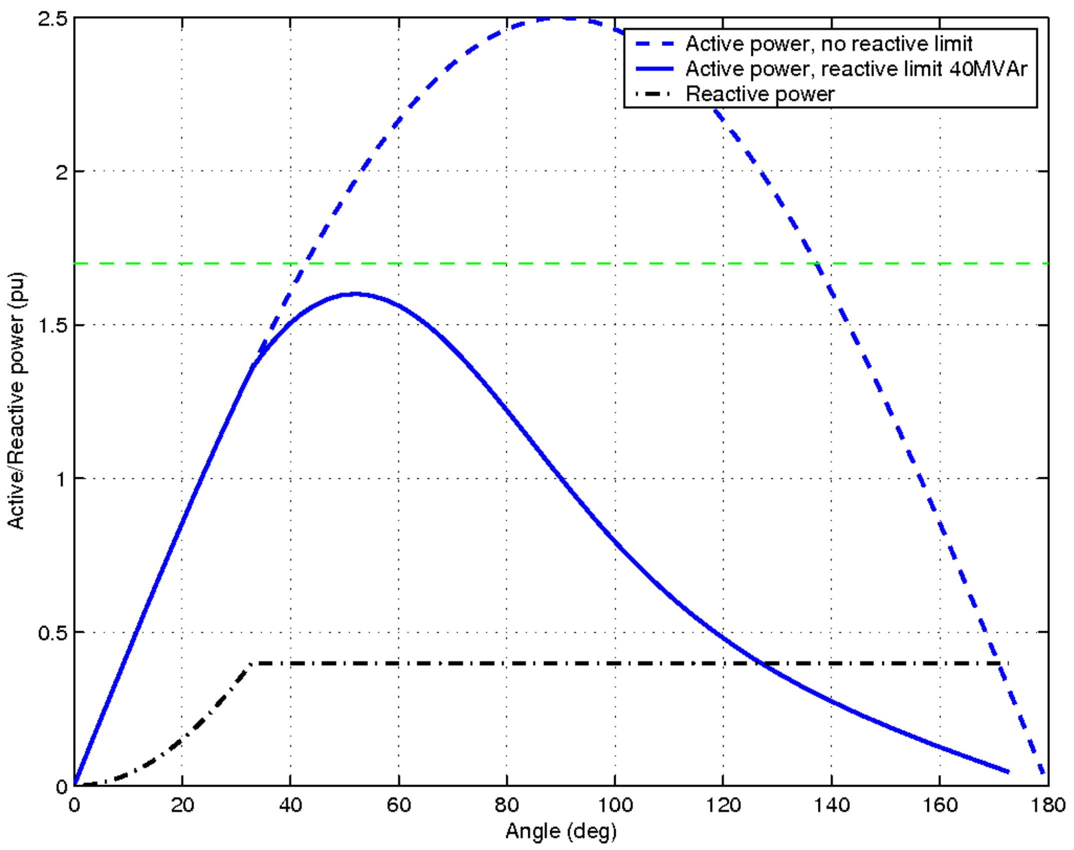
- Critical clearing refers to the (hypothetical) situation where the fault is removed when the state lies exactly on the stability boundary.
  - Conceptually, the resulting trajectory would run exactly to the unstable equilibrium point and stay there.
  - This is equivalent to bumping a pendulum so that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



Voltage reduction

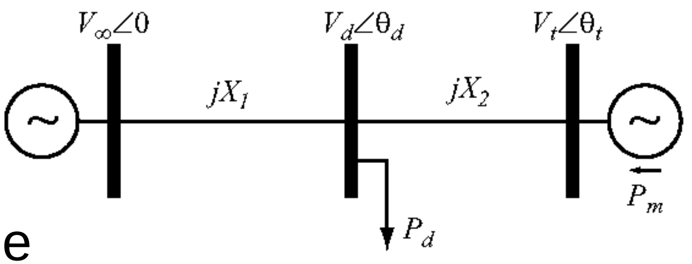
- The single machine infinite bus example assumes the generator will maintain a constant terminal voltage.
  - The reactive power required to support the voltage is limited.
  - Upon encountering this limit, the over-excitation limiter will act to reduce the terminal voltage.



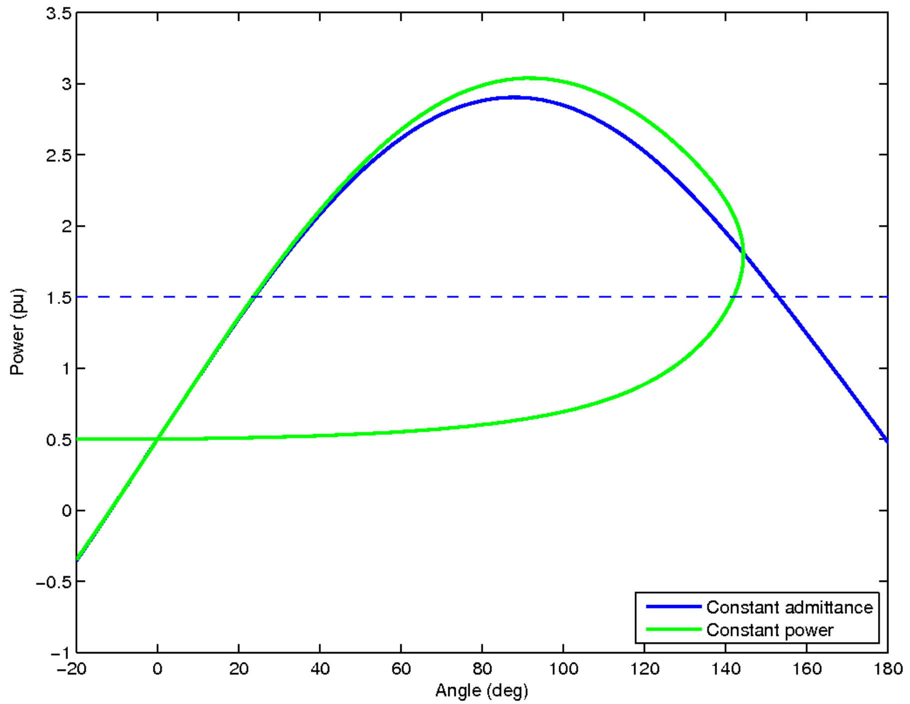


Effect of load

- Consider the effect of load behavior on stability.
- Two cases:
  - Constant admittance: $P_d = K_a V_d^2$
  - Constant power: $P_d = K_p$



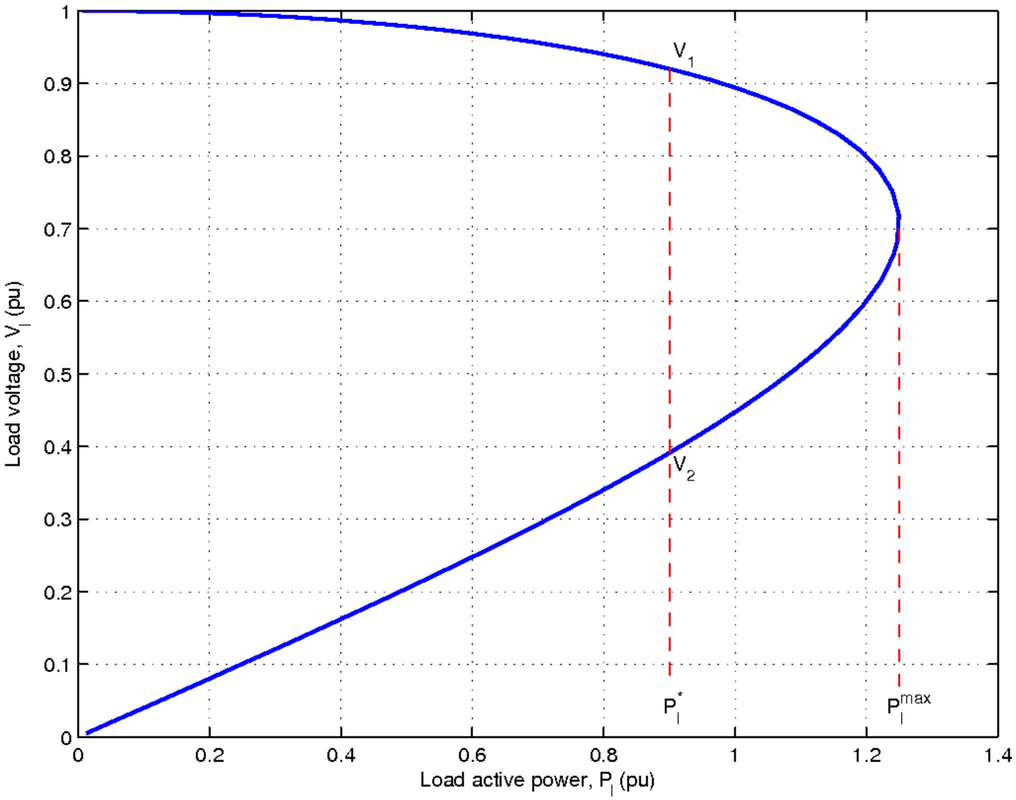
- Notice the loss of structural stability as the voltage index changes.



- 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.

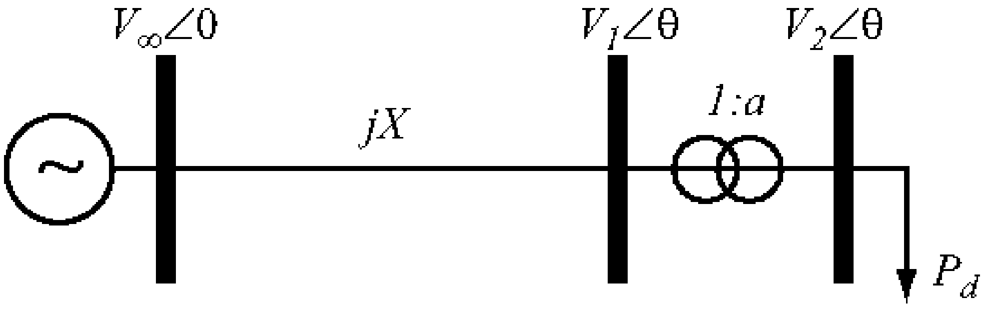
Voltage collapse

- 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.

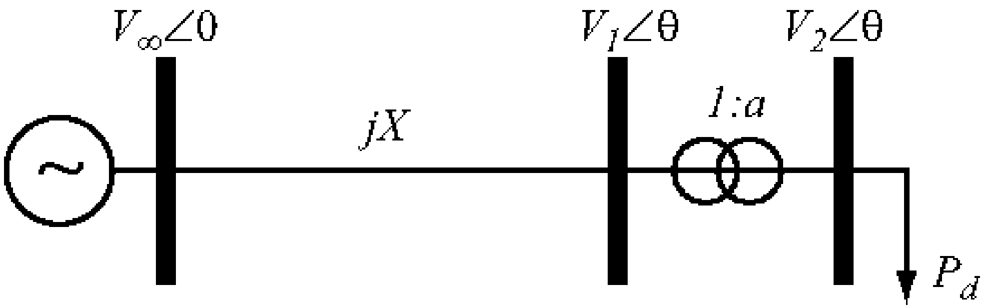


Load restoration dynamics

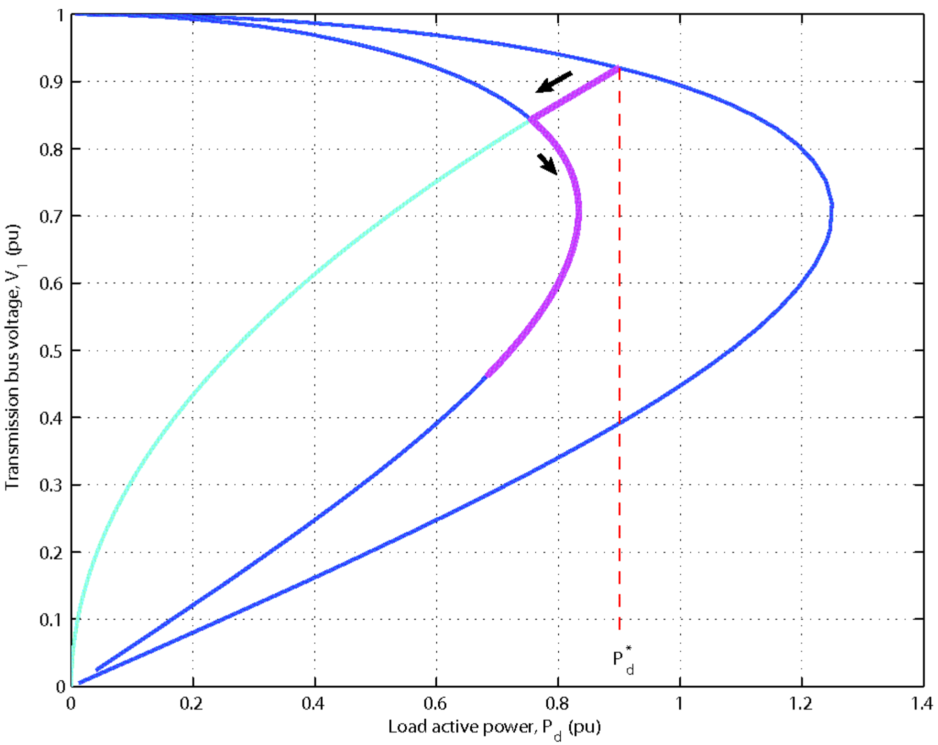
- Transformers are frequently used to regulate load-bus voltages.
- Sequence of events:
  - Line trips out, raising the network impedance.
  - Load-bus voltage drops, so transformer increases its tap ratio to try to restore the voltage.
  - Load is voltage dependent, so the initial voltage increase causes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

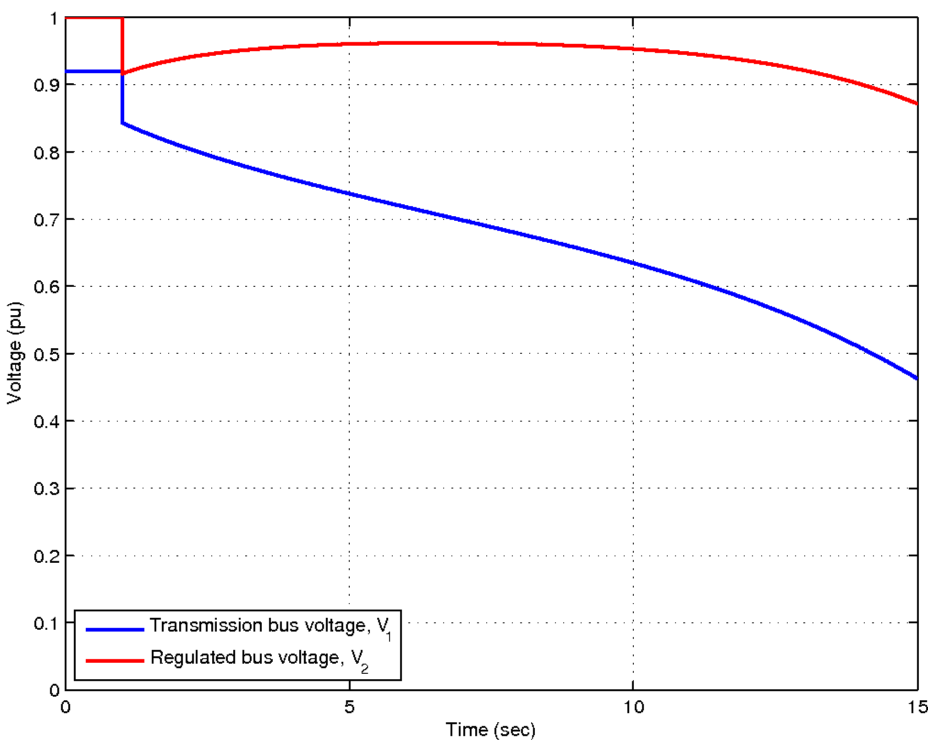


Load restoration dynamics



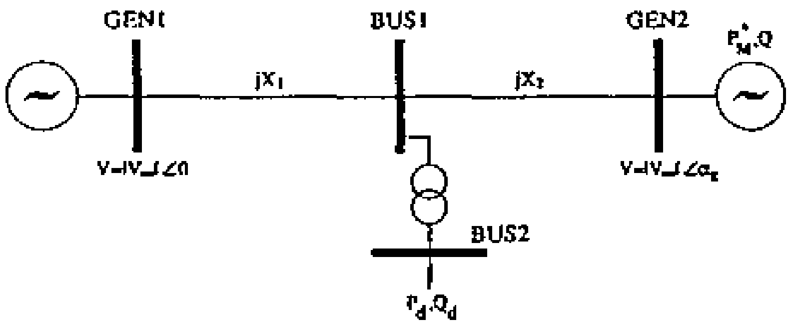
$$\frac{da}{dt} = \frac{1}{T}(V_{set} - V_2)$$
$$V_2 = aV_1$$
$$P_d = P_0 \left(\frac{V_2}{V_{set}}\right)^2$$

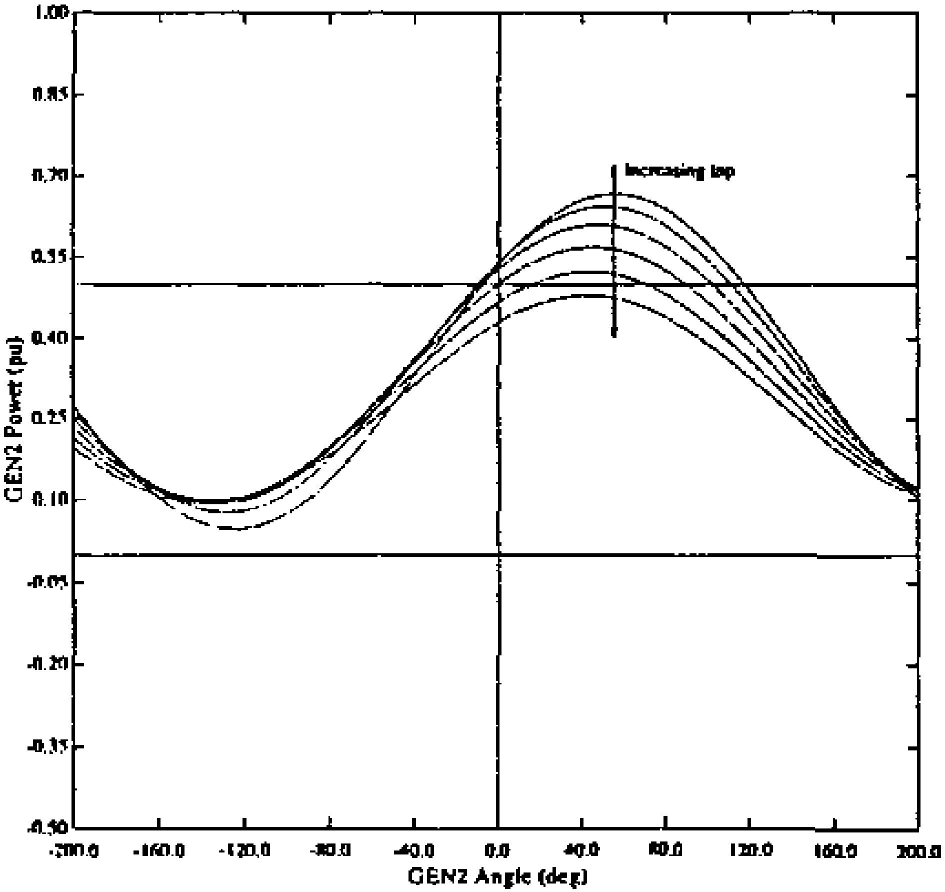




Voltage-angle interactions

- 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 modeling

- Traditional static load models (which are still in common use) have the form:

$$P_d = P_0 \left(\alpha_1 \left(\frac{V}{V_0} \right)^2 + \alpha_2 \left(\frac{V}{V_0} \right) + \alpha_3 \right) (1 + L\Delta f)$$

or

$$P_d = P_0 \left(\frac{V}{V_0} \right)^{\alpha}$$

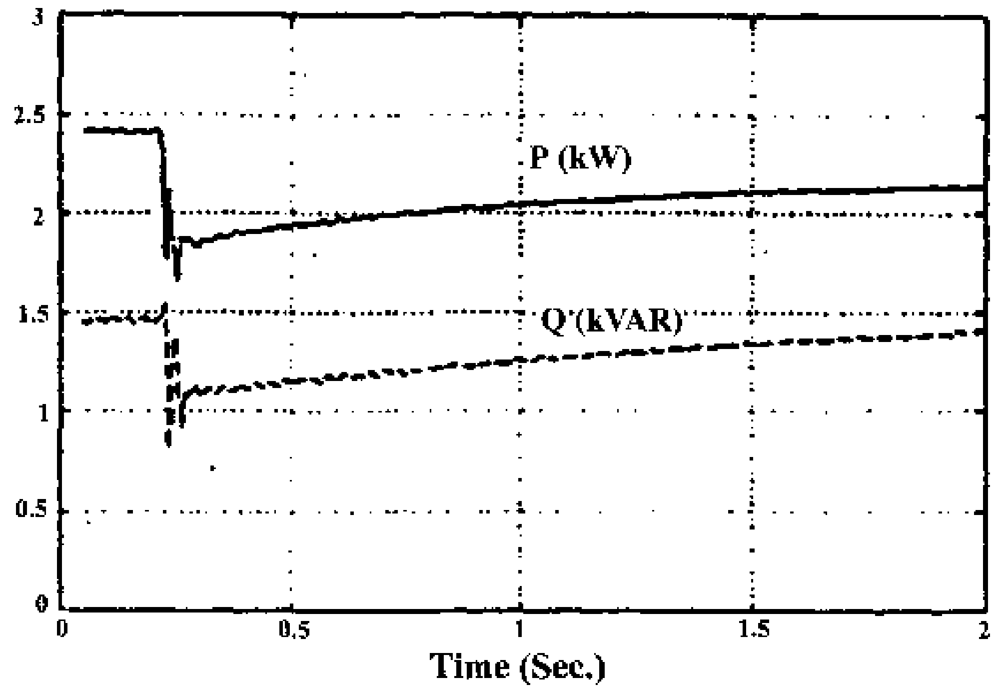
- Reactive power is modeled similarly.

Generic dynamic load model

- Load response often consists of an initial step followed by a period of recovery.
  - Recall the tap-changer driven load recovery earlier.
- A common generic load model:

$$\dot{x}_p = \frac{1}{T_p}(P_s(V) - P_d)$$

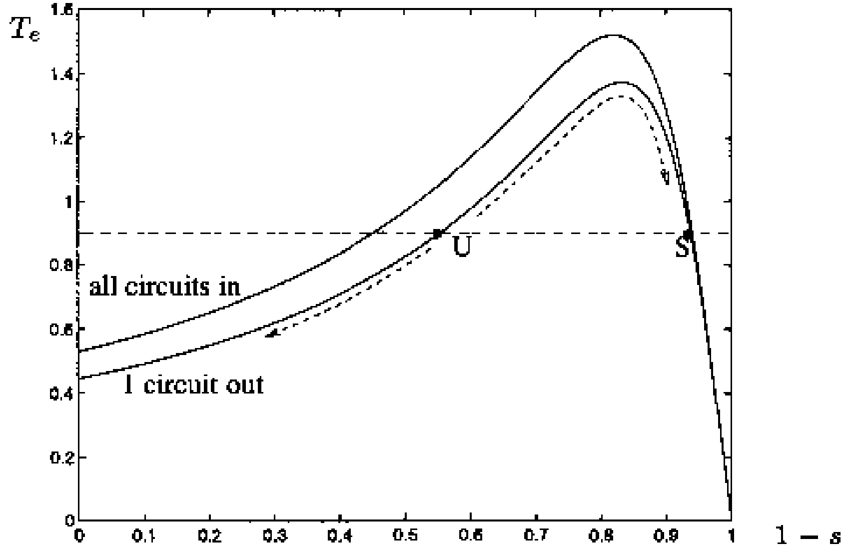
$$P_d = x_p + P_t(V)$$

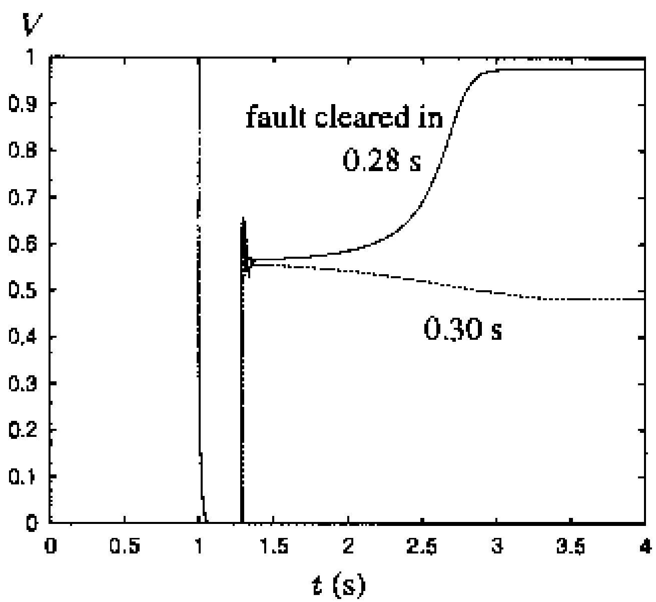


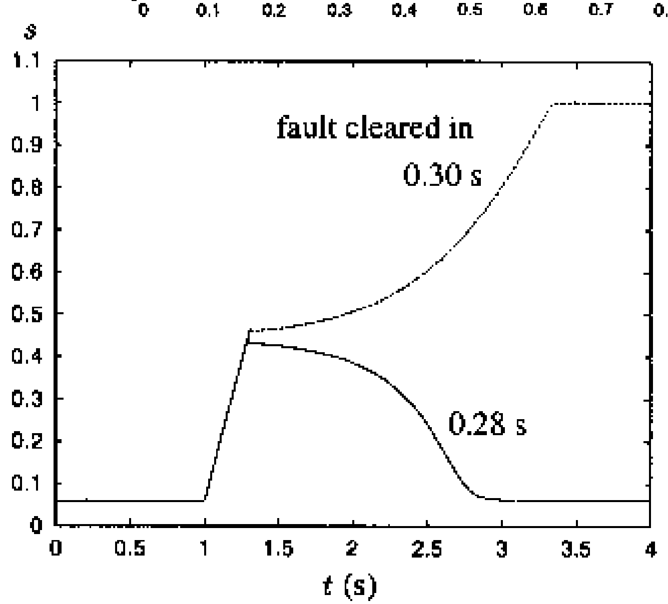
Induction motor loads

- Induction motor slip is driven by:

$$\dot{s} \approx T_m - T_e$$

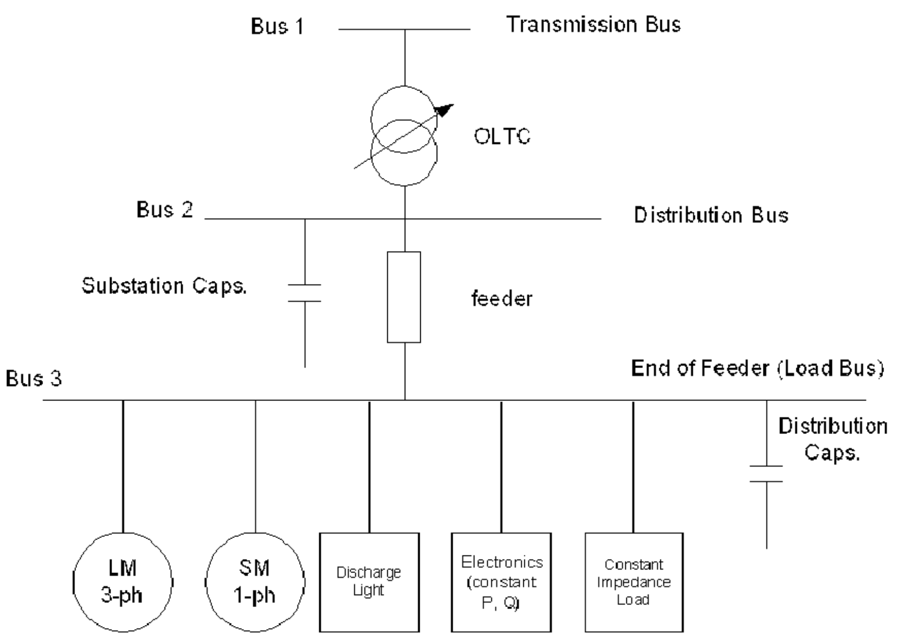


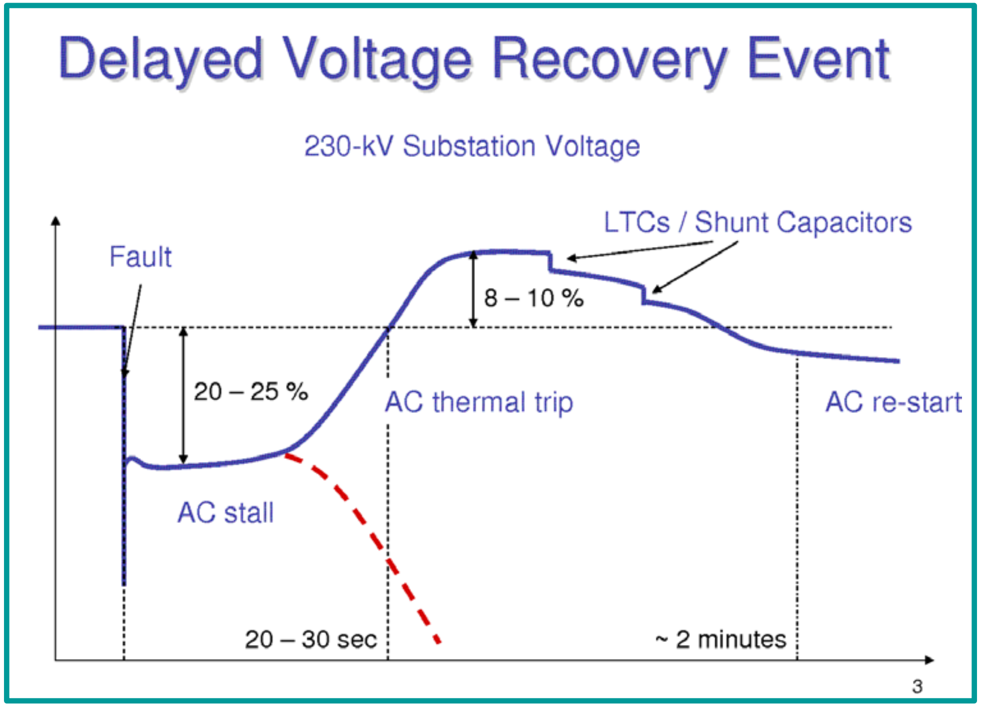




Detailed load model

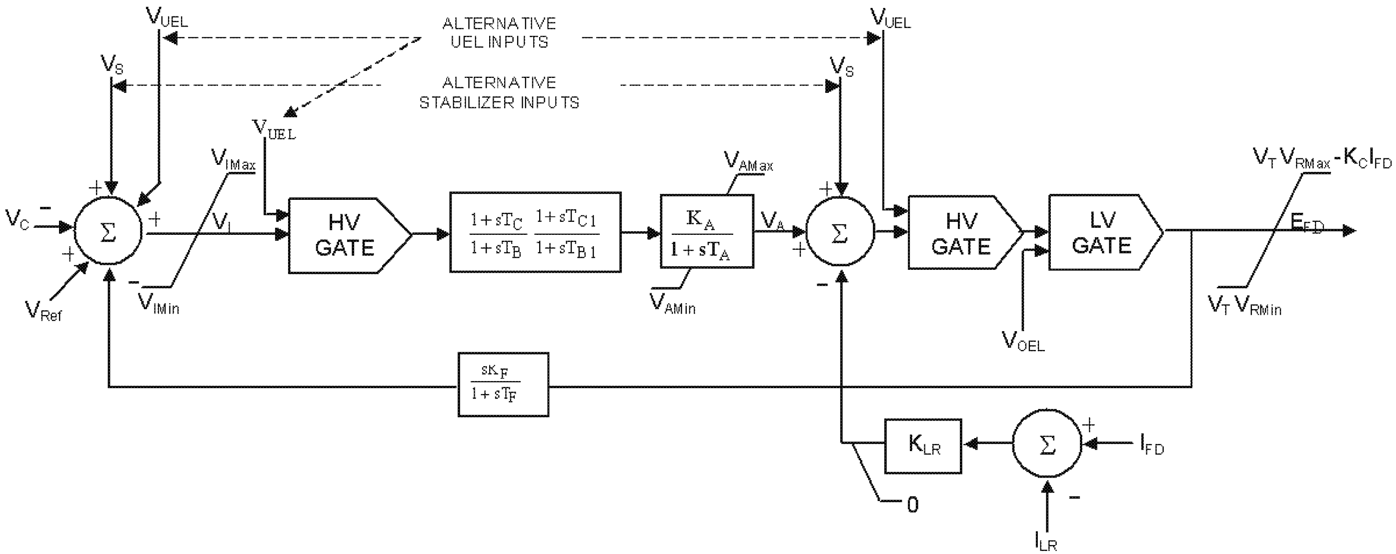
- Motivated by a desire to capture phenomena such as “fault induced delayed voltage recovery”.
- WECC load model:





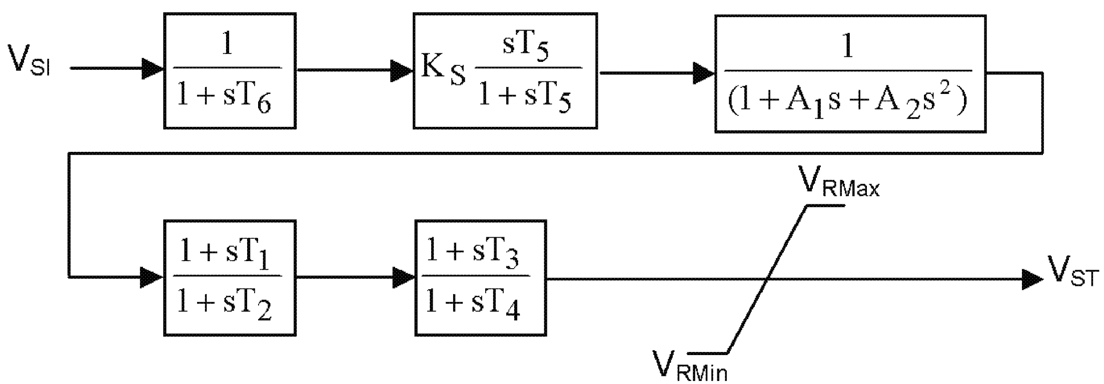
Generator voltage control

- 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.



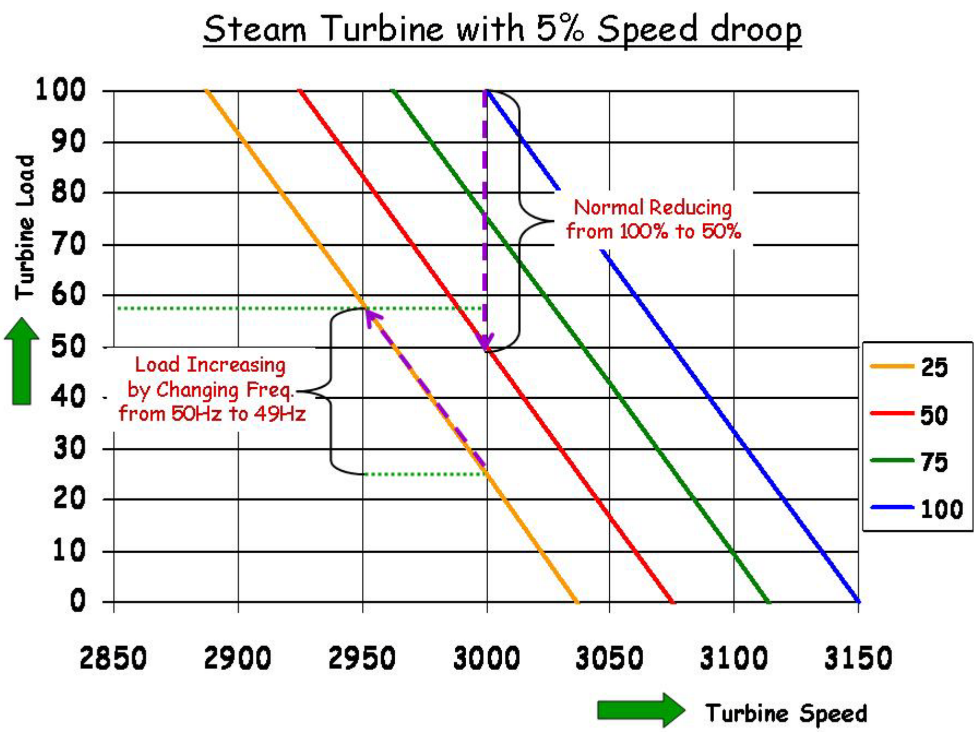
Power system stabilizers

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



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.

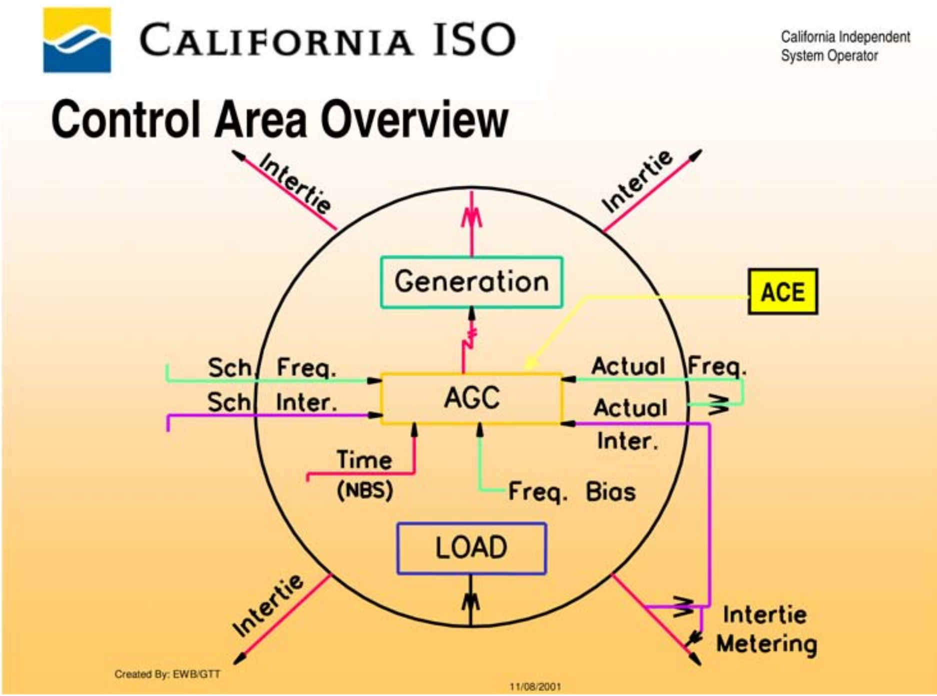


Automatic generation control (AGC)

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

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

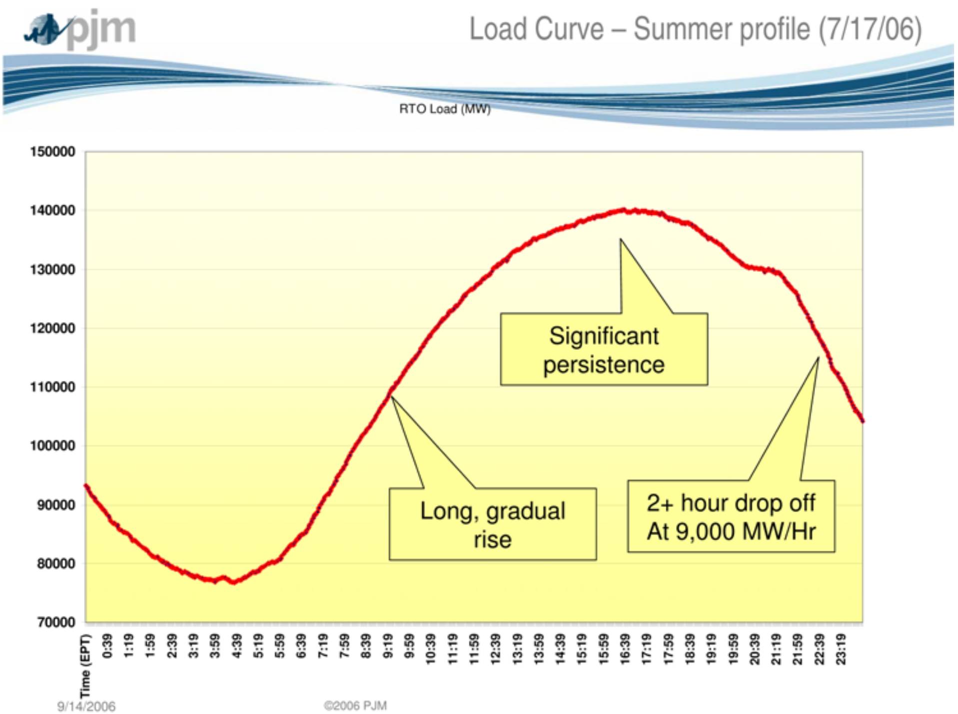
where B is the frequency bias factor.

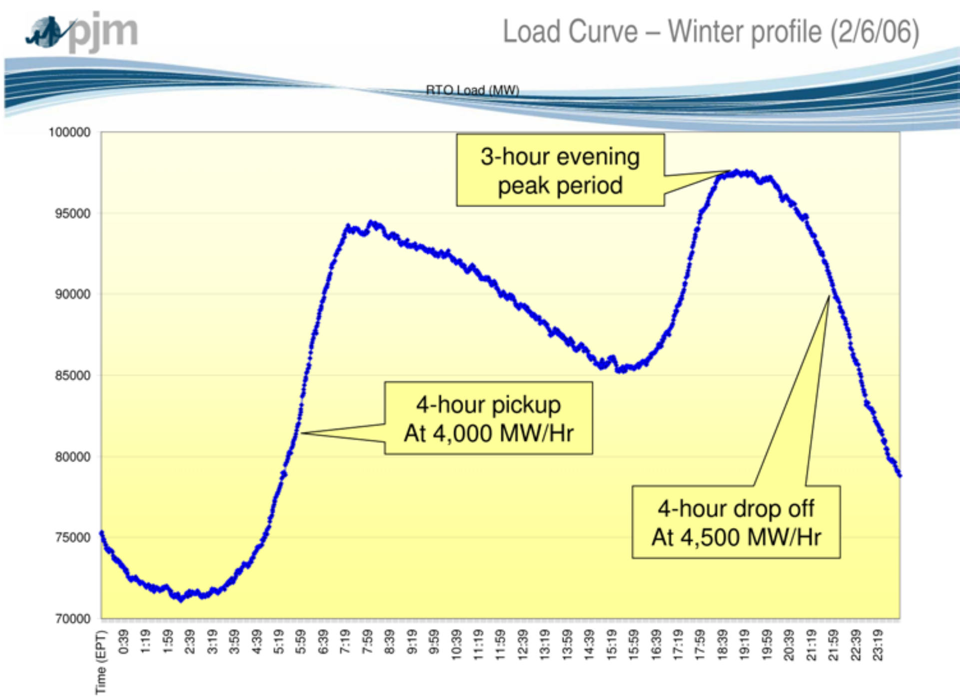


- The ACE signal is used by AGC to adjust governor setpoints at participating generators.
  - This restores frequency and tie-line flows to their scheduled values.
  - Economic dispatch operates on a slower timescale to re-establish the most economic generation schedule.

Daily load variation, demand response

- Loads follow a daily cycle.
- The aim of traditional demand response is to flatten the load curves.
- Open-loop schemes have been in place for around 50 years.
  - Examples include controlled water-heating and air-conditioning.



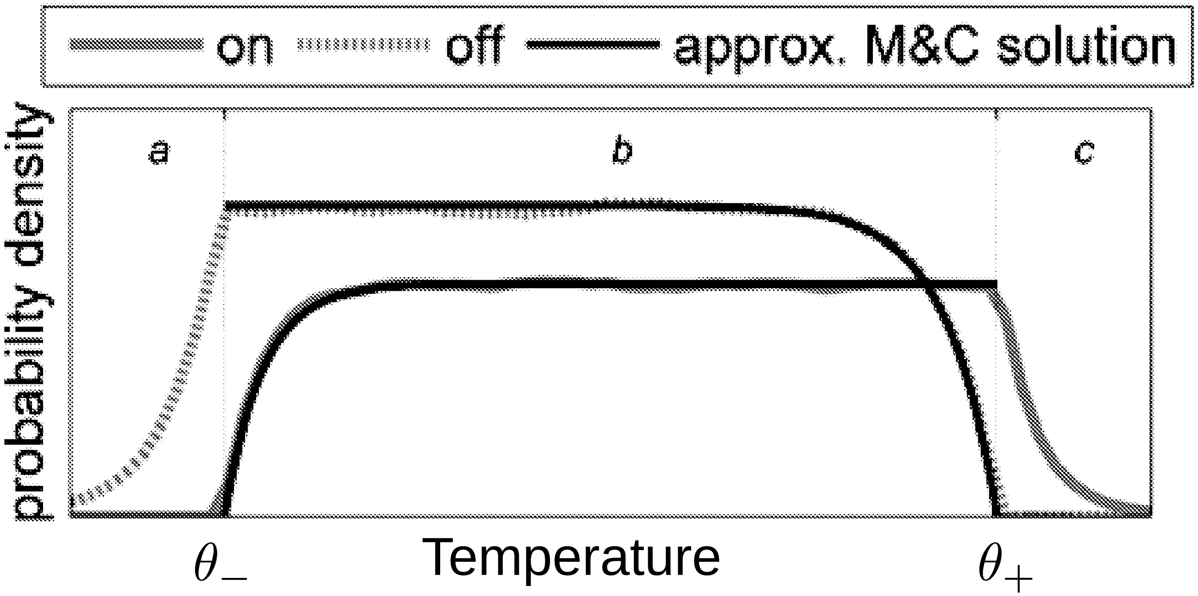


Responsive load control: air conditioning

- Temperature behavior modeled according to:

$$\theta_{n+1} = a\theta_n + (1-a)(\theta_{amb} - m_n K) + w_n$$

- Regions:
  - 'a' contains only loads in the off state.
  - 'b' contains loads in both the on and off state.
  - 'c' contains only loads in the on state.
- Steady-state temperature distribution for 10,000 cooling loads:

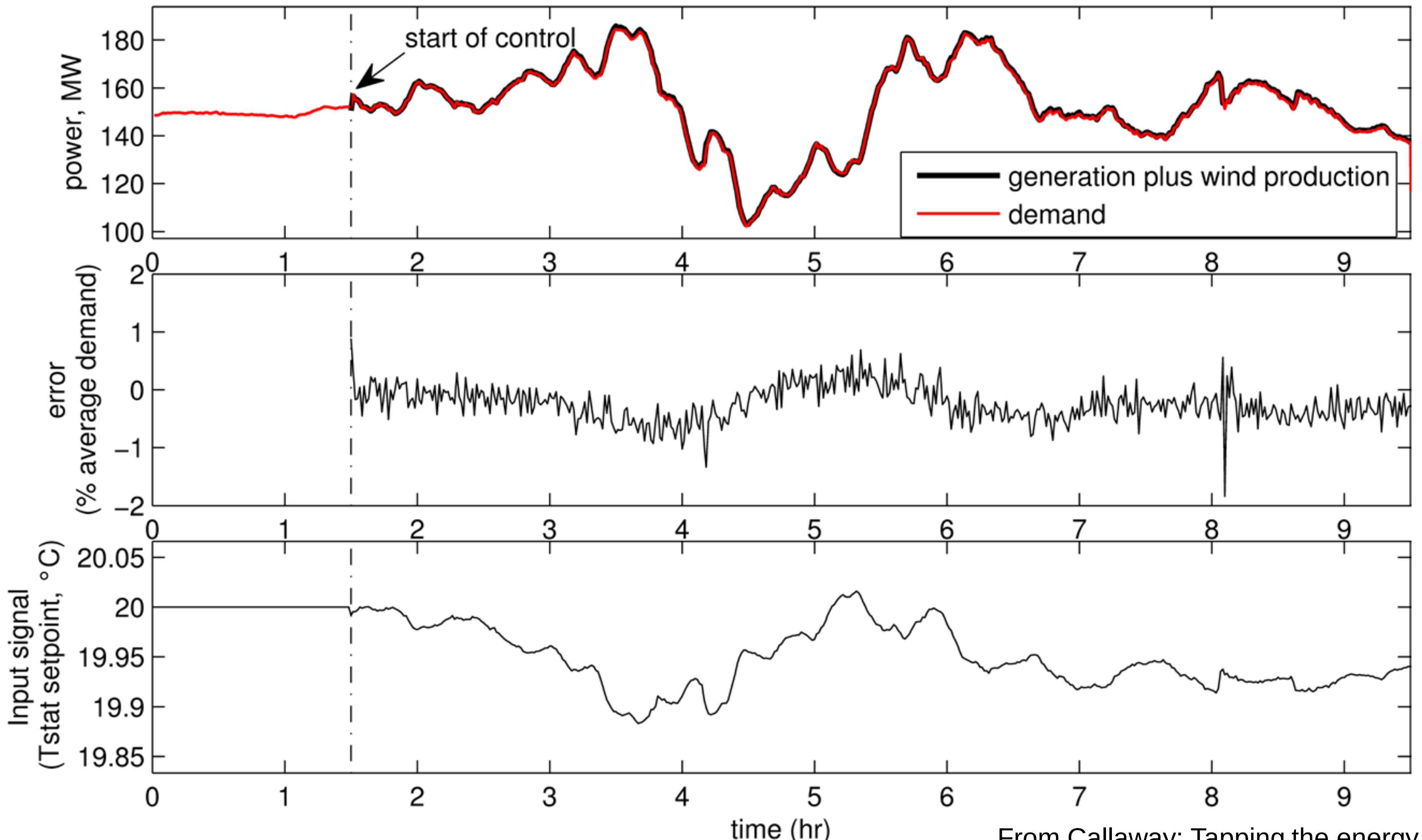


- **Control strategy:**
  - Increase load by lowering setpoint.
  - Decrease load by raising setpoint.

From Callaway: Tapping the energy storage potential in electric loads.

Load control: tracking wind variations

- Controlling 60,000 AC loads to follow wind variations.



From Callaway: Tapping the energy storage potential in electric loads.