Voltage Stability for Undergraduates

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Objective (from Ned Mohan)

- If our undergraduates were to take just *one* course in Power Systems before graduating, what should they learn about Voltage Stability in 1-3 lectures?

- Assume that they have already studied Transmission Line Characteristics, Power Flow, Transformers, HVDC and FACTS, and Synchronous Generators in their previous lectures.

Motivating Questions

- What is voltage stability?
- How is it related to angle (synchronous) stability?
- What are types of voltage instability and time frames?
- What are countermeasures?
- Is it static or dynamic phenomena?
- Can it be analyzed via static power flow simulation?
- What is role of active and reactive power transmission?

Approach

- Emphasize physical phenomena
- Emphasize dynamics
- Examples of actual events
- Relate to other power system topics, control engineering, power electronics, electromechanical energy conversion, math

An Important Industry Problem

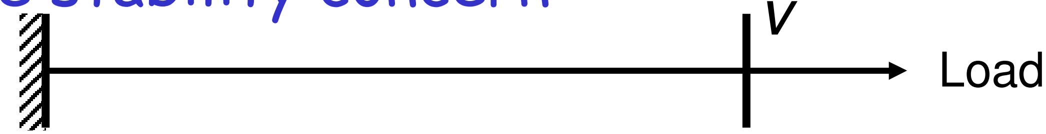
Voltage collapse is still the biggest single threat to the transmission system. It's what keeps me awake at night.

Phil Harris, PJM President and CEO, March 2004

PJM (**P**ennsylvania, New **J**ersey, **M**aryland — now expanded to the Midwest) is one of the world's largest power transmission organizations.

What is Voltage Stability (Instability)?

- Voltage stability is *load* stability
- Angle (synchronous) stability is *generator* stability
- Radial feed from large system to load — pure voltage stability concern



- Radial feed from remote generator to large system — pure rotor angle stability concern

- Angle and voltage stability phenomena interact:
  - e.g., rotor angle swings cause voltage swings
- Two time frames: short- and long-term stability
- Typically involves a load area of a power system, but can cascade to blackout larger area

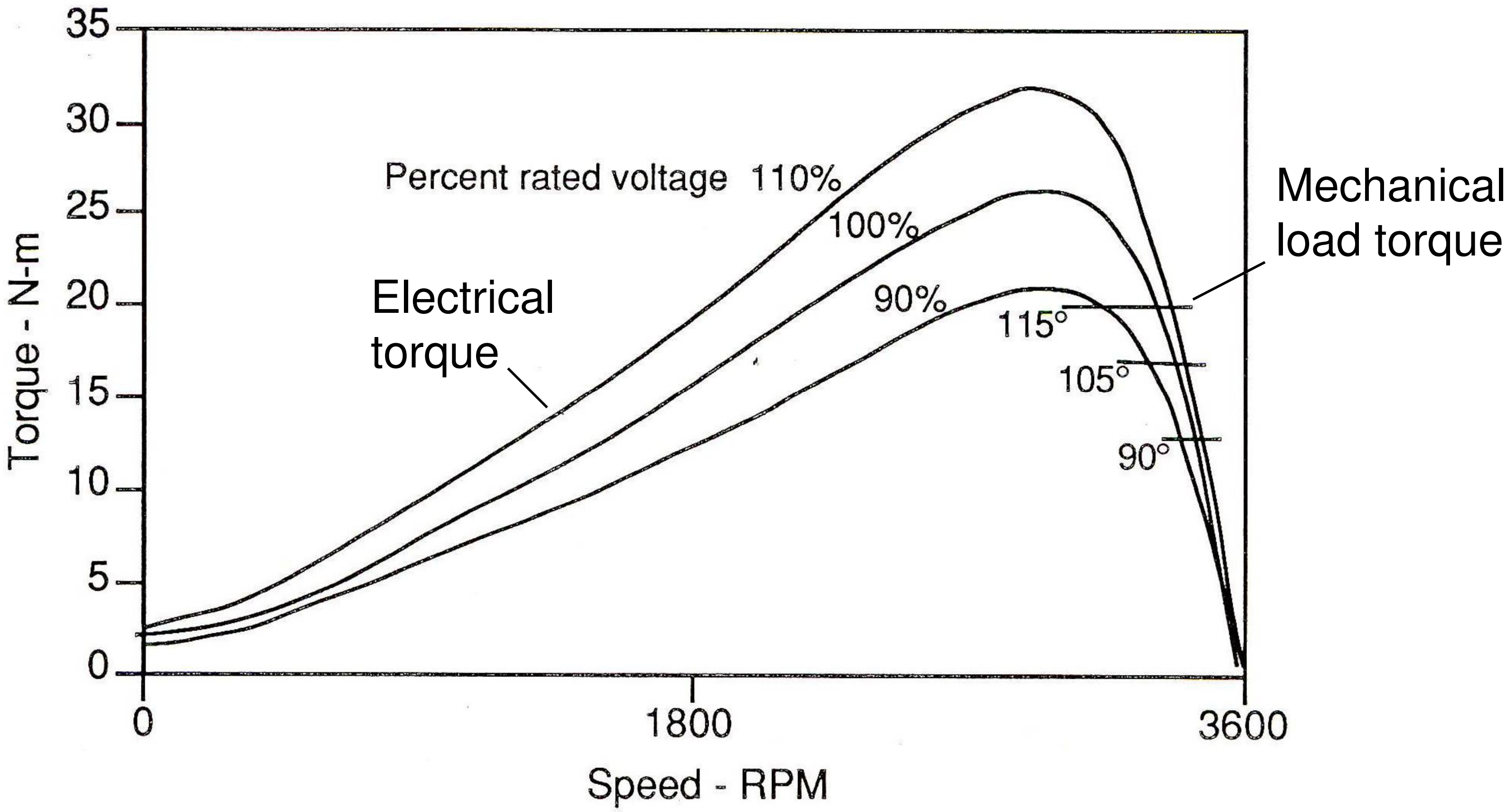
What Are Voltage Instability Mechanisms?

- Part of a power system is heavily loaded and then one or several important transmission lines trip:
  - Voltages will sag
  - Many loads are voltage sensitive and thus will reduce, which is *stabilizing*
  - If transmission outages are because of short circuits, induction motors will slow down and require more reactive power, and perhaps stall
- Regulating mechanisms try to restore power to meet demand at normal voltage
- Load restoration further stresses and overloads power system, resulting in voltage instability and collapse — voltage stability is load stability, related to load demand versus load supply capability

Short-Term Voltage Stability

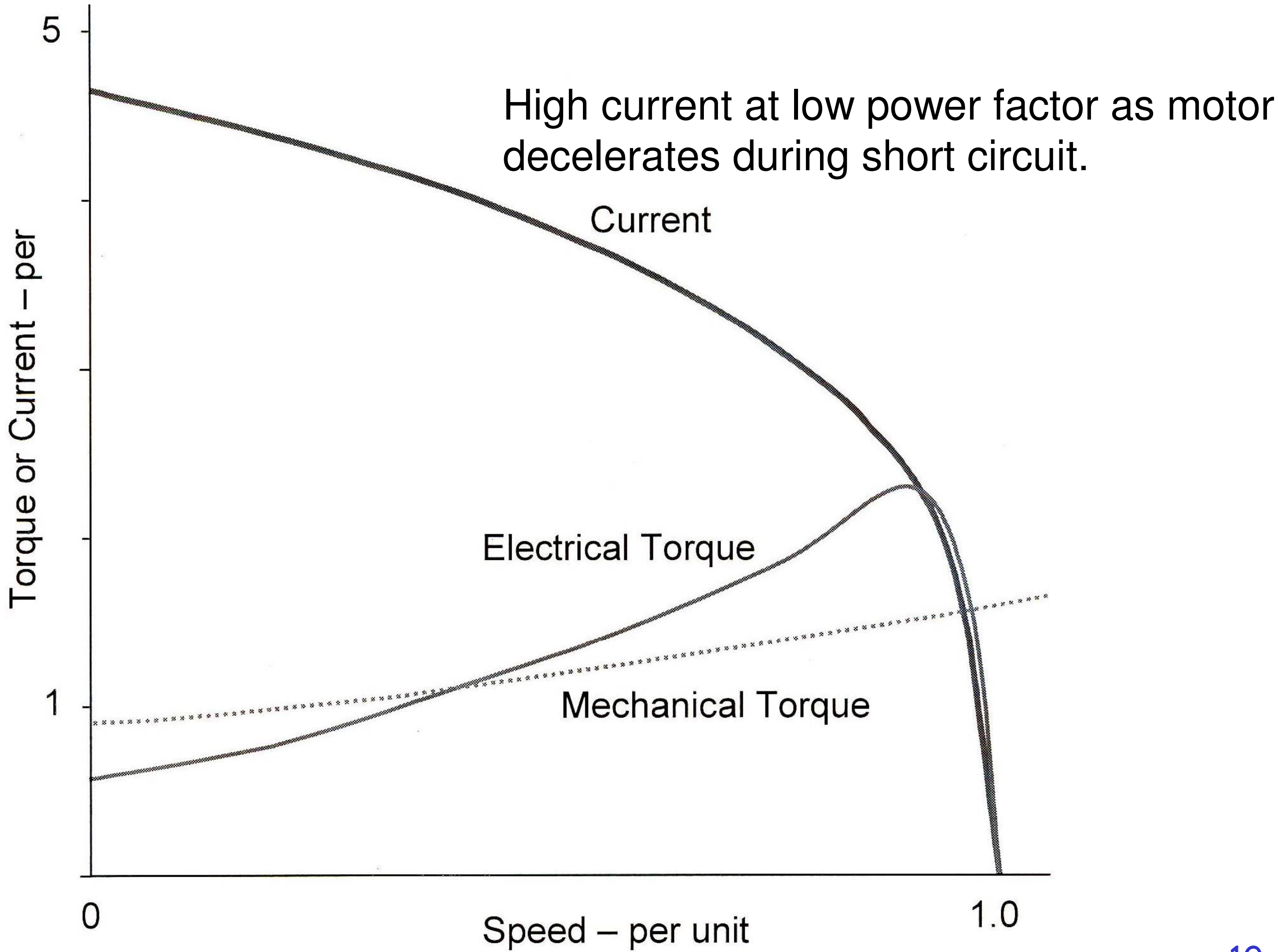
- Short term associated with induction motors, especially residential air conditioners and heat pumps:
  - Short circuits slow low-inertia air conditioner compressor motors, requiring high current similar to starting current
  - Motors may stall, preventing fast voltage recovery after short circuit clearing
  - Compressor motors are tripped only after overheating, 3–15 seconds after stalling
  - Cascading of motor stalling within few seconds
- Recall induction motor torque-speed curves
- Recall motor electrical torque is proportional to voltage squared
- How to model single-phase motors?

Induction Motor Torque-Speed Curves



Torque-speed curve for 5 HP, single-phase residential central air conditioner compressor motor. Compressor mechanical torque is nearly constant with respect to speed but increases with ambient temperature.
Source: GE

Induction Motor Torque/Current-Speed Curves



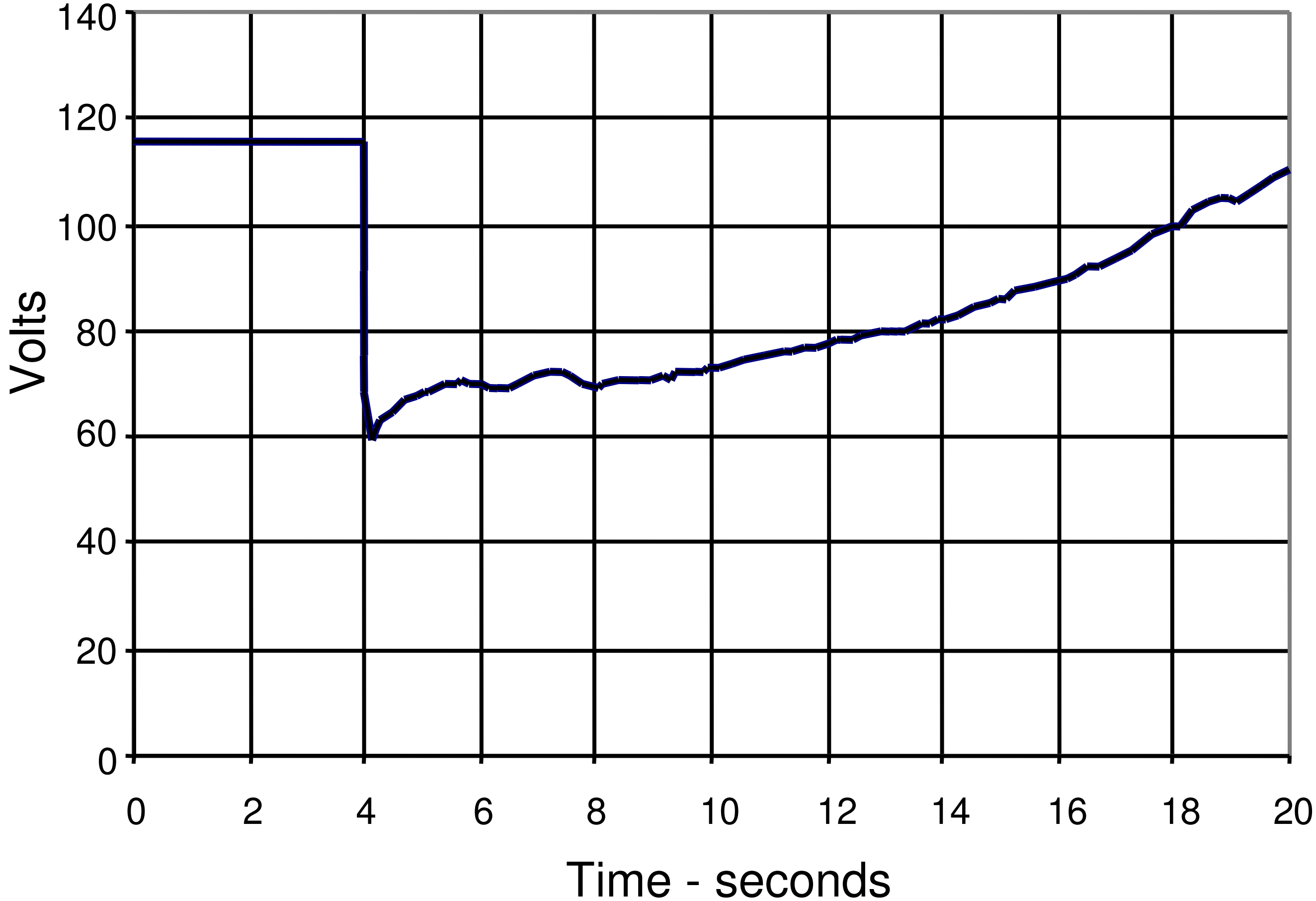
Short-Term Voltage Stability Example

- Phoenix, Arizona area on 29 July 1995
- Saturday afternoon, 112°F, 44°C
- 230-kV capacitor bank fault with delayed clearing:
  - Five 230-kV lines tripped
  - After 3 seconds, two 230/69-kV transformers tripped
- Stalling of air conditioning motors:
  - About 2100 MW of load lost
  - 20 seconds for voltage recovery
- High reactive power output from generators prevented collapse

- Generators *might* trip during severe events causing complete blackout (accidents waiting to happen, dozens of control and protection devices)

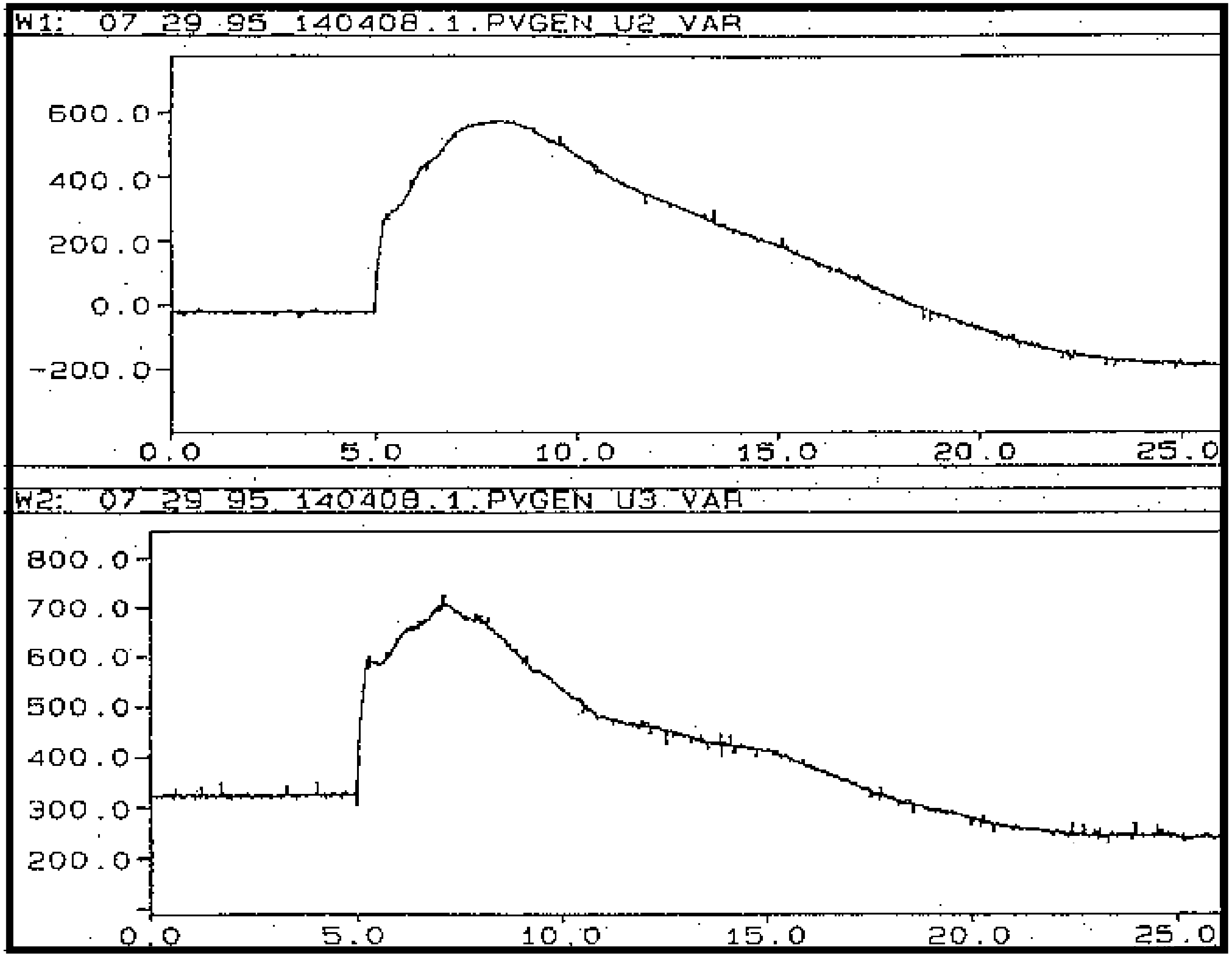
Short-Term Voltage Stability: Phoenix Area

Residential voltage: 58.4 volts RMS minimum, 15.8 seconds below threshold. A/C tripping by thermal protectors probably started around ten seconds.



Short-Term Voltage Stability: Phoenix Area

Palo Verde nuclear power plant reactive power outputs (megavar)



Long-Term Voltage Stability

- Long term typically associated with voltage regulation by tap changers close to loads:
  - Voltage regulation restores voltage-sensitive loads
  - Time frame of tens of seconds, minutes

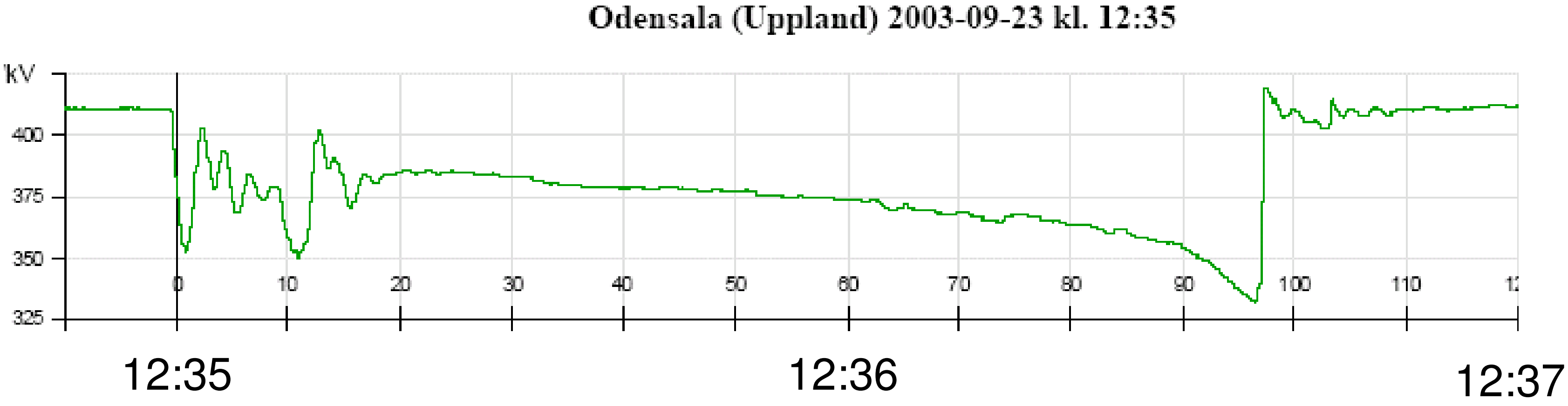
- Long-term instability also caused by constant energy loads such as thermostatically controlled heating load:
  - Loss of load diversity; more heaters must be on to satisfy energy demand
  - Time frame of many minutes

- Load restoration may cause generator field currents to exceed time-overload capability:
  - Overexcitation limiters on generator voltage regulators

Long-Term Voltage Instability: South Sweden/Denmark Blackout, 23 Sept. 2003

- In Sweden, two 400-kV lines and four nuclear units out for maintenance; system adjusted
- At 12:30, loss of a 1200 MW nuclear unit in southeastern Sweden
- At 12:35, double bus-bar fault in southwestern Sweden causing loss of two 900 MW nuclear units:
  - N-3 event
- Voltage instability with separation 97 seconds later:
  - Blackout of Southern Sweden and eastern Denmark (Malmö, Copenhagen)
  - 4700 MW load lost in Sweden, 1850 MW in Denmark

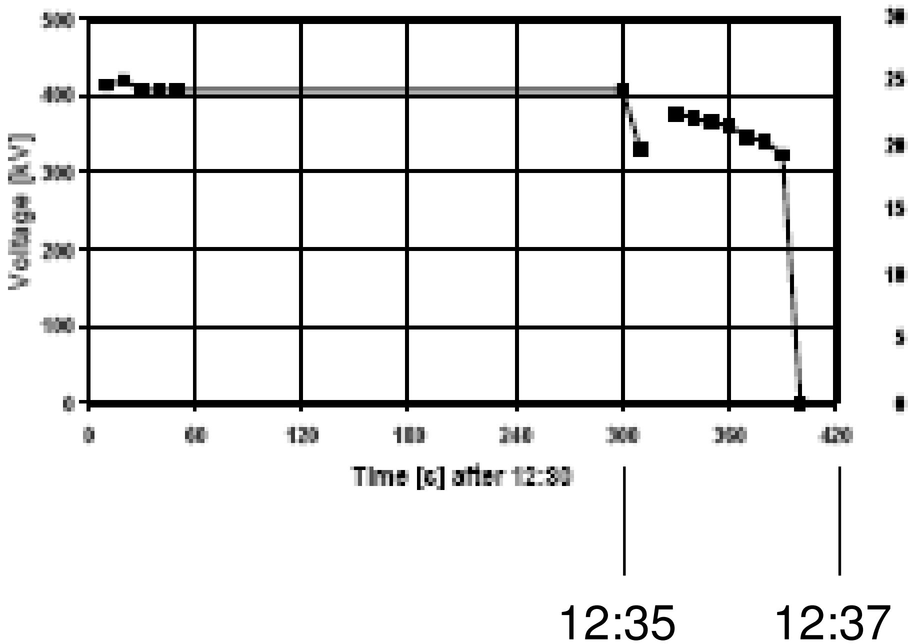
South Sweden/Denmark Blackout, 23 Sept. 2003



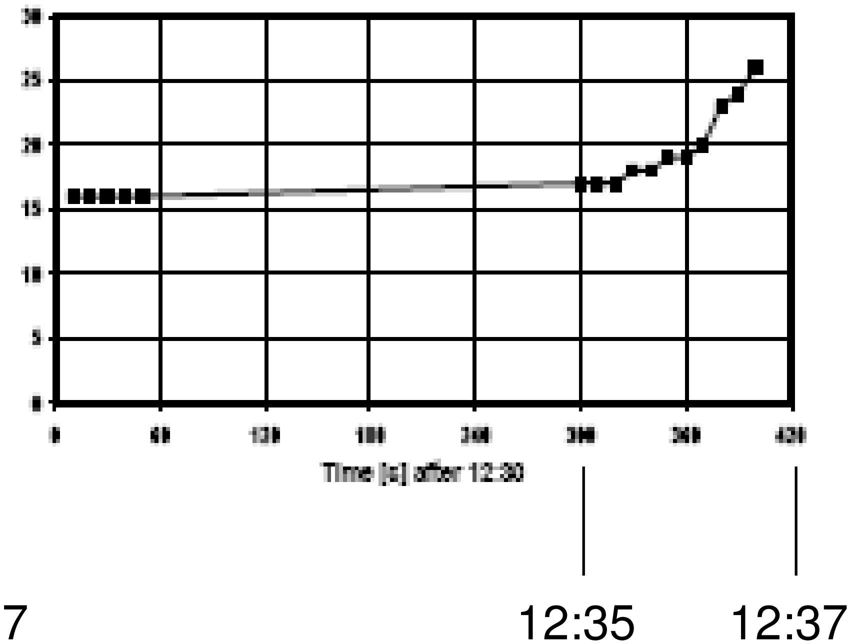
Odensala on stable side following separation at 97 seconds

South Sweden/Denmark Blackout, 400/130-kV Transformer Tap Changing at Simpevarp

400-kV Side Voltage



Tap Changer Position

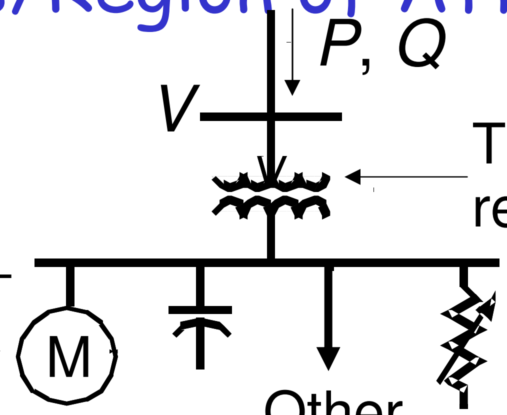


Source: Gajiĉ, Karlsson, Kockott, "Advanced OLTC Control to Counteract Power System Voltage Instability," ABB web site.

Voltage Stability Dynamics

- Voltage stability involves large disturbance, non-linear, discontinuous dynamics
- Load restoration concepts understood from first-order differential equations (*highly* oversimplified)
- Stabilizing actions must be timely to ensure *Region of Attraction* to post-disturbance operating point (equilibrium point)
- State variables are slip (s), turns ratio (n), and load conduction (G)

Load Dynamics/Region of Attraction



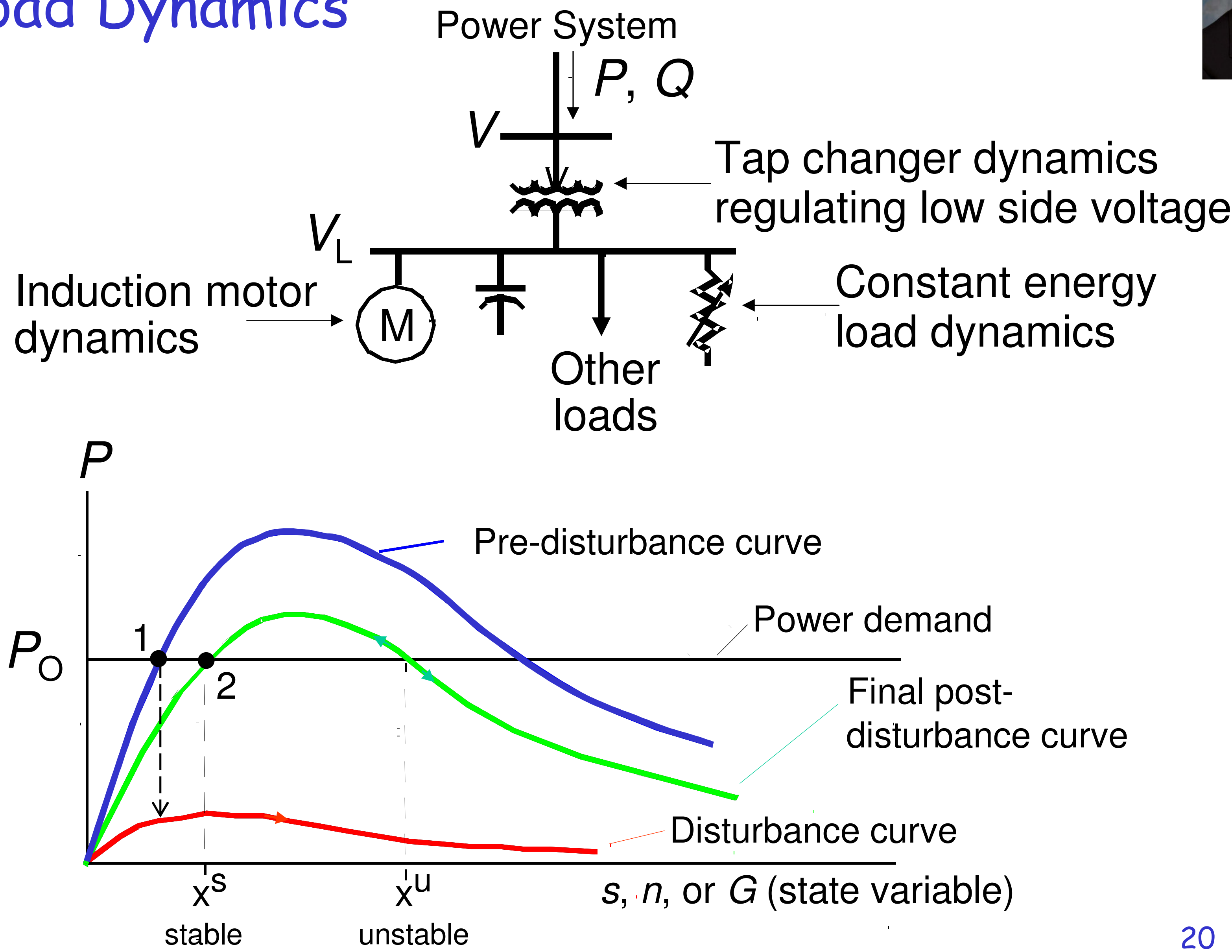
Load dynamics are basically first order

$$2H\omega\frac{ds}{dt} = P_o - P_e$$ Motor

$$T_T\frac{dn}{dt} = P_o - P_o\left[\frac{V_L}{V_o}\right]^{\alpha}$$ Tap changer

$$T_E\frac{dG}{dt} = P_o - G_o\left[\frac{V_L}{V_o}\right]^{2}$$ Constant energy

Load Dynamics



Exercise

Integrate both sides of one or more of the differential equations and draw block diagram using integrators. One block is the power system with state variable as input and electrical power as output. Explain what happens for a disturbance in the power system (short circuit for motor load), including how equilibrium is reached. What happens if tap changer limits are reached?

Compare previous figure with equal area diagram for angle stability. What must balance for equilibrium?

The block diagram is similar to how an analog computer is programmed, but also applies to numerical integration used nowadays for time domain simulation.

Three Aspects of Voltage Stability

1. Load as seen from the bulk power system — load restoration dynamics:
   - Motors, tap changers, constant energy/thermostats

2. Voltage control at generators and in network:
   - Generator AVRs
   - Switched capacitor banks, SVCs, STATCOMS

3. Network ability to transfer power from point of production to point of consumption:
   - Voltage drop mainly due to reactive power transfer
   - Reactive power loss (I^2X) mainly due to active power transfer

Voltage Instability Countermeasures

- Engineers must *economically* ensure reliable power delivery. Economical solutions often control based.
- Basic strategy: Apply shunt capacitor banks, mainly in distribution and load area transmission substations to minimize reactive power transmission, allowing automatically controlled reactive power reserve at generators.
  - Design and operate transmission network for high, flat voltage profile to minimize I^2X losses.

Further Voltage Instability Countermeasures

- Switched shunt capacitor banks:
  - Local or wide-area control
- Series capacitor banks
- Static var compensators or STATCOMs for short-term voltage stability:
  - Large transmission devices versus multiple distribution devices?
- Transmission-side voltage control at generators similar to SVC
- Tap changer blocking, reverse control, or repositioning for upstream-side voltage sag
- Load shedding:
  - Local undervoltage or wide-area

Voltage Stability Definitions (IEEE/CIGRE)

- *Voltage stability* is the ability of a power system to maintain *steady* voltages after a disturbance. Must maintain or restore *equilibrium* between *connected* load, and load supply from the power system. Instability is progressive fall or rise of voltages at some buses:
  - Parallel definitions for angle and frequency stability. What must be in equilibrium?
  - The driving force for voltage instability is usually the *loads*. After a disturbance, load power restoration is attempted by motor slip adjustment, tap changing, and thermostats.
  - Short-term, long-term voltage instability
  - Instability is runaway, positive feedback phenomena

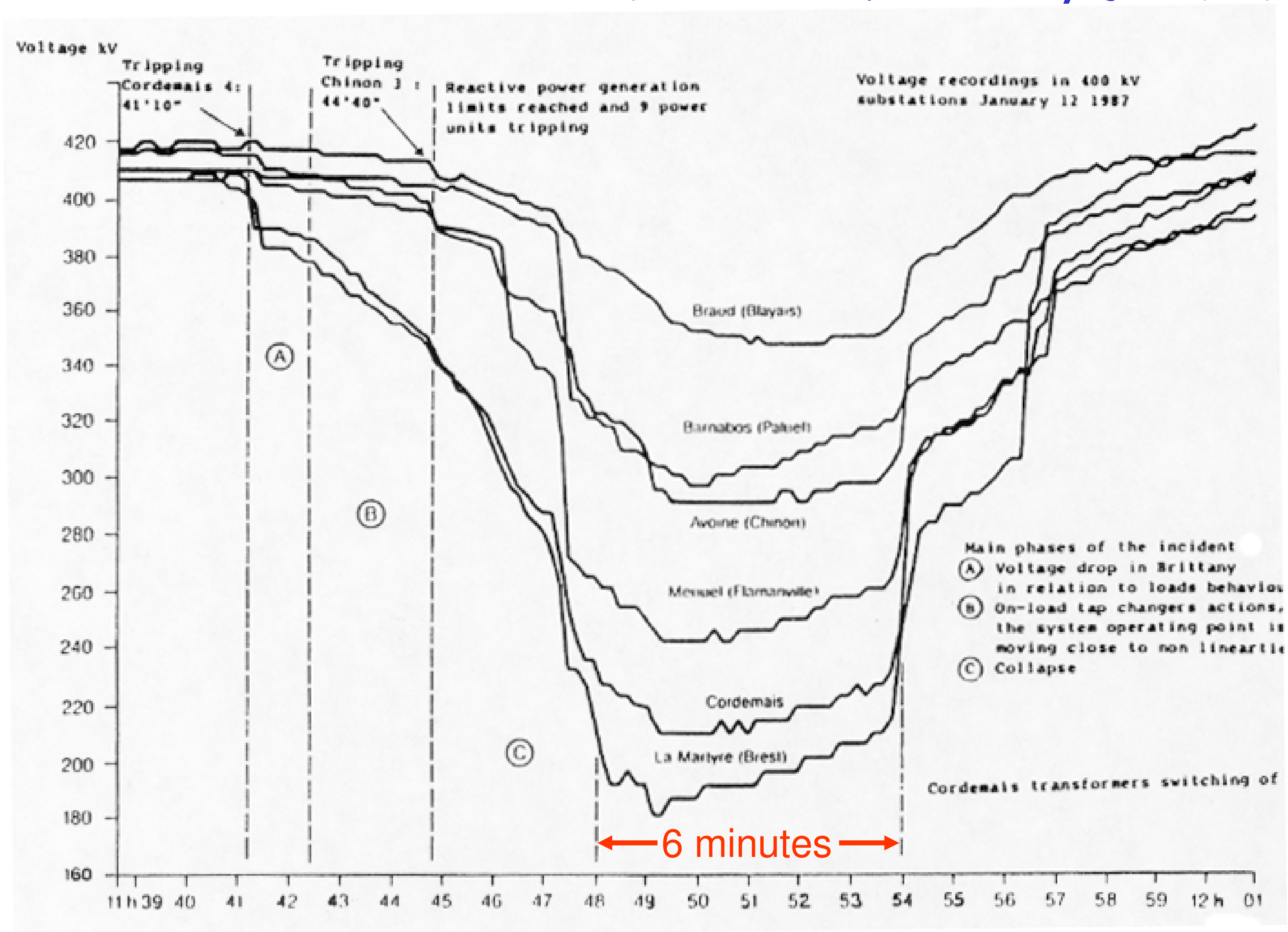
Voltage Stability Definitions

- A power system at an operating state is *voltage stable* if following a disturbance, voltages near loads approach stable post-disturbance equilibrium values:
  - Within region of attraction of post-disturbance equilibrium after switching and control actions
  - Stability may be due to destabilizing controls reaching limits, or other actions such as load disconnection
  - Voltage instability may cause voltage collapse or abnormally high voltages

Voltage Stability Definitions

- A power system undergoes *voltage collapse* if post-disturbance equilibrium voltages are below acceptable limits:
  - Voltage collapse may be total (blackout) or partial
  - Voltage collapse may be due to voltage or angle instability
  - Inadequate voltage support may cause angle instability
- Underside of *P-V* curve is partial voltage collapse with *power uncontrollability*
  - Adding load reduces voltage (normal), but reduces total power (abnormal)
  - Stable operation possible with voltage-sensitive loads
- Distinguish between load power at nominal voltage and load power consumed at actual voltage

Stable or Unstable? Western France, Jan. 1987



Voltage Security, Control Centers

- Voltage *security* quantified by margins or indices

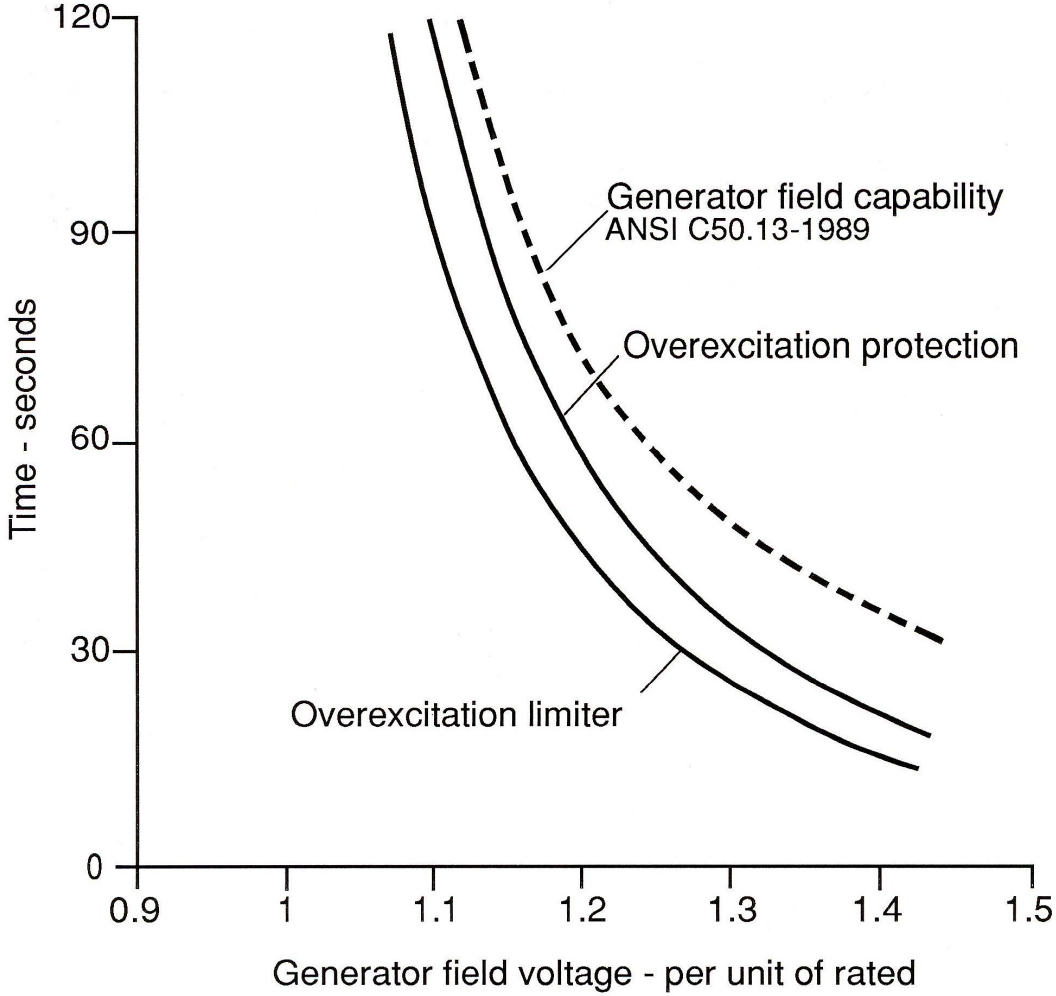
- Candidate margins or indices?
  - Voltage monitoring sufficient?
  - What else should be monitored? Answer: reactive power reserves

- Voltage secure for a specified direction of stress when the margin for credible contingencies is larger than reliability criteria margin:
  - Example: 5% power margin determined by on-line, close to real-time simulation

Generator Time-Overload Capability

- Field circuit overload usually occurs first, but armature current overload also important:
  - Field current overload caused by outages and load restoration is key mechanism of long-term voltage instability
  - Field current (generator excitation) closely related to reactive power output. But armature current overload also usually reduced by field current reduction (reactive power rather than active power typically reduced).
- Generator automatic voltage regulator includes limiter of field current time-overload:
  - Time frame is tens of seconds
  - Limiter set inside time-overload capability required by standards

Generator Time-Overload Capability



Similar curve for armature capability.

Voltage Stability Simulation

- Dynamic simulation essential for short-term voltage stability (as for angle stability):
  - Dynamic models for motor load, generators, SVCs
- Dynamic simulation also valuable for long-term voltage stability:
  - Coordination of controls
  - Greater accuracy and insight
- Power flow program static simulation for approximate analysis and screening:
  - *P-V* and *V-Q* curves widely used

P-V, *S-V* Curves

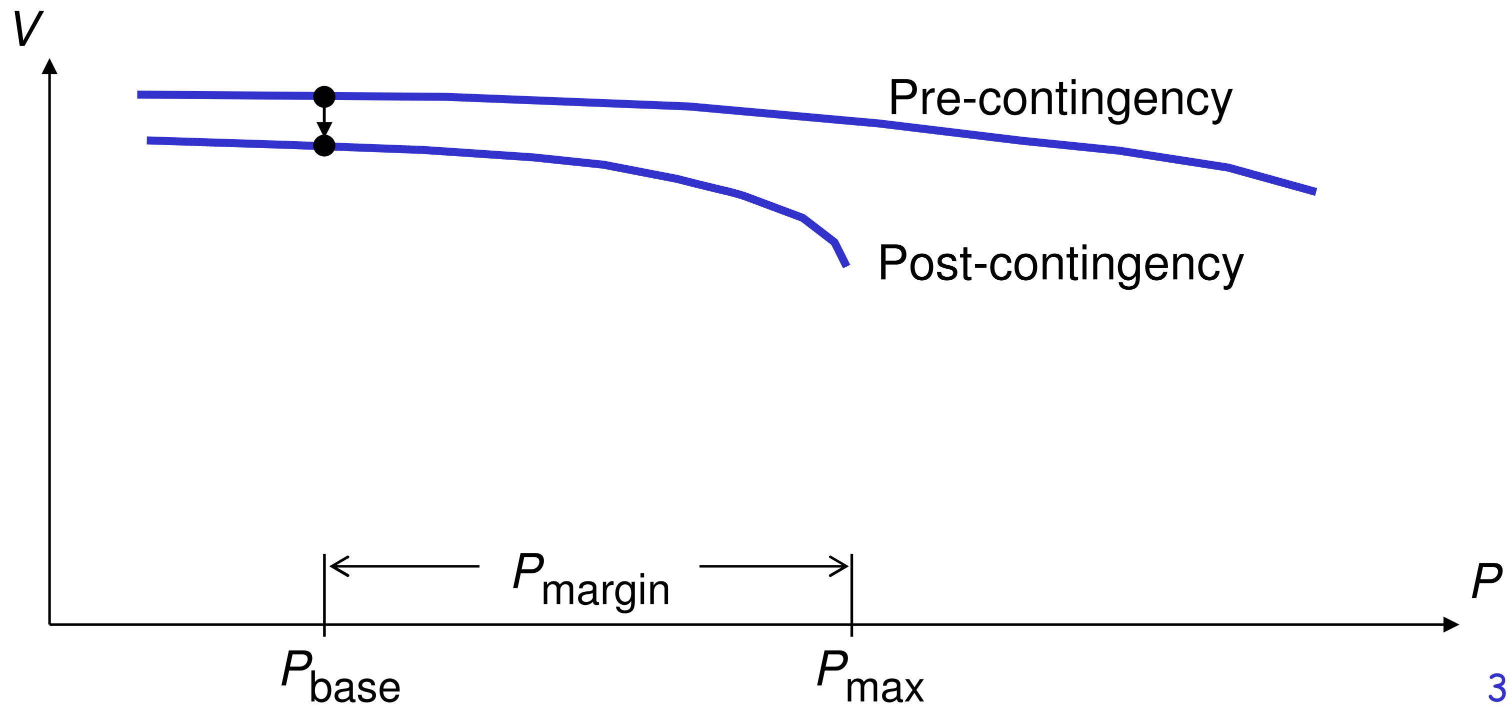
- Voltage stability is dynamic phenomena:
  - Automation of individual power flow cases.
- *P-V* curve: power import increase to load area by decrease in load area generation
- *S-V* curve: proportional increase in load at area busses at constant power factor
- Generation redispatch required as load or import is substantially increased
- Possible power flow convergence problems near "nose":
  - Avoided by dynamic simulation of load ramp

P-V Curves: Two Concepts (Van Cutsem)

- Post-disturbance loadability
- Secure operating point

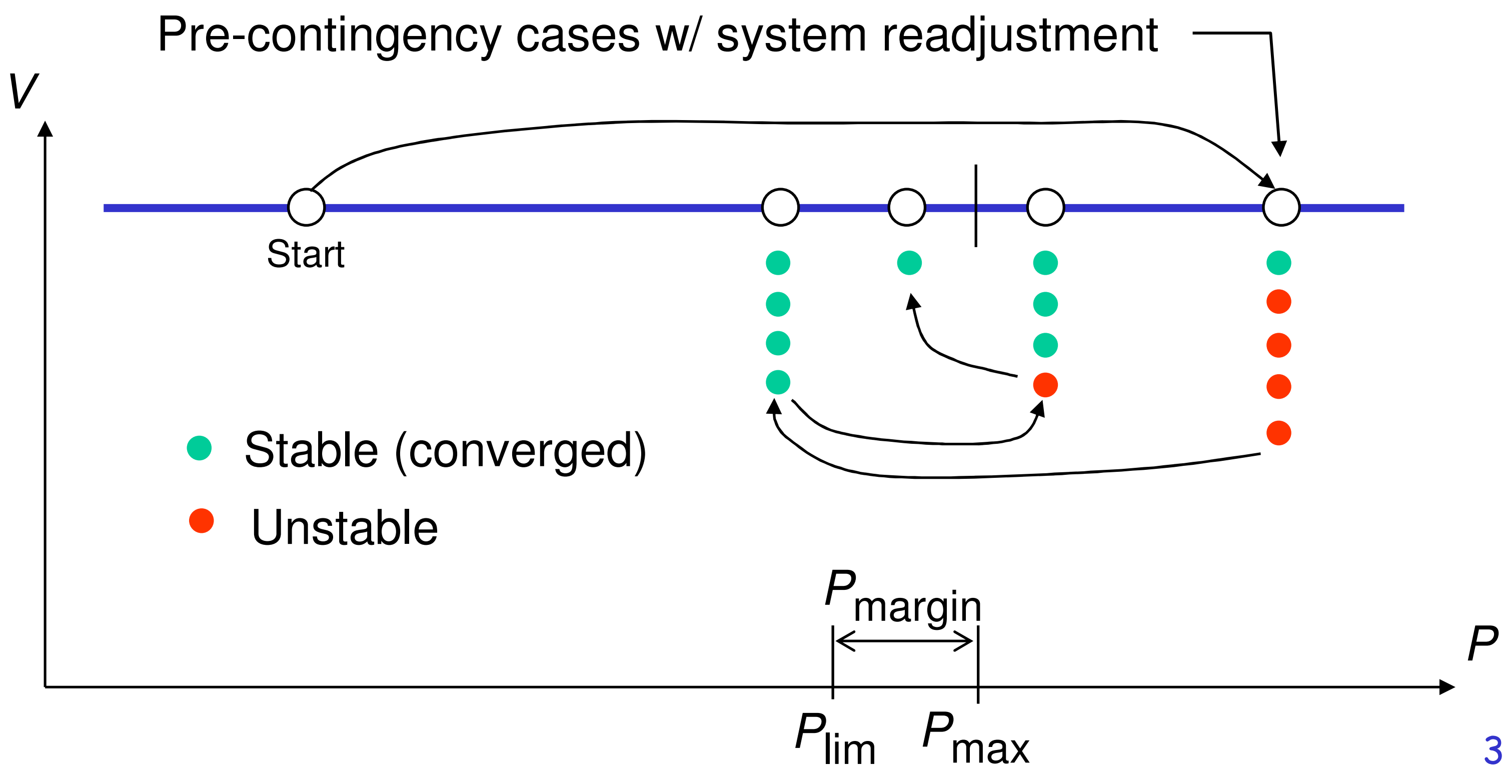
P-V (nose) Curve: Post-Disturbance Loadability

- Test post-disturbance robustness and margin from operating point or base case:
  - Must iterate to find transfer limit
  - Contingencies simulated without system adjustment



P-V Curve: Secure Operating Limit

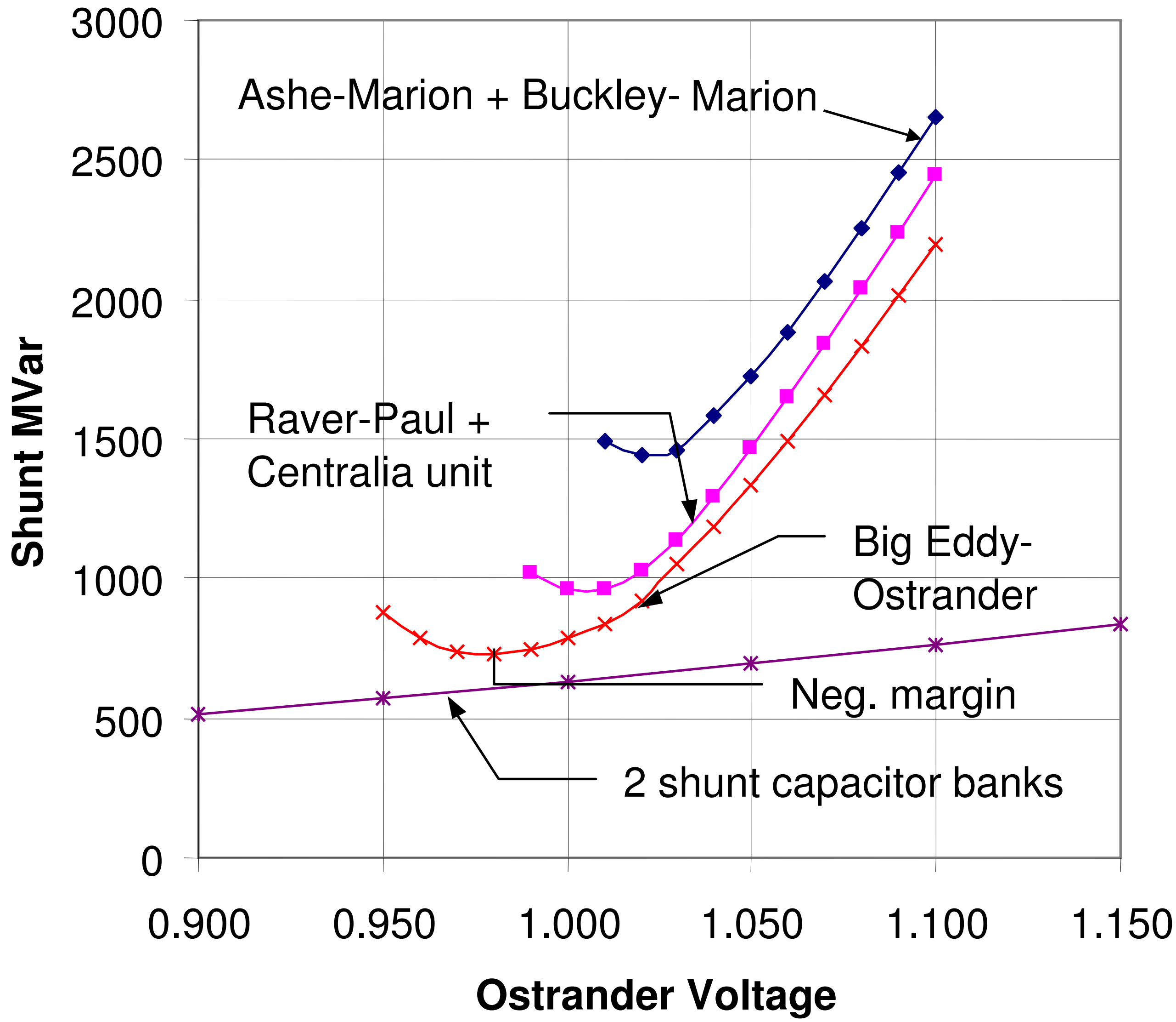
- Binary search most efficient method:
  - Can use dynamic simulation for greater accuracy



Q-V, V-Q Curves

- *x-y*, not *y-x* terminology. *x* is independent variable.
- *Q-V* curve: proportional increase in reactive power load at area busses. Similar to *P-V* curve methods.
  - Reactive power increase tests area voltage stability
  - Area busses stressed uniformly, weak points identified
  - Generation redispatch not necessary
- *V-Q* curve: set of scheduled voltages at a single bus (fictitious PV/synchronous condenser bus):
  - *V* is independent (*x*) variable, *Q* injection is dependent
  - Tests bus strength and helps determine reactive power compensation need. Robust convergence.
  - Single bus test may be unrealistic
  - Generation redispatch not necessary

Typical *V-Q* Curve



The three outages are “unstable” because the system curves don’t cross the available reactive power curve of the 2 shunt capacitor banks.

Exercises: *P-V* Curves of Radial System

For *P-V* curves, describe relation between nose of curve and maximum loadability. Can instability occur on upper side of curve? Can operation on underside be stable? (Answers: yes, yes.)

Consider Examples 2-2 and 2-3, and Section 2-7 in my book.

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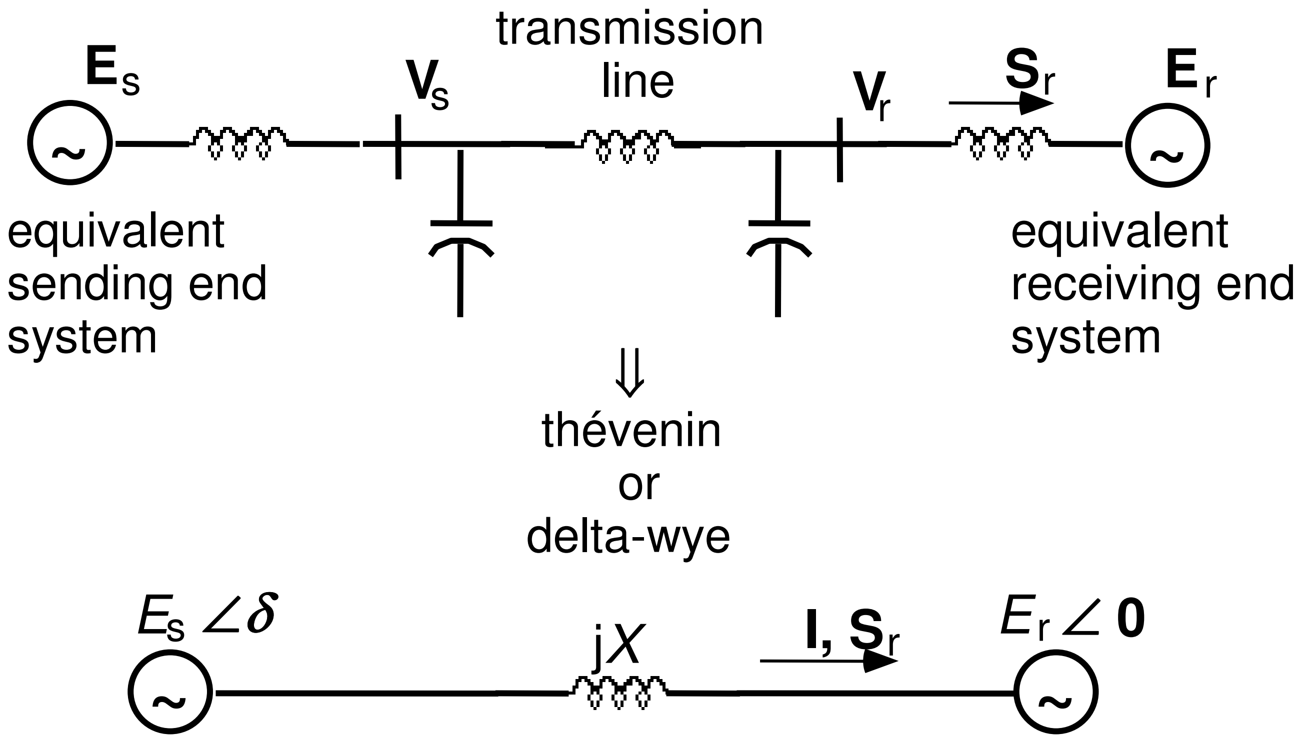
12. IEEE/PES Task Force on Recent Blackout Experience, Mitigation, and Role of New Technologies (Power System Dynamic Performance Committee), *Blackout Experiences and Lessons, Best Practices for System Dynamic Performance, and Role of New Technologies*, IEEE Special Publication 07TP190, 2007.
13. IEEE/PES 2008 General Meeting panel session on load modeling.

Extras

Basic Power Transmission



- δ is "load angle"
- Draw phasor diagram

Basic Power Transmission

$$S_r = P_r + jQ_r = E_r I^*$$

$$= E_r \left[\frac{E_s \cos\delta + jE_s \sin\delta}{jX} \right]$$

$$= \frac{E_s E_r}{X} \sin\delta + j \frac{E_s E_r \cos\delta - E_r^2}{X}$$

$$P_r = P_s = \frac{E_s E_r}{X} \sin\delta$$

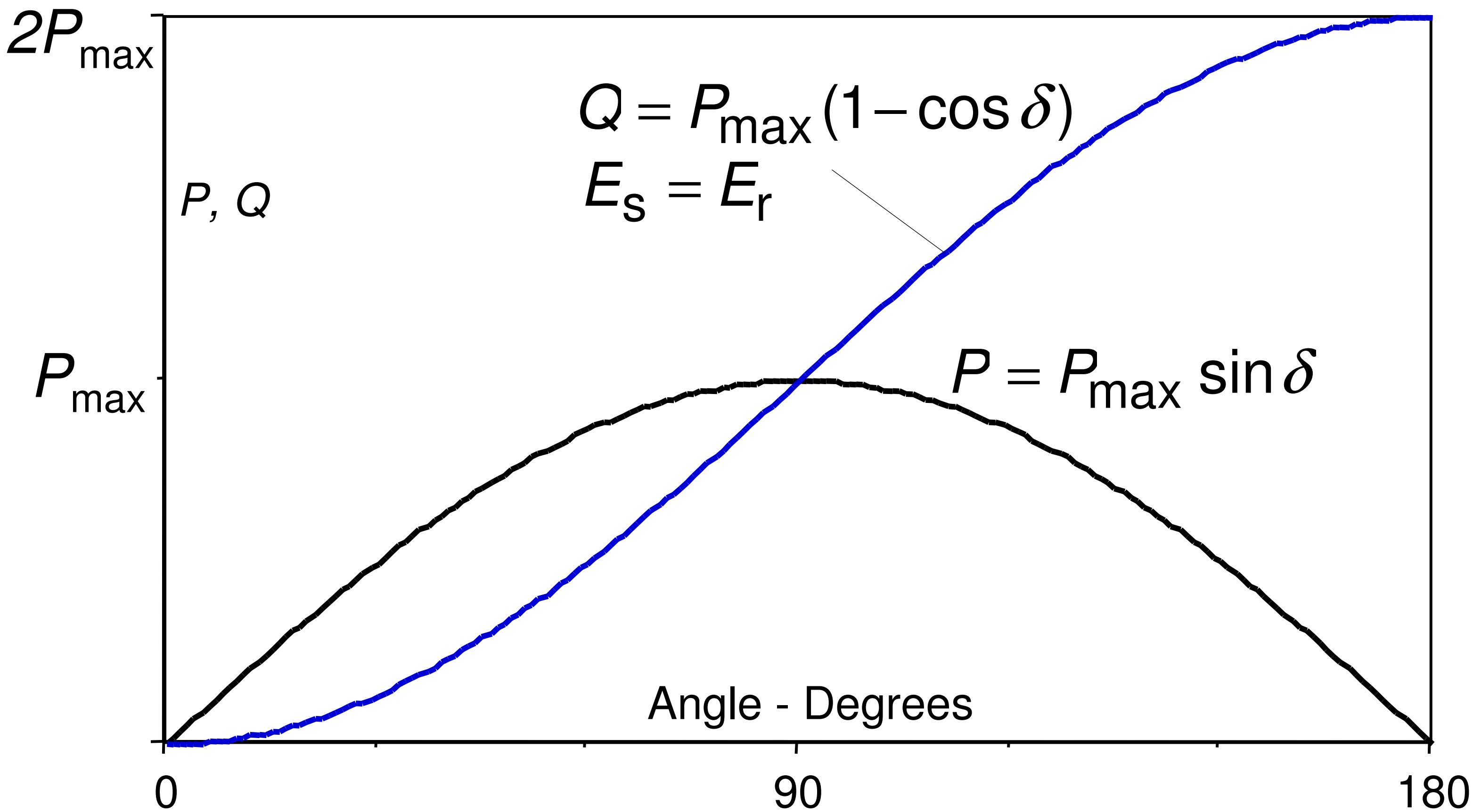
$$Q_r = \frac{E_s E_r \cos\delta - E_r^2}{X}$$

$$Q_s = \frac{E_s^2 - E_s E_r \cos\delta}{X}$$

Basic Power Transmission

$$P = \frac{E_s E_r}{X} \sin\delta = P_{max} \sin\delta$$

$P_{max} \propto E^2$ Maximum power at 90°



Basic Power Transmission

$$P = P_{max} \sin\delta \cong P_{max}\delta \qquad \delta < 30°$$

Real or active power transfer depends mainly on load angle.

Steady-state angle across a transmission path between "voltage secure" busses normally less than 45°.

Basic Reactive Power Transmission

$$Q_r = \frac{V_s V_r \cos\delta - V_r^2}{X} \cong \frac{V_r(V_s - V_r)}{X}$$

$$Q_s = \frac{V_s^2 - V_s V_r \cos\delta}{X} \cong \frac{V_s(V_s - V_r)}{X}$$

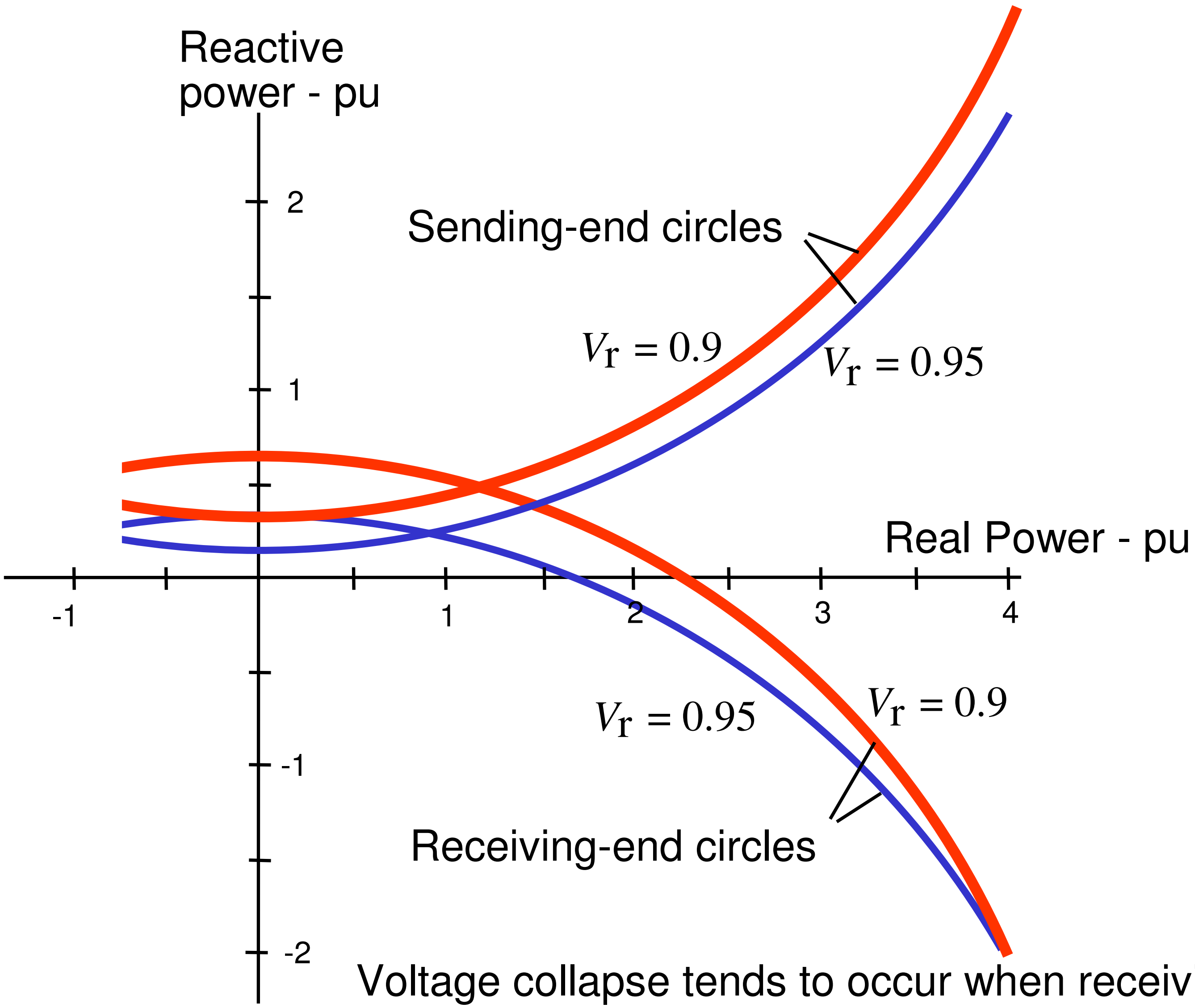
Reactive power transfer depends mainly on voltage magnitudes and flows from highest voltage to lowest voltage.

- P and δ are closely coupled
- Q and V are closely coupled
- Can reactive power be transferred long distances?
- What happens to Q_s and Q_r at large angles?

Basic Reactive Power Transmission

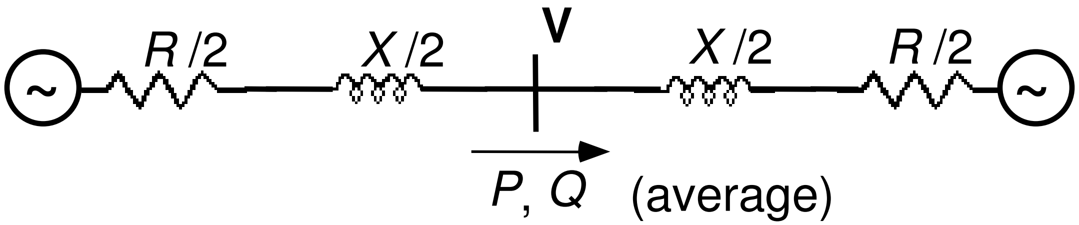
- Power circle diagrams show reactive power transmission capability (pages 8–10 of my book)
- Sketch shows real and reactive power transfer of a lossless 500-kV line:
  - 161 km line, π model
  - V_s = 1 pu
  - P, Q in per unit of *surge impedance loading*
- Surge impedance loading or natural loading is MW loading where reactive power loss (I^2X) equals reactive power generation V^2B:
  - Flat voltage profile and no reactive power injections at terminals if terminal voltages are equal

Basic Reactive Power Transmission



Voltage collapse tends to occur when receiving end must supply reactive power to network.

Transmission Losses



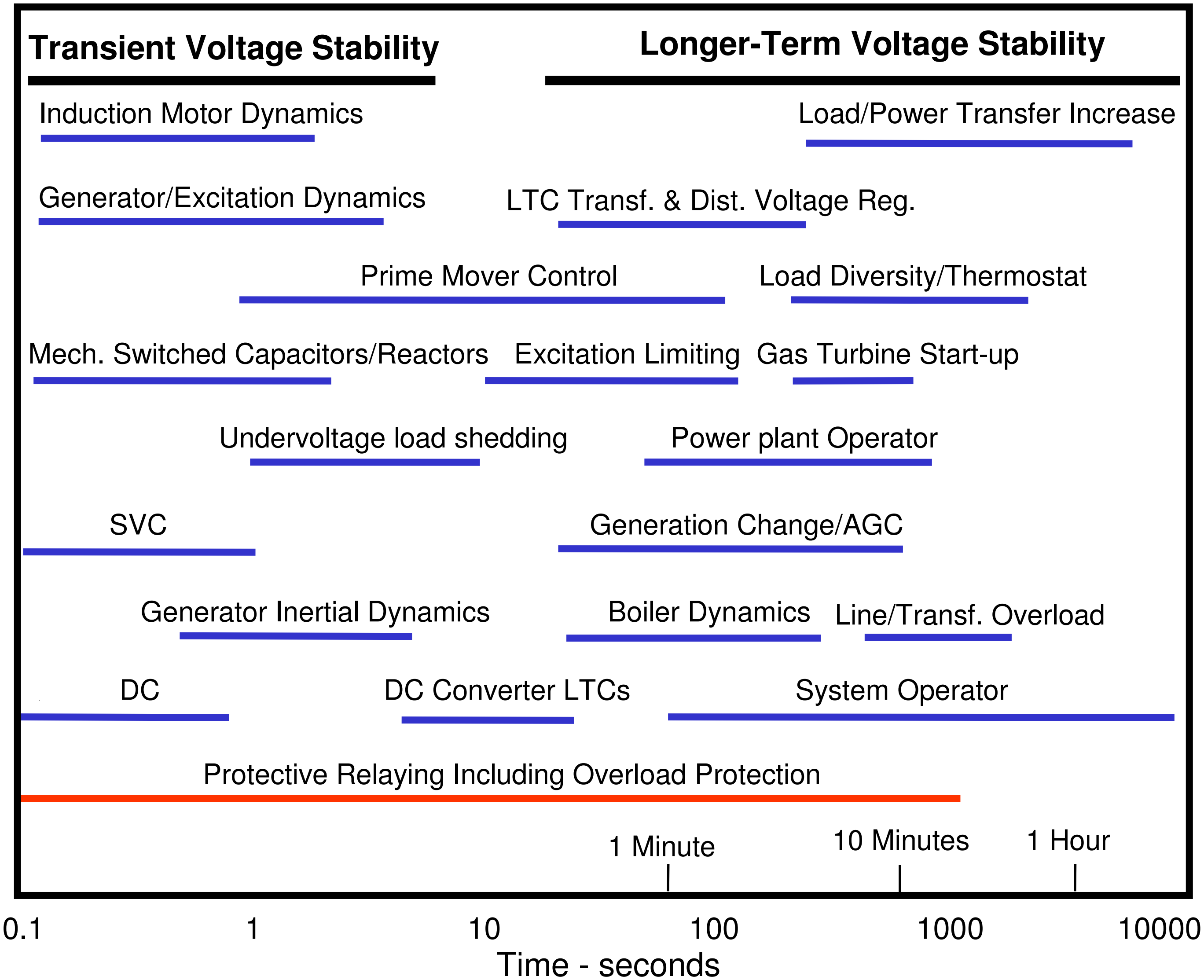
$$I^2 = \left[\frac{P + jQ}{V}\right]\left[\frac{P - jQ}{V}\right] = \frac{P^2 + Q^2}{V^2}$$

$$P_{loss} = I^2 R = \frac{P^2 + Q^2}{V^2} R$$

$$Q_{loss} = I^2 X = \frac{P^2 + Q^2}{V^2} X$$

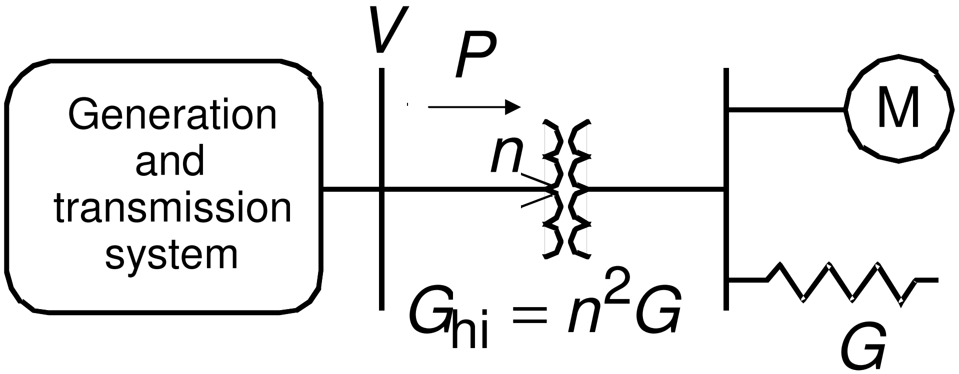
- Effect of reducing Q transfer?
- Effect of voltage?
- Real and reactive power losses dominated by *P* transfer

Voltage Instability Phenomena



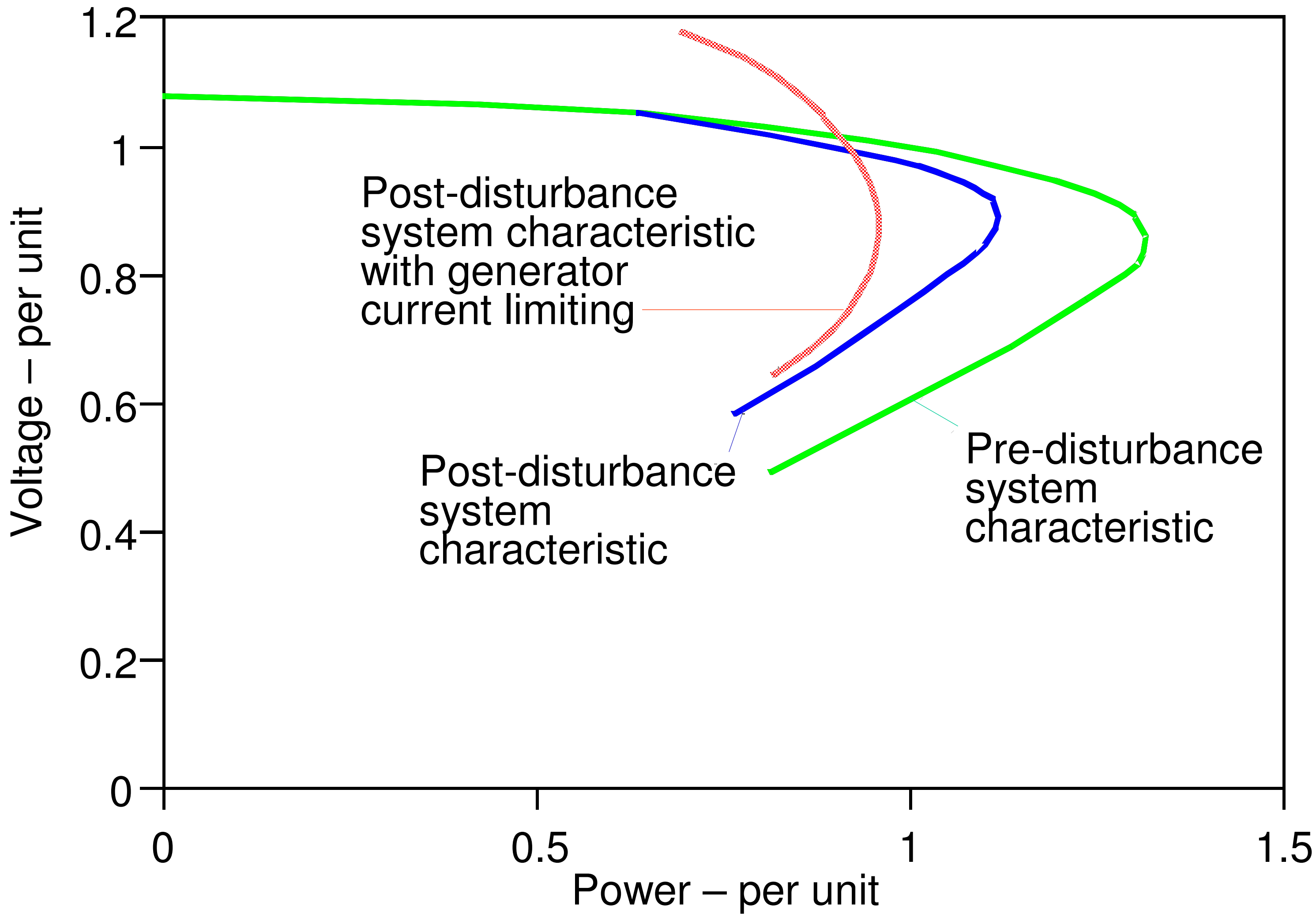
Voltage Stability — Load Characteristics

Conceptual Model

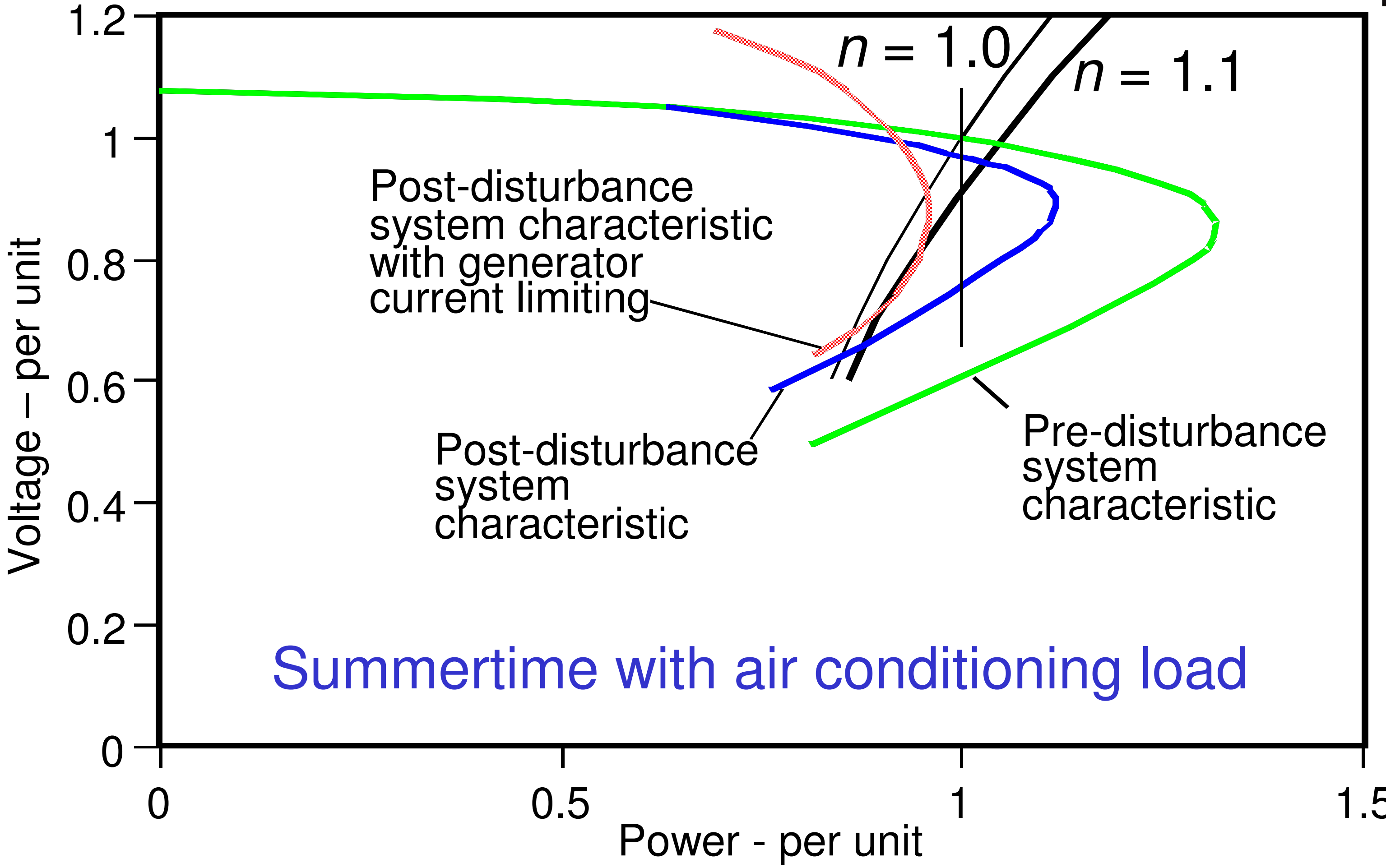


n = 1 initially. Limit is n = 1.1.

Voltage Stability—System Characteristics

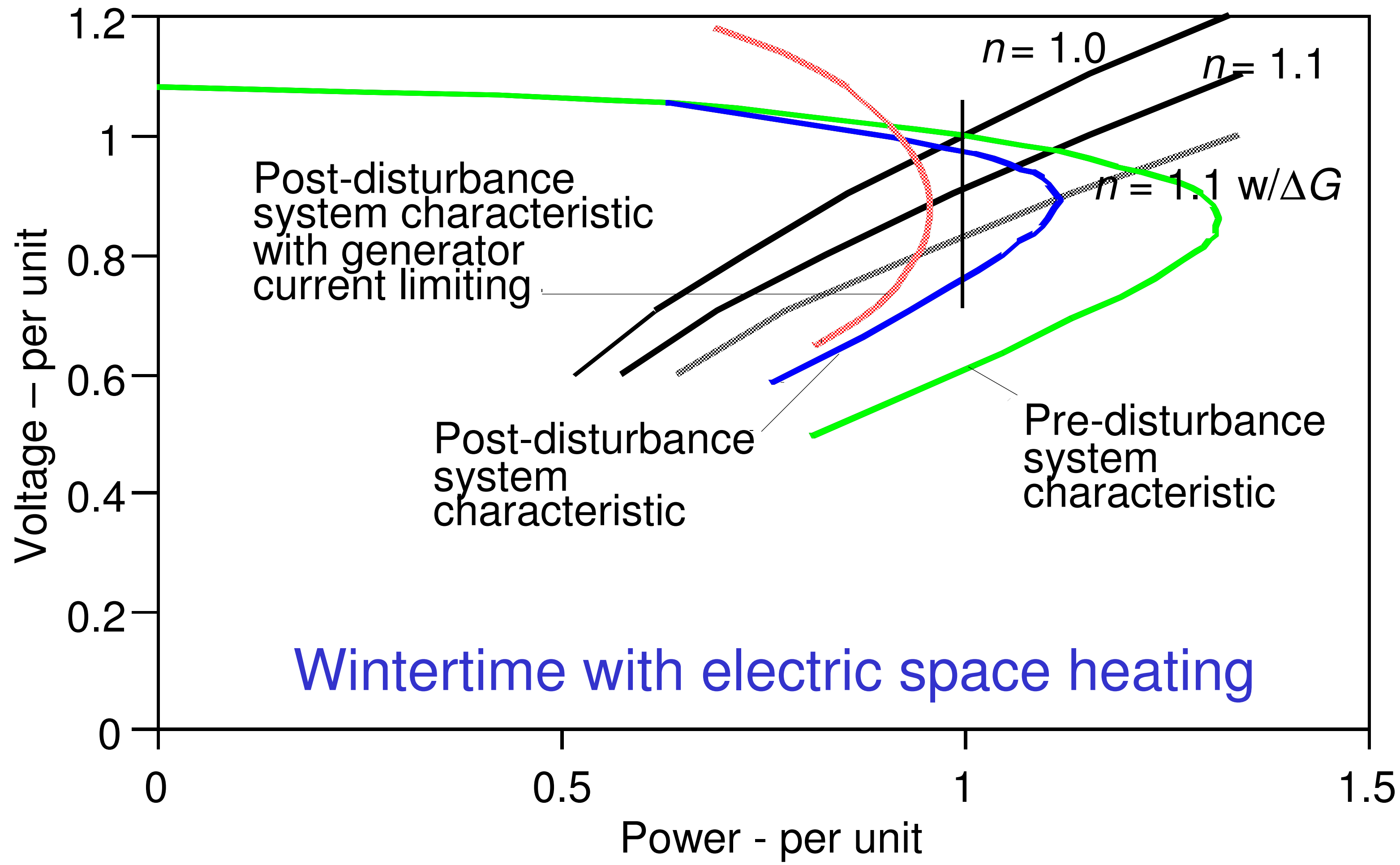


Load Characteristics—High Motor Load



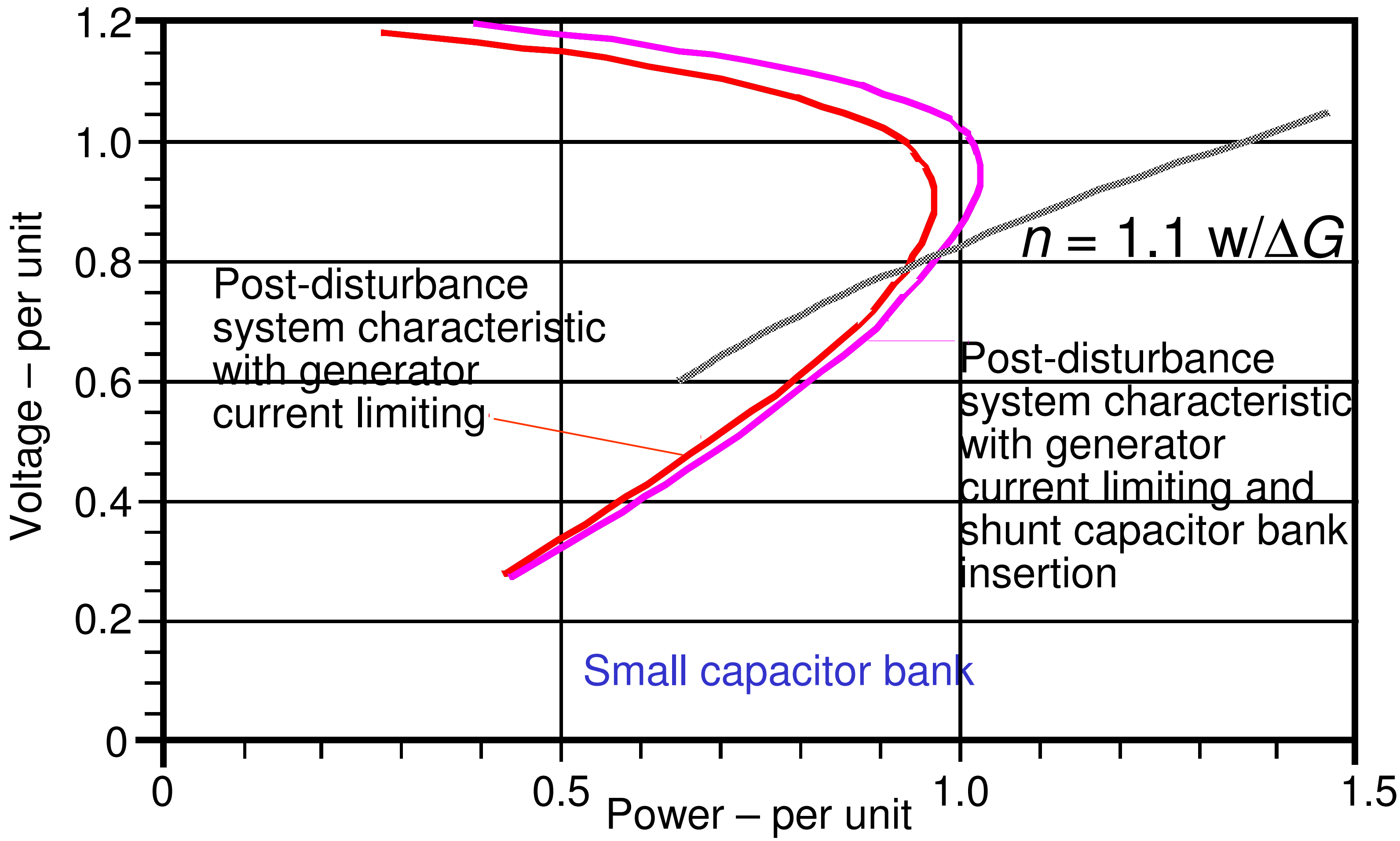
$$P = 0.75 + 0.25 n^2 G V^2$$

Load Characteristics—High Resistive Load



Load: $P = 0.25 + 0.75 n^2 G V^2$

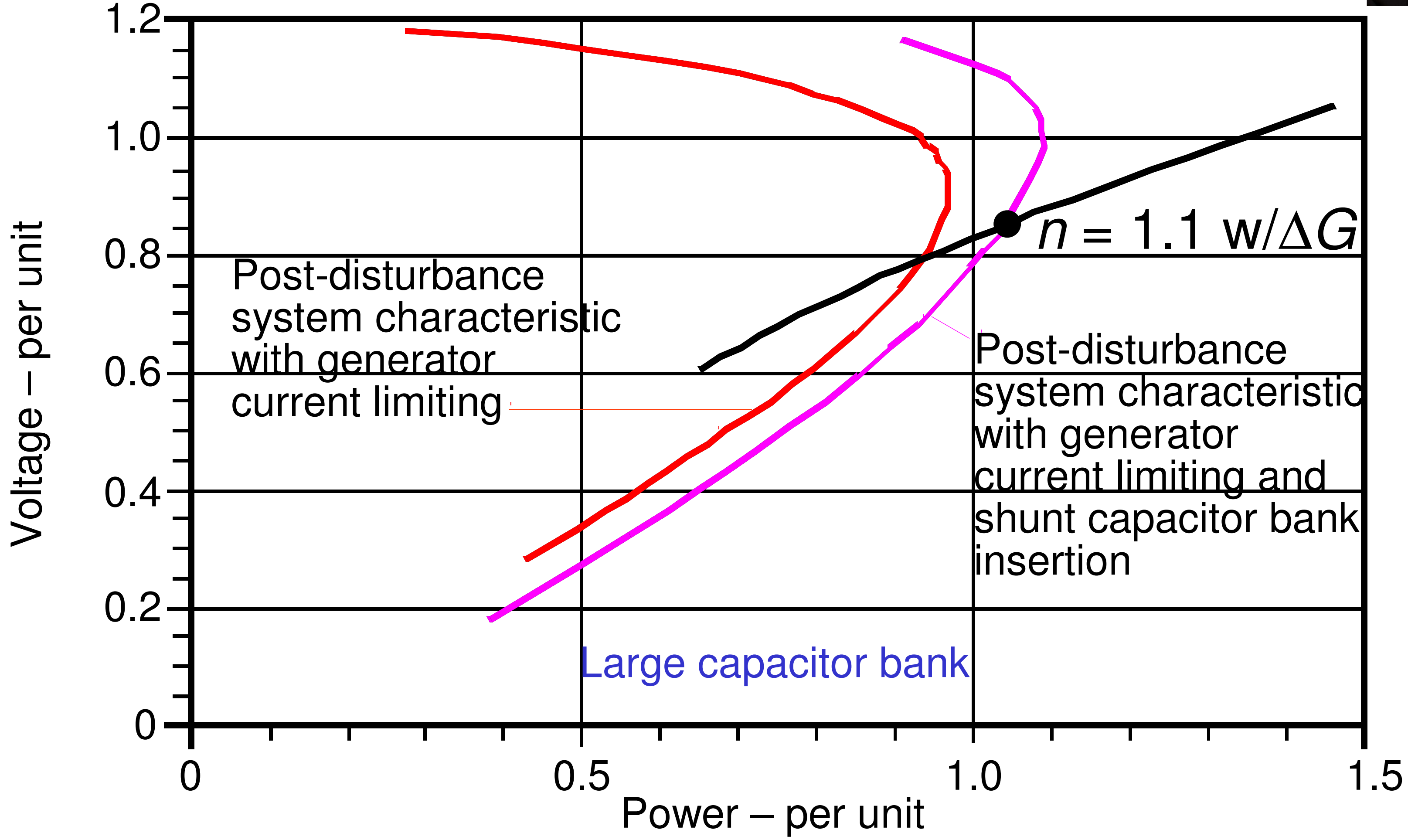
Capacitor Bank Insertion on Underside of *P-V*



Both power and voltage increased

Insufficient region of attraction

Capacitor Bank Insertion on Underside of *P-V*



Sufficient region of attraction, reverse tap changing occurs because power at purple/black curve intersection is >1.0