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EE 521: Analysis of Power Systems

Lecture 19
Voltage Stability

Fall 2009

Mondays & Wednesdays 5:45-7:00

August 24 – December 18

Test 216

Topics

- Review of Voltage Stability Concept
- Power-Voltage Curve
  - Not to be confused with Power-Angle Curve/Equation
- Analysis Methods for Large Systems
  - PV Curve
  - QV Curve

Review

Load Stability (Voltage Stability)

- Study the interaction between the system and the load.
  - How much power can be transferred to the load from a system without voltage collapse?
- Voltage stability is highly affected by load characteristics
  - ZIP load (algebraic equations)
  - Motor load (differential equations)
- Load modeling is very challenging due to diversity, variability, and aggregation.
  - Many efforts are ongoing (e.g. WECC)

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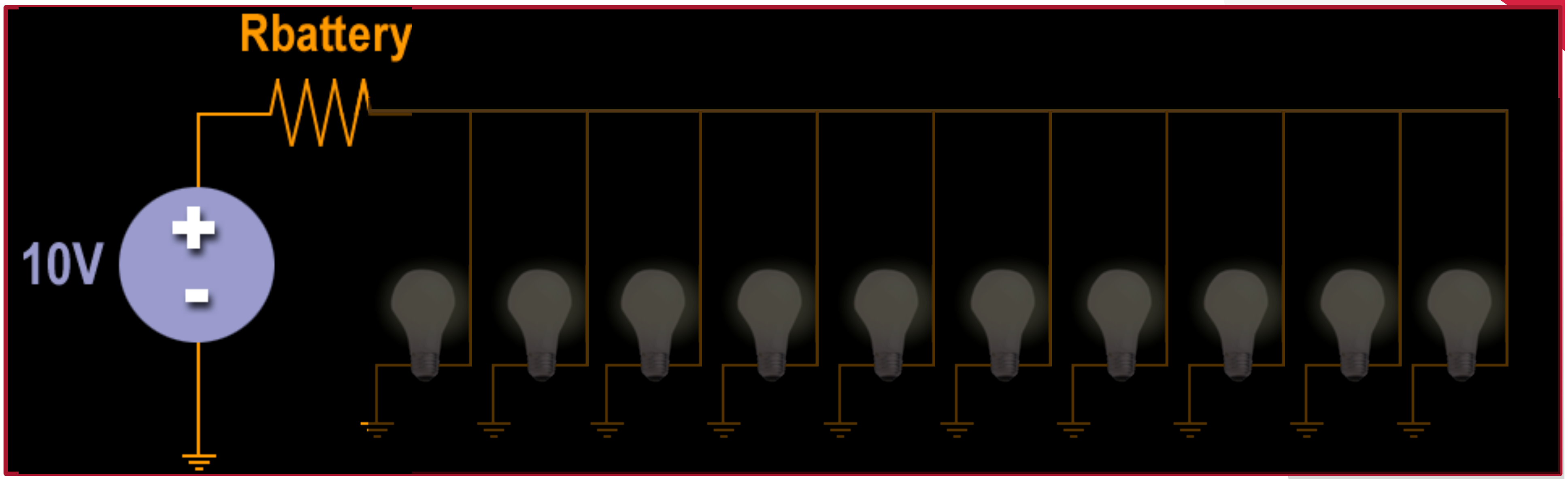
Bulb Examples



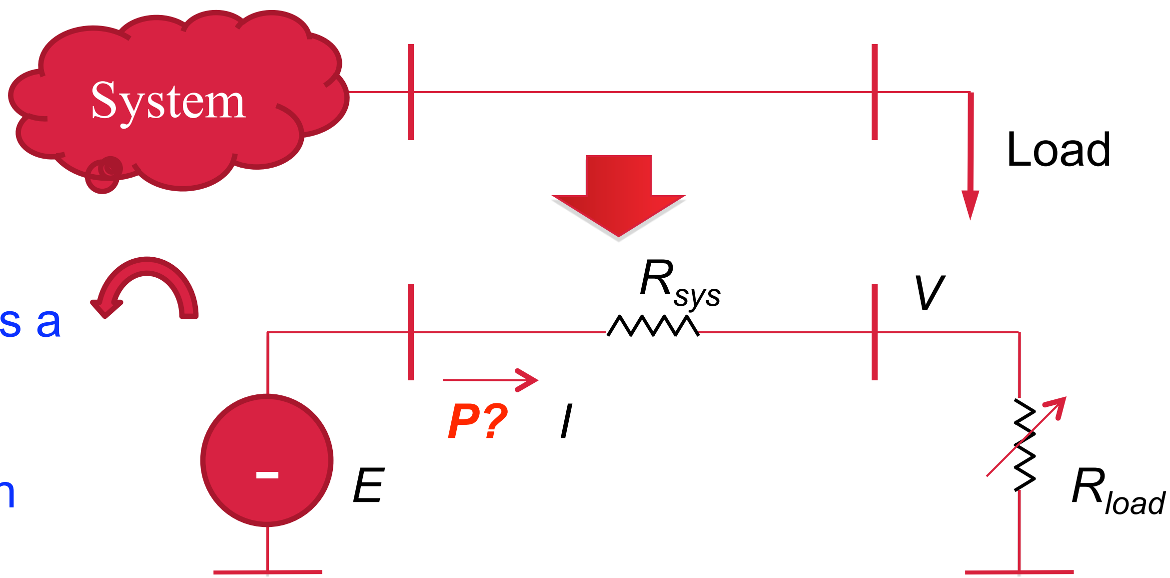
- 10 Volt battery
  - Internal resistance of 1 Ohm
- 20 Watt Light bulbs
  - Each light bulb resistance is 5 Ohms

Why the room becomes darker with more bulbs added?

Review

Power-Voltage Curve

System is modeled as a constant voltage source with an impedance



$$P = VI = V\frac{E-V}{R_{sys}} = \left(\frac{E}{R_{sys}}\right)V - \left(\frac{1}{R_{sys}}\right)V^2$$

$$\boxed{\left(\frac{1}{R_{sys}}\right)V^2 - \left(\frac{E}{R_{sys}}\right)V + P = 0}$$

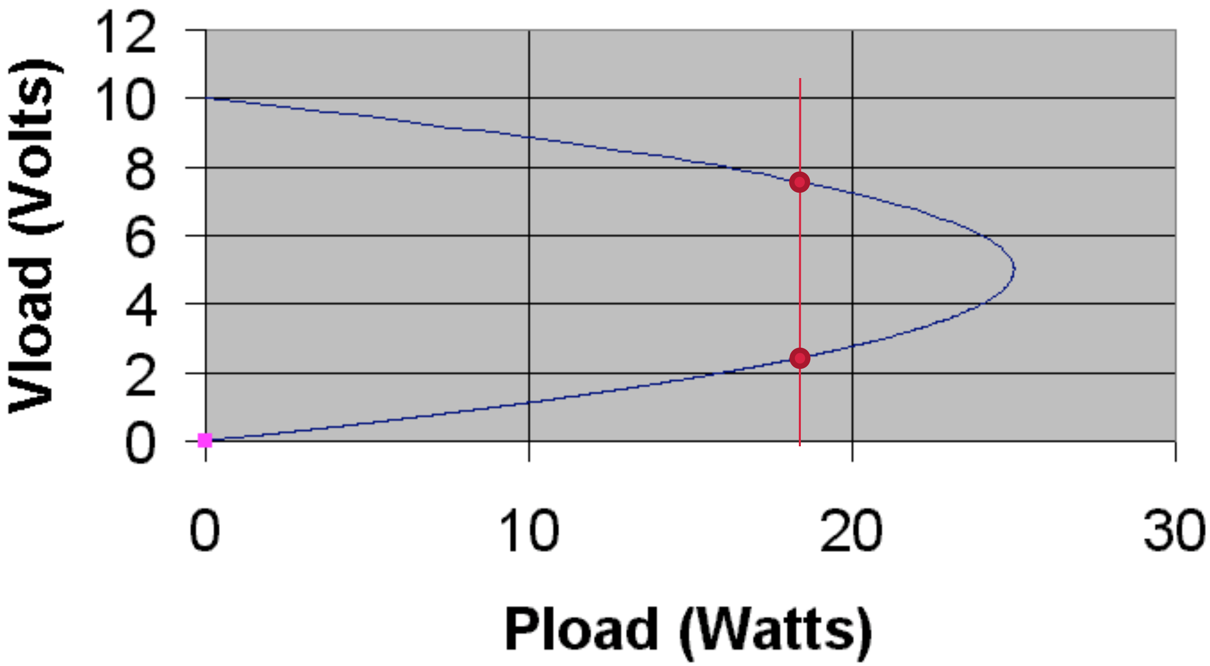
Maximum Power Transfer

$$\left(\frac{1}{R_{sys}}\right)V^2 - \left(\frac{E}{R_{sys}}\right)V + P = 0$$

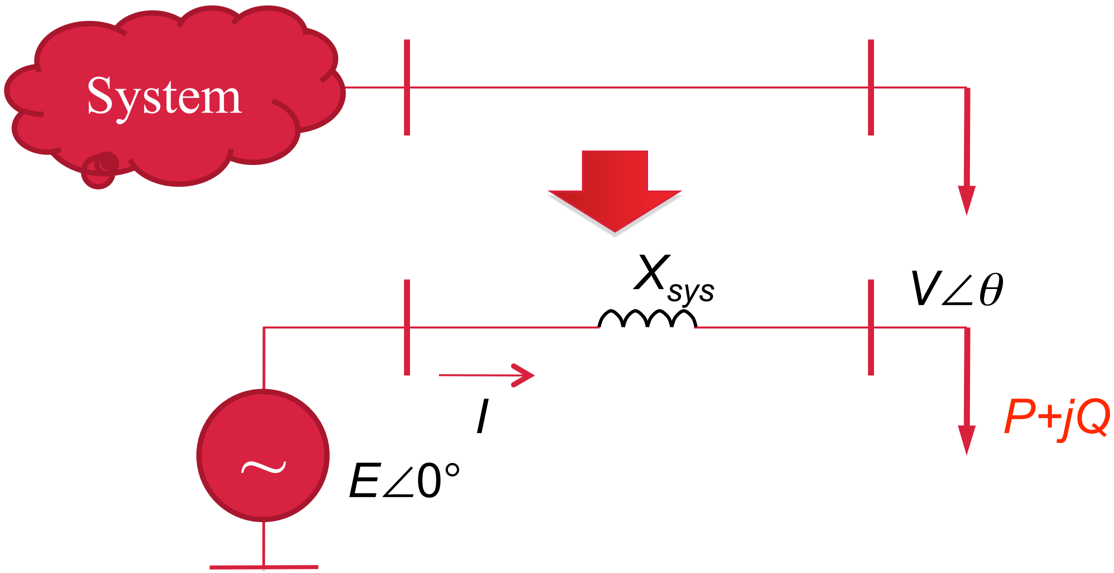
Observations:

1. Maximum power transfer at $V = E/2$, i.e. $R_{load} = R_{sys}$.
2. With a given constant load P_{load}, the operating point, i.e. V, can be found at the intersection point.
3. There exist two operating points. Only the higher voltage point is feasible.

Voltage vs. Power Curve



Power-Voltage Curve for AC Systems



Objective: ***P* = *P(V)***

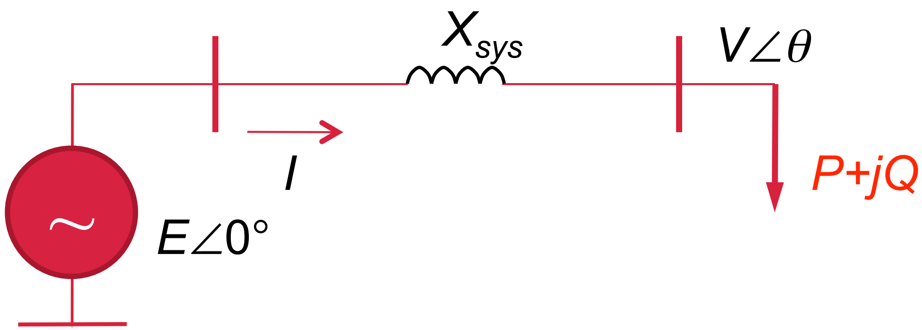
Procedure:

1. $P = P(V,\theta)$, and Q = = $Q(V,\theta)$.
2. Obtain $f(P,V,Q) = 0$ by eliminating θ.
3. Write $P = P(V)$ if possible.

Not to be confused with *P-δ* equation

1. For different situations.
2. For different analysis.
3. With different assumptions.

Power-Voltage Curve (pure resistive load)



Procedure:

1. $P = P(V,\theta)$, and $Q = Q(V,\theta)$.

$$P + jQ = (V\angle\theta)(I\angle\theta_I)^* \Rightarrow P = -\frac{EV}{X_{sys}}\sin\theta \qquad Q = \frac{-V^2 + EV\cos\theta}{X_{sys}}$$

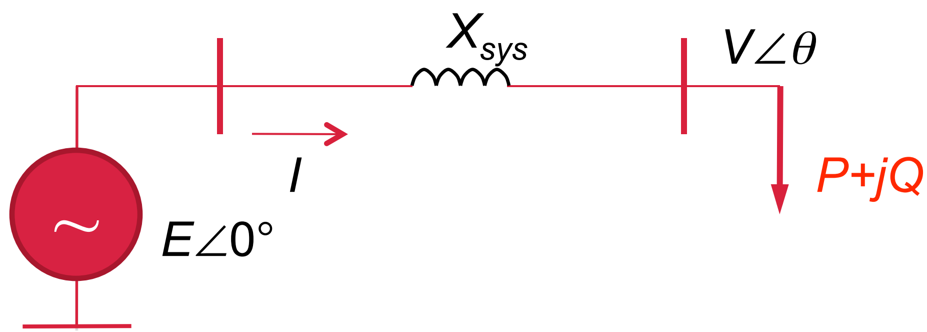
2. Obtain $f(P,V,Q) = 0$ by eliminating θ.

$$\sin\theta = -\frac{PX_{sys}}{EV} \qquad \cos\theta = \frac{QX_{sys} + V^2}{EV} \Rightarrow (PX_{sys})^2 + (V^2 + QX_{sys})^2 - (EV)^2 = 0$$

3. Write $P = P(V)$ if possible.

   If Q =0 (pure resistive load): $P = \frac{1}{X_{sys}}\sqrt{(EV)^2 - V^4}$

Power-Voltage Curve (pure resistive load)



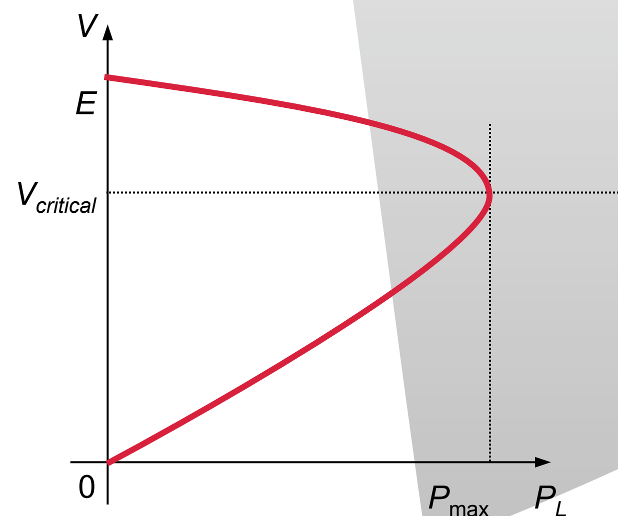
Observations:

1. $P = 0$ ➔ $V = E$ (unloaded line) or $V = 0$ (short circuit at the load point).
2. P_{max}:

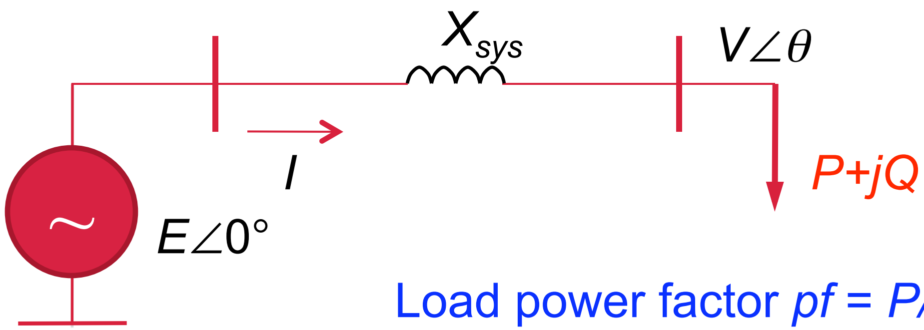
$$P = \frac{1}{X_{sys}}\sqrt{(EV)^2 - V^4}$$

$$\frac{dP}{dV} = \frac{2E^2V - 4V^3}{X_{sys}\sqrt{(EV)^2 - V^4}} = 0$$

$$V = \frac{E}{\sqrt{2}} \quad (R_{load} = X_{sys}) \qquad P_{max} = \frac{E^2}{2X_{sys}}$$



Power-Voltage Curve (general case)



Load power factor $pf = P/S$.

$$(PX_{sys})^2 + (V^2 + QX_{sys})^2 - (EV)^2 = 0$$

$$Q = \pm\frac{\sqrt{1-pf^2}}{pf}P = kP$$

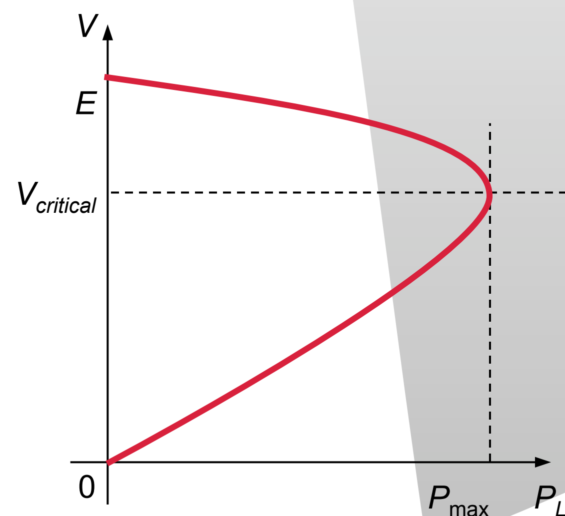
$$\Rightarrow (PX_{sys})^2 + (V^2 + kPX_{sys})^2 - (EV)^2 = 0$$

Hint: $a(V^2)^2+b(V^2)+c = 0$ and $b^2-4ac = 0$

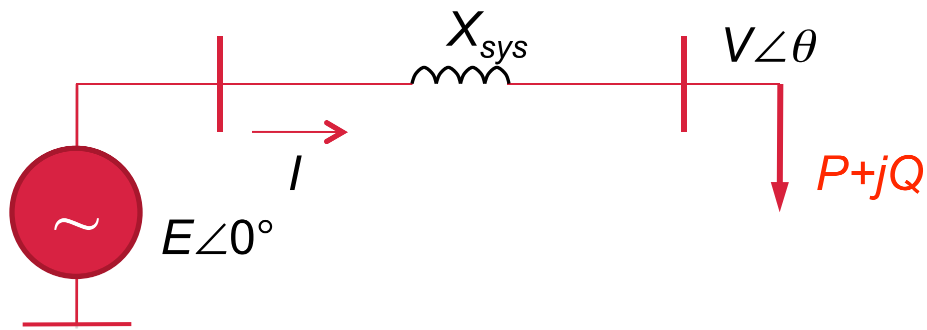
$$\Rightarrow E^4 - 4kPX_{sys}E^2 - 4P^2X_{sys}^2 = 0$$

$$\Rightarrow P_{max} = \frac{E^2}{2X_{sys}}\left(-k + \sqrt{(1+k^2)}\right)$$

$$V_{critical} = \frac{E}{\sqrt{2}}\sqrt{1 + k^2 - k\sqrt{(1+k^2)}}$$



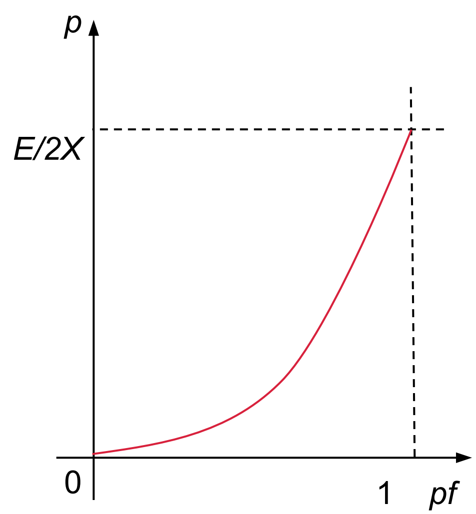
Power-Voltage Curve (general case)

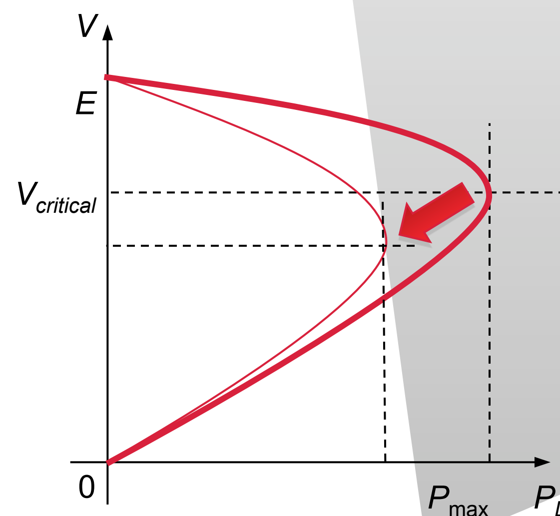


$$P_{\max} = \frac{E^2}{2X_{sys}}\left(-k + \sqrt{(1+k^2)}\right) \qquad V_{critical} = \frac{E}{\sqrt{2}}\sqrt{1+k^2 - k\sqrt{(1+k^2)}}$$

Observations:

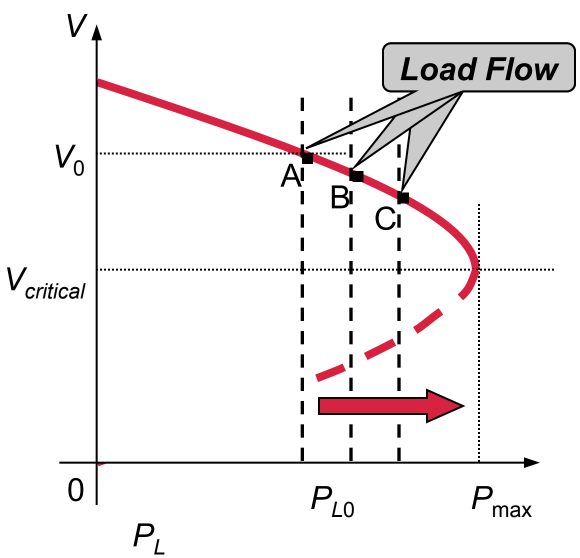
1. Pure resistive load:
   pf = 1, $k = 0$, $P = E^2/2X_{sys}$.
2. Pure reactive load:
   pf = 0, $k = \infty$, $P = 0$.
3. X_{sys}: longer line, larger X, and less P_{max}.
4. True for larger systems

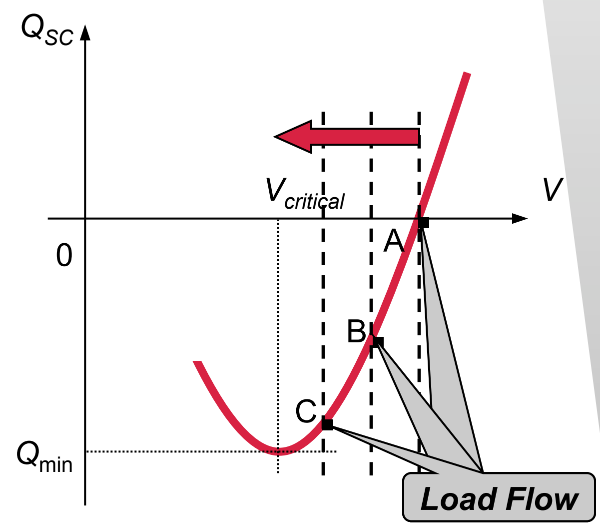




Voltage Stability Analysis Methods for Large-Scale Power Systems

- PV Curve Method
  - Determine the load margin for the whole system
- QV Curve Method
  - Determine reactive margin for a specific location (bus)



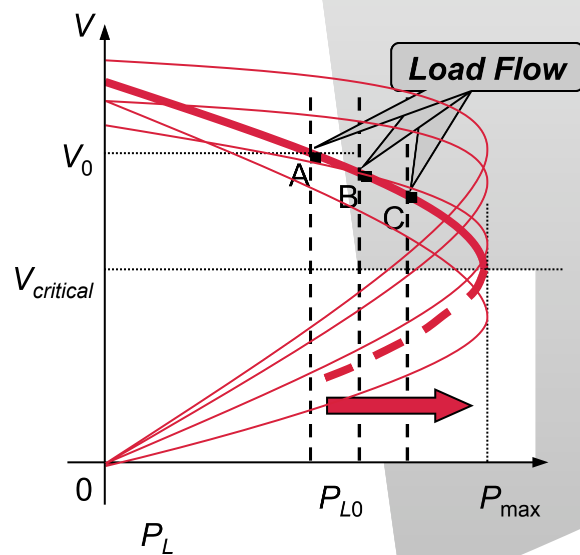


PV Curve Method

Procedure:

1. Select test buses (one, multiple or all).
2. Scale up bus loads with a constant power factor (P and Q at PQ or load buses)
3. Scale up generation (P of PV or generation buses).
4. Solve power flow for each scaled case.
5. Repeat 2-4 until the case can not be solved, i.e. the power flow solution does not converge.
6. Plot bus voltage(s) against the system loads.

Load Margin = $P_{max} - P_0$



Discussion

1. Numerical instability.
   Smaller steps near the nose point.
2. Do all bus voltages reach the nose point at the same load level?
   Yes, all buses collapse at the same time.

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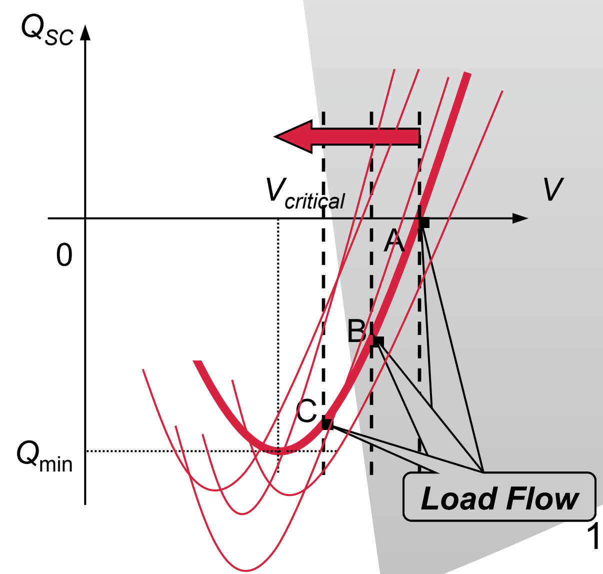
QV Curve Method

Objective: find out change of Q by specifying V at a bus

Procedure:

1. Select a test bus.
2. Add a synchronous condenser (SC) to the test bus (P = 0).
3. Change the bus type to be PV bus. Initial V setting = V_0, so Q_{SC} = 0.
4. Lower the V setting in steps (e.g. ΔV = 0.05 pu). This will result in the SC absorbs Q, i.e. Q_{SC} < 0.
5. Repeat step 4 until the case can not be solved or the voltage reaches a pre-specified voltage level.
6. Plot Q_{SC} against V.

Reactive Margin = Q_{min}

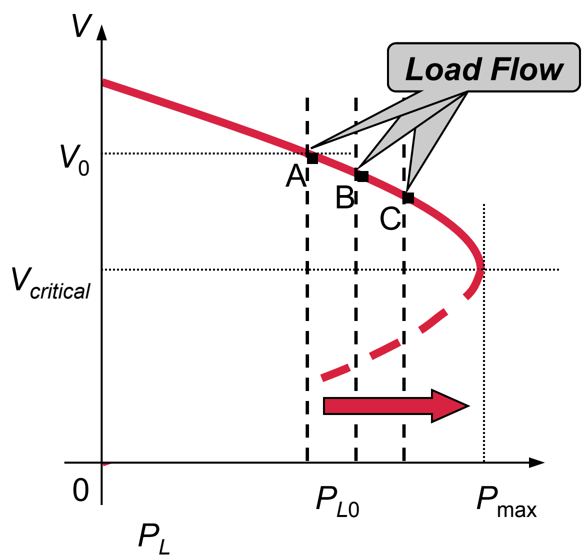


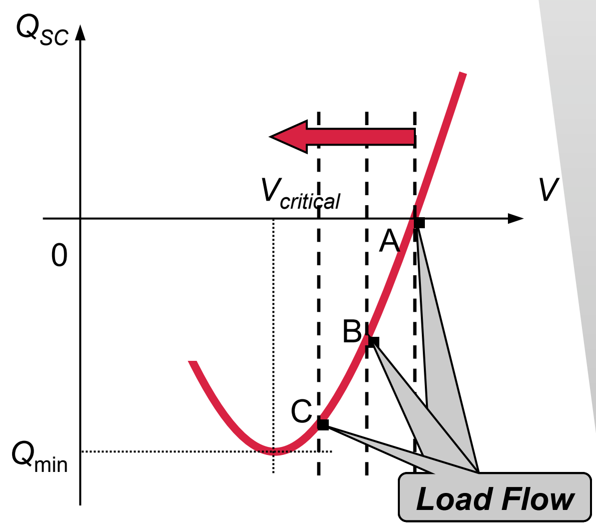
Discussion

1. Numerical stability
2. Do all bus voltages reach the minimum point at the same Q_{min}?
   No, QV curve is valid for the test bus only.

Limitations of PV and QV Methods

1. Arbitrary selection of test bus(es)
2. Arbitrary selection of stress patterns
3. Variations in power factors
4. Variations in generation dispatch
5. Many PV and QV curves to plot and examine. Possibility of missing key information.





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Questions?