

Analysis of electric power and energy systems

Lecture 7: Voltage regulation and voltage instability

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What will we learn today?

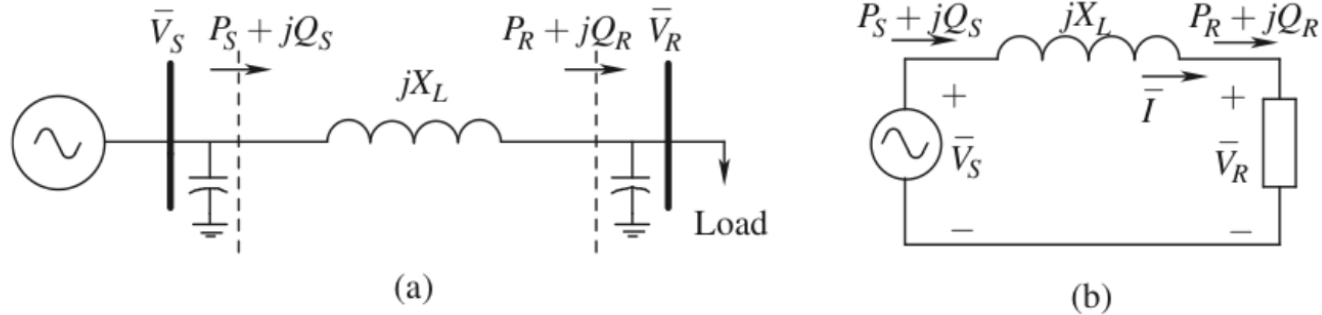
- Voltage regulation and reactive power compensation in EHV grids
- Voltage instability and voltage collapse
- EHV Voltage control and reactive power compensation devices
- Voltage control in the distribution systems
- Likely impact of the energy transition on these topics

This lecture expands on Chapter 10 from the Ned Mohan's book.

Voltage regulation and reactive power compensation in EHV grids

Radial system as an example

We want to transfer some active power P_R to a load through an EHV-line



Neglecting line resistance R_L , we have $\bar{V}_S = \bar{V}_R + jX_L \bar{I}$ and hence

$$P_R = \frac{V_R V_S}{X_L} \sin \delta = P_S$$

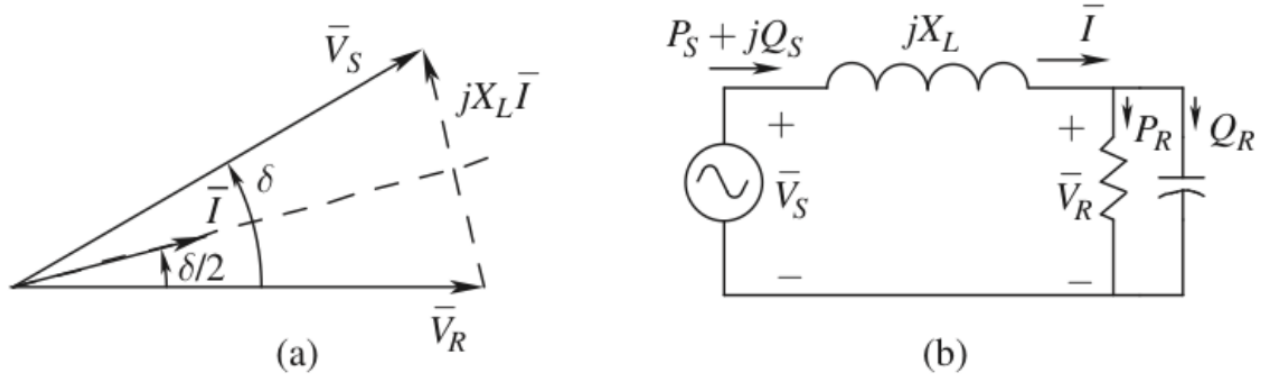
$$Q_R = \frac{V_R}{X_L} (V_S \cos \delta - V_R)$$

where δ is the angle of the source (generator) bus w.r.t. the receiving (load) bus.

Notice that in EHV (transmission systems) at 100kV-750kV: $X_L/R_L \approx 10 - 30$.

Voltage regulation

In practice we also want the voltage magnitude at both ends to be close to 1 pu.



We see that under these conditions Q_S is positive and Q_R is negative and, assuming $V_R = V_S = 1$, we have

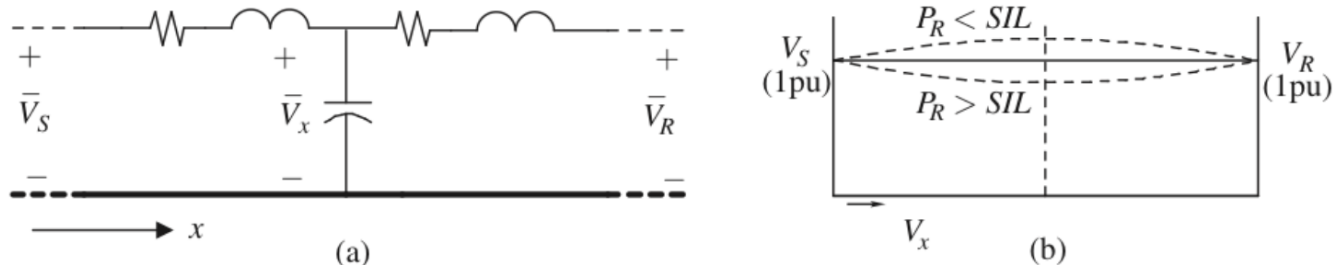
$$Q_S = -Q_R = \frac{X_L I^2}{2}$$

Part of this reactive power is already produced by the capacitance of the line itself.

The rest, depending on the amount of power P_R transferred to the load, has to be compensated for at both ends.

Voltage profile along the line

The voltage profile V_x along the line depends on the amount of power transferred P_R , in comparison with the surge impedance loading (SIL) of the line:



If $P_R > SIL$, the line consumes more reactive power than it produces, and we have to supply $Q'_S > 0$ and $Q'_R < 0$ at both ends. In these conditions, the voltage profile along the line will be $V_x < V_S$.

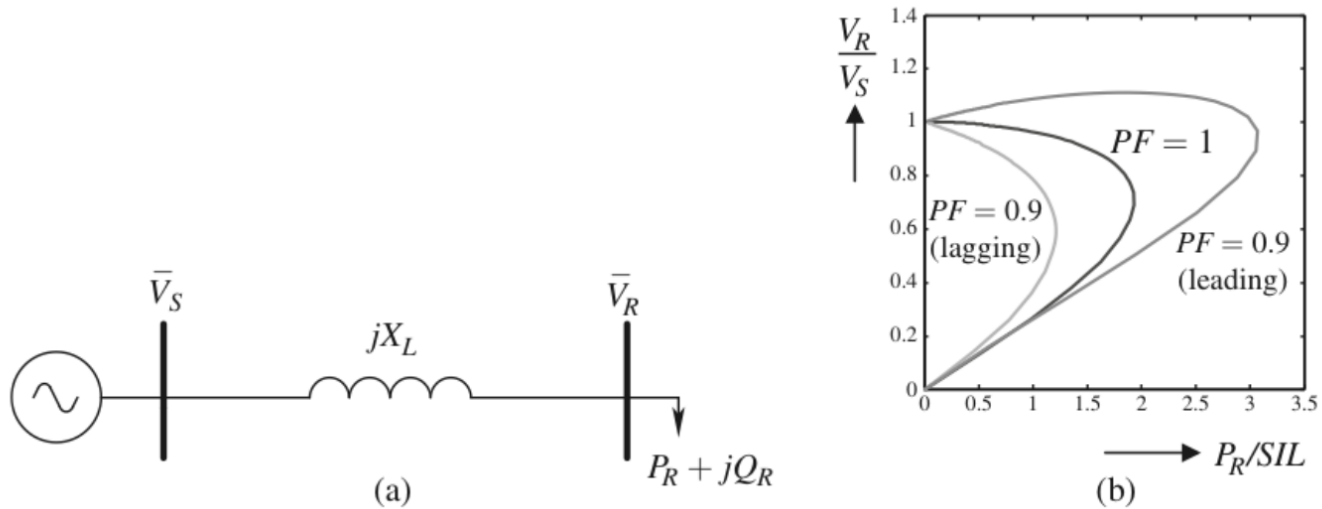
If $P_R < SIL$, the line produces reactive power and we have to absorb the surplus at its ends. The voltage profile along the line will be $V_x > V_S$.

In this latter case (e.g. cables, or very long transmission lines), the insulation capability may impose reactive power compensation 'along' the line, e.g. in the form of shunt reactors.

Voltage instability and the voltage collapse problem

The (P_R, V_R) curve (aka 'nose or PV curve')

Consider the case of Figure (a) below, assuming an ideal voltage source and neglecting line resistance and line capacitance:



From Figure (b) above, we see that (for each PF) there is a maximum value of P_R that can be transferred to the load. Below this maximum of P_R , there are two possible modes of operation

- the high voltage solution, which is stable
- the low voltage solution, which is unstable

The (P_R, Q_R, V_R) surface

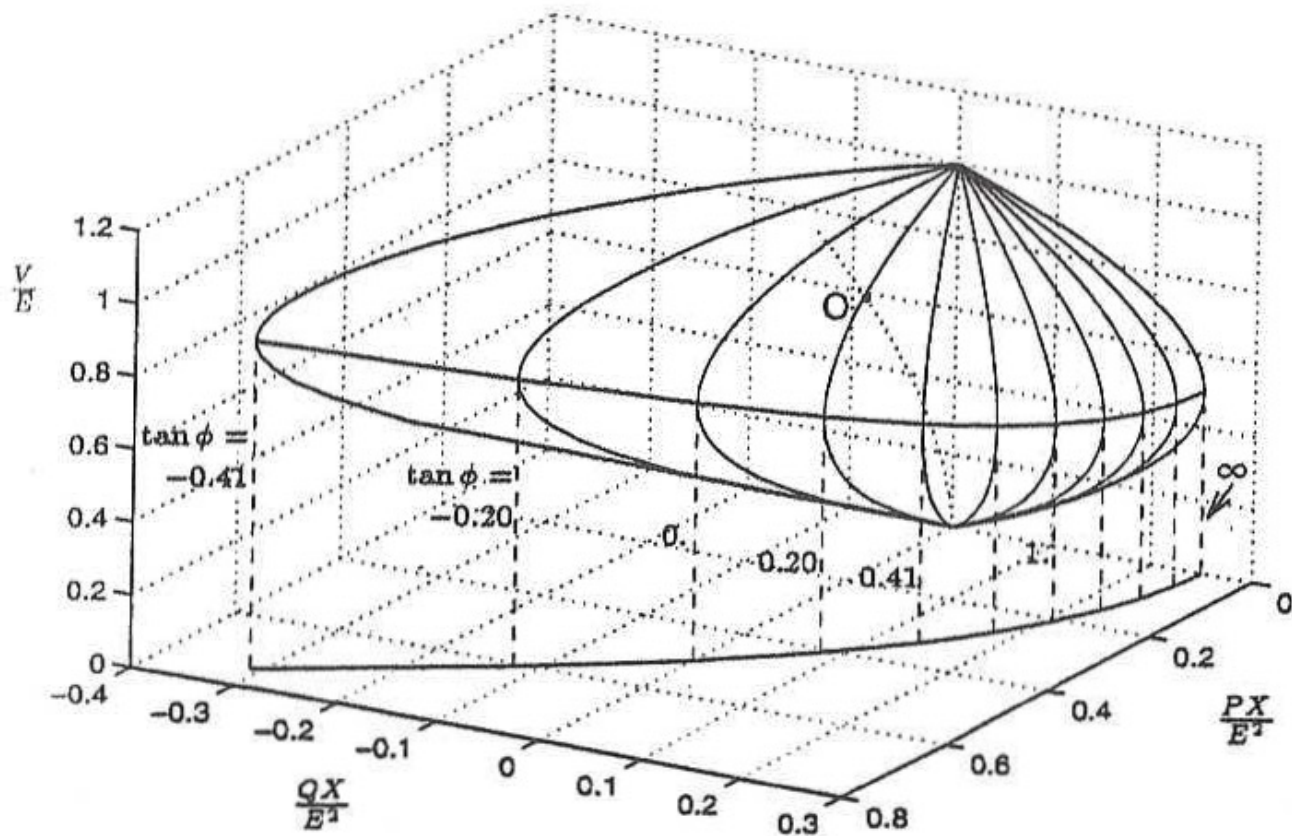


Figure from: Voltage stability of electric power systems. T. Van Cutsem & C. Vournas, KAP 1998

NB: in our notations: $E \equiv V_S$, $V \equiv V_R$, $X \equiv X_L$, $P \equiv P_R$, $Q \equiv Q_R$

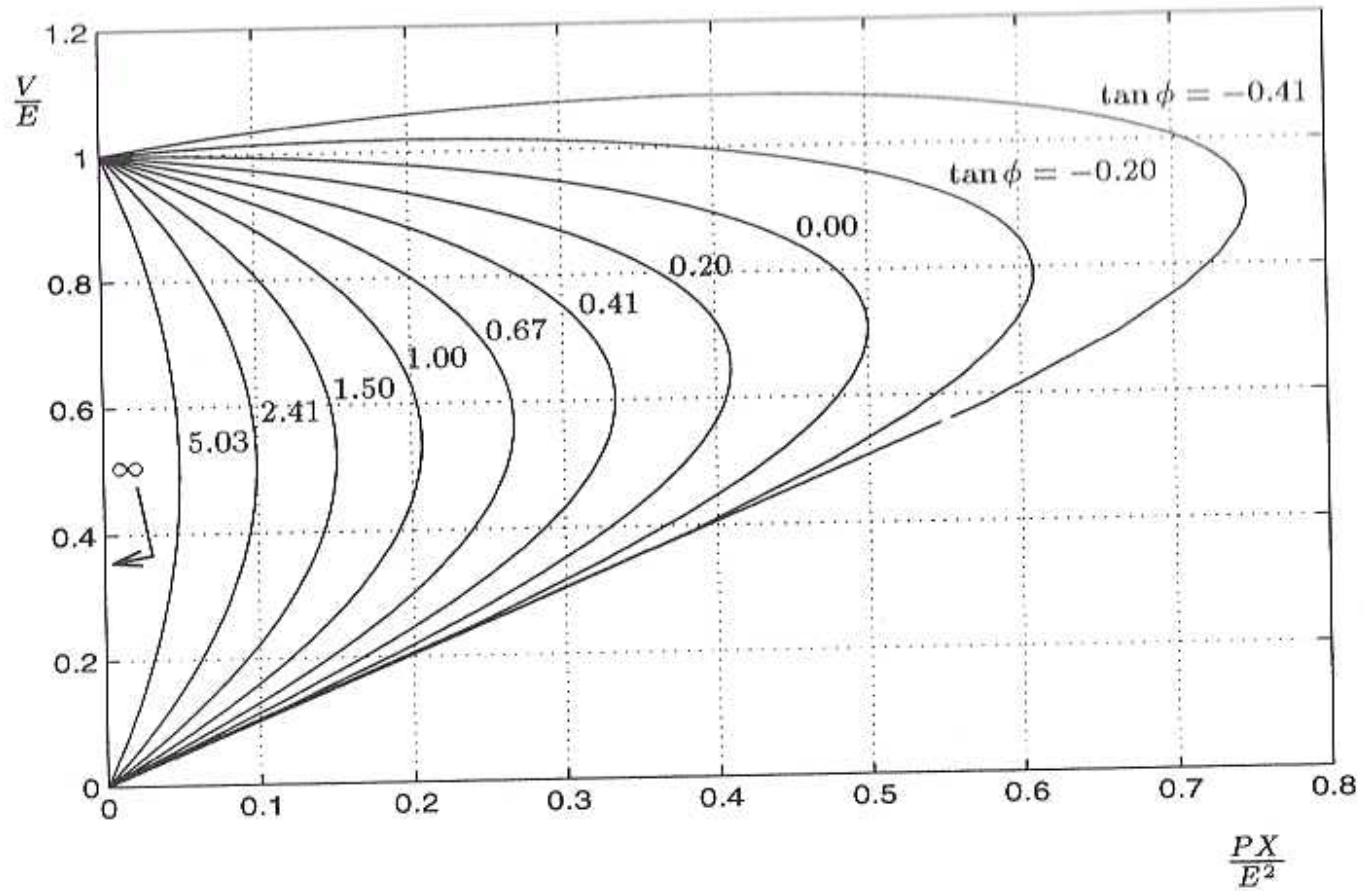
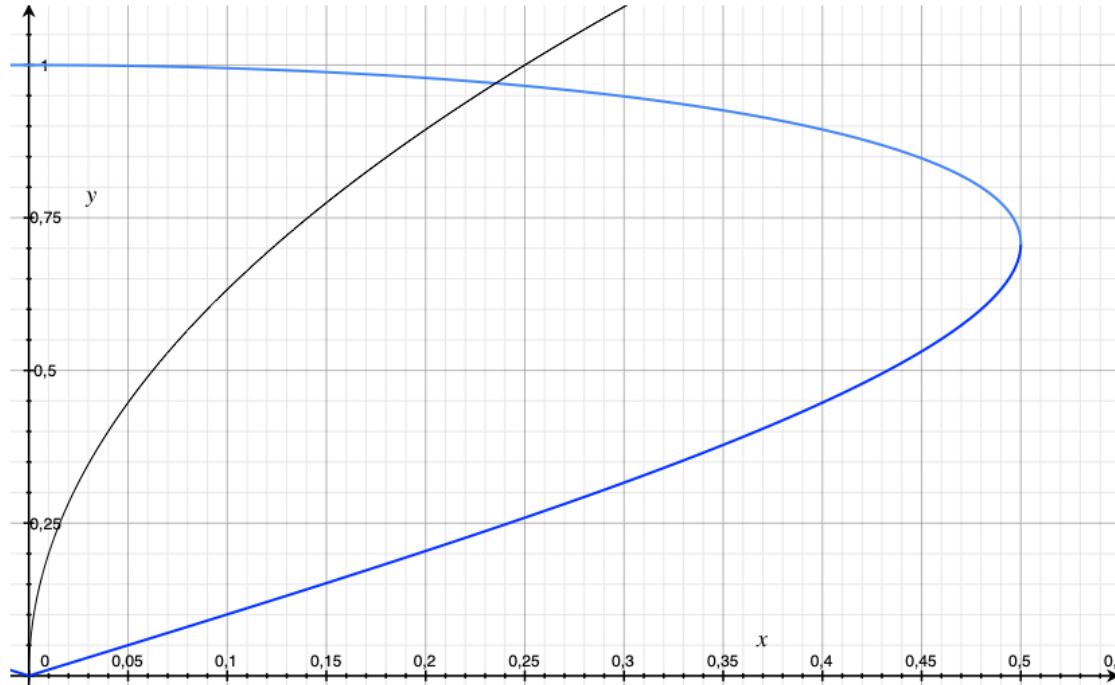


Figure from: Voltage stability of electric power systems. T. Van Cutsem & C. Vournas, KAP 1998

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Assume a purely resistive load, i.e. $\text{PF}=1$ (i.e. $\tan \phi = 0$)

Setting $y = \frac{V_R}{V_S}$ and $x = \frac{P_R X_L}{V_S^2}$, the (blue) nose curve is $y = \sqrt{\frac{1}{2} \pm \sqrt{\frac{1}{4} - x^2}}$

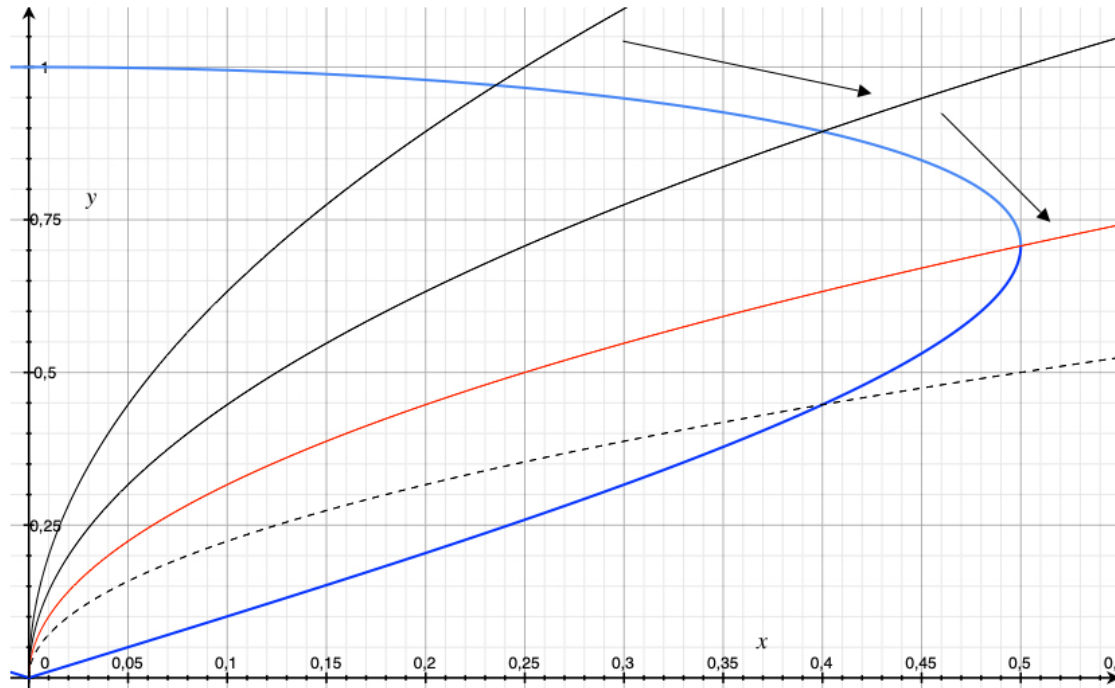


The load characteristic (black curve) is defined by $P_R = \frac{V_R^2}{R_R}$, i.e. $y = \sqrt{x \frac{R_R}{X_L}}$

The operating point is obtained as the intersection of the nose curve and the load characteristic.

Voltage instability mechanism 1: increasing the load level

Increasing the load essentially consists in adding further loads in parallel with already existing ones, and thus results in a decrease of the total load resistance.

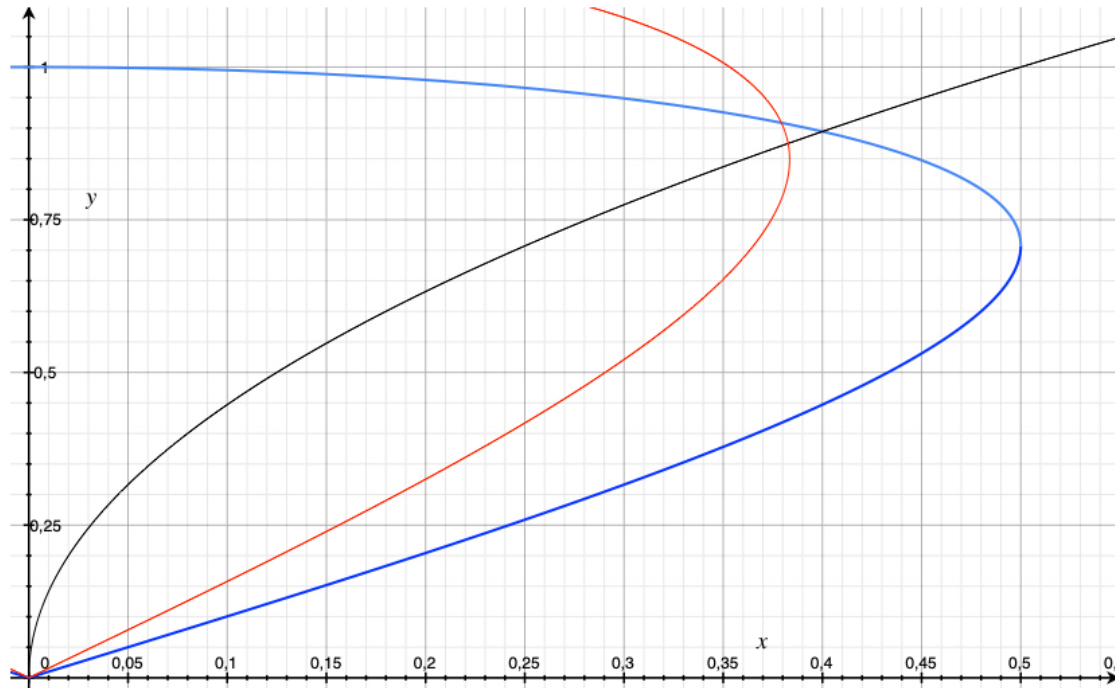


The red curve corresponds to $R_R = X_L$, $V_R = V_S/\sqrt{2}$ and $P_R = V_S^2/(2X_L)$.

Beyond this level, further decreasing the load resistance R_R actually decreases the load power P_R and voltage V_R starts to drop, more and more quickly.

Voltage instability mechanism 2: reactive power limit of generators

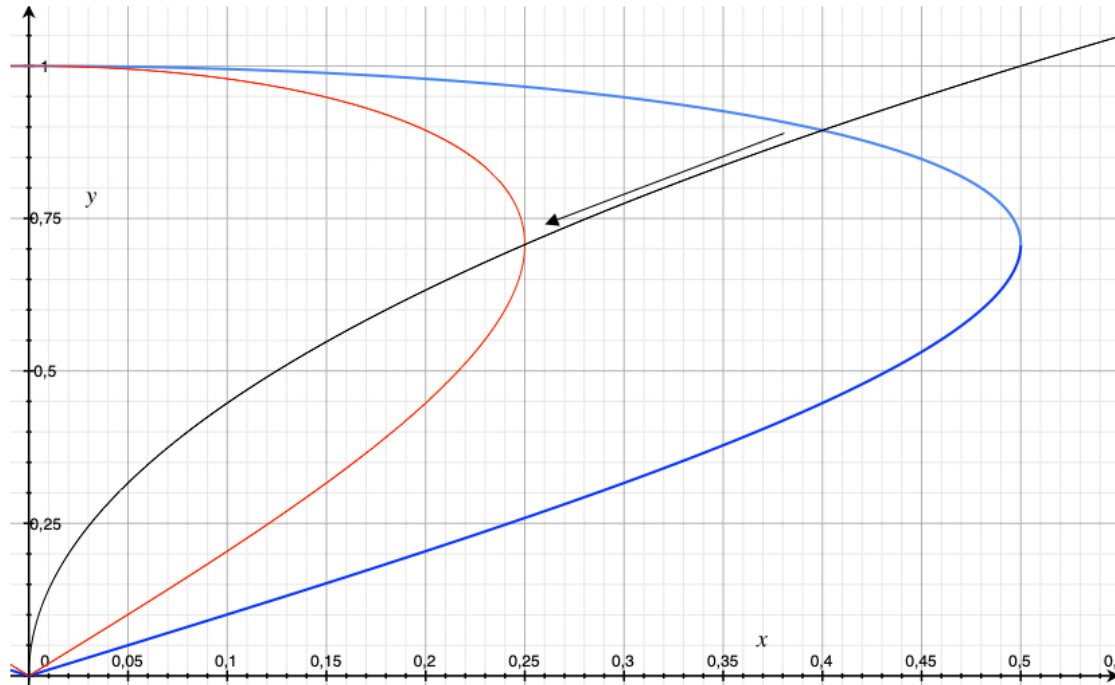
When the load power increases, the source generator must supply more and more reactive power.



The red "PV-curve" corresponds to the source generator reaching its excitation current limit: the ideal voltage source is replaced by adding its synchronous reactance in series with the line.

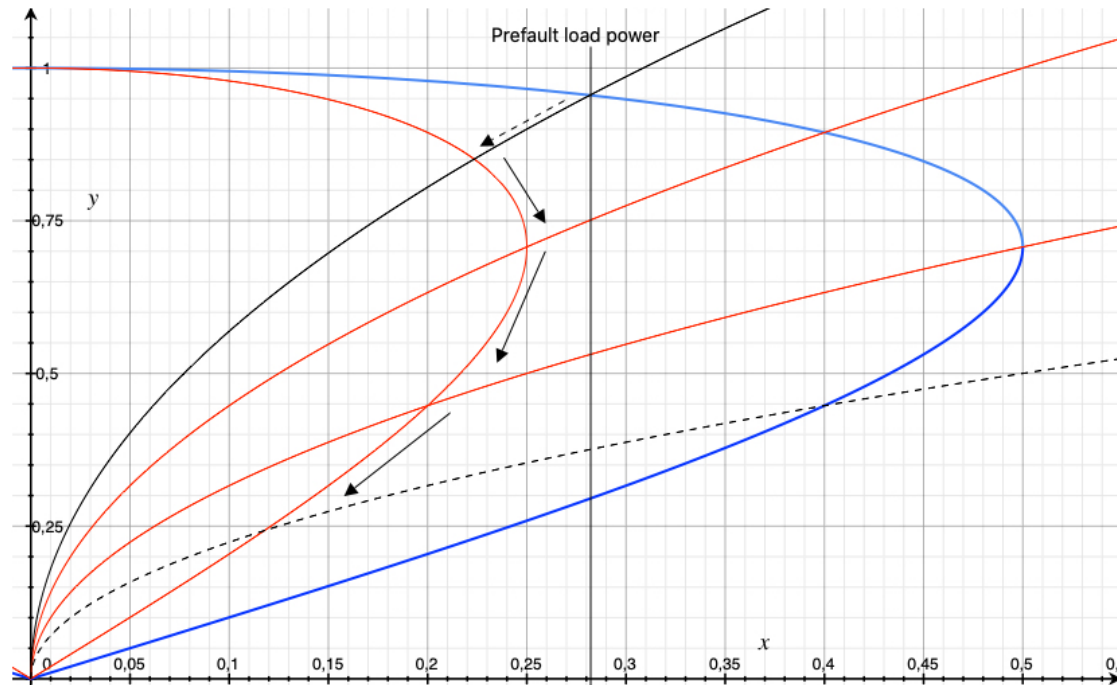
Voltage instability mechanism 3: line tripping

Imagine that X_L represents the equivalent reactance of a double circuit EHV line, and that one of the two-circuits suddenly trips out of operation: the equivalent line reactance becomes $2X_L$ (red nose curve).



The operating point "instantaneously" switches to the intersection of the load characteristic and the new system characteristic, leading to a significant drop in voltage and received power.

Voltage instability mechanism 4: load restoration



After the "instantaneous" (dashed arrow) switch of the operating point, the load power has well decreased.

Subsequently, the load active power tries to restore itself to the level at which it was before the line tripping (plain arrows).

This restoration process can yield voltage collapse as shown on the graph. Its speed depends on the nature of the load restoration process.

Load power restoration mechanisms

- **Fast** (less than a minute): automatic controls acting on electric loads, such as speed control of trains, elevators, and in general motors
- **Medium speed** (a few minutes): automatic controls of transformer ratios (taps) acting on the voltage level in the distribution system (since most loads are voltage sensitive)
- **Slow** (tens of minutes): thermostatic loads, manual 'human-driven' feedback mechanisms

NB: in practice, the various voltage instability and load-restoration mechanisms may act in combination.

NB-bis: although we made a 2-bus analysis, the same phenomena are observed in multi-bus systems.

NB-ter: voltage instability has led to several large-scale power system blackouts.

Systemic threats to voltage stability

- Increasing the distance (X_L) between supply and demand
- Reducing the reactive power generation reserves
- Faster load restoration mechanisms, slower reactive power controls

Counter-measures

- Switchable reactive power compensation devices (capacitors, inductors)
- Ensuring the availability of reactive power reserves close to load areas
- Ad hoc and clever voltage control schemes

Voltage control

Control devices (see section 10.4 of reference book)

- Voltage controls of synchronous generators and synchronous condensers
- Switching of reactive compensation devices (capacitors and inductors)
- Power electronics empowered devices: SVC, STATCOM, HVDC, TCSC

Control strategies and methods

- Preventive control
 - Must-run generators (days/hours ahead in time)
 - Setting of control device parameters (weeks/months ahead in time)
 - Installation of reactive compensation devices (months/years ahead in time)
- Corrective control
 - Primary/Secondary/Tertiary voltage control
 - Fast backup generation unit start-up
- Emergency control
 - On-load transformer tap changer blocking
 - Under voltage load-shedding

Voltage control in distribution networks

Distribution systems are (typically) radial, operate at lower voltage levels, and have no synchronous generation installed.

Voltage is mostly controlled by using tap-changing transformers. Wires copper sections are chosen in order to cover peak demand along the feeder.

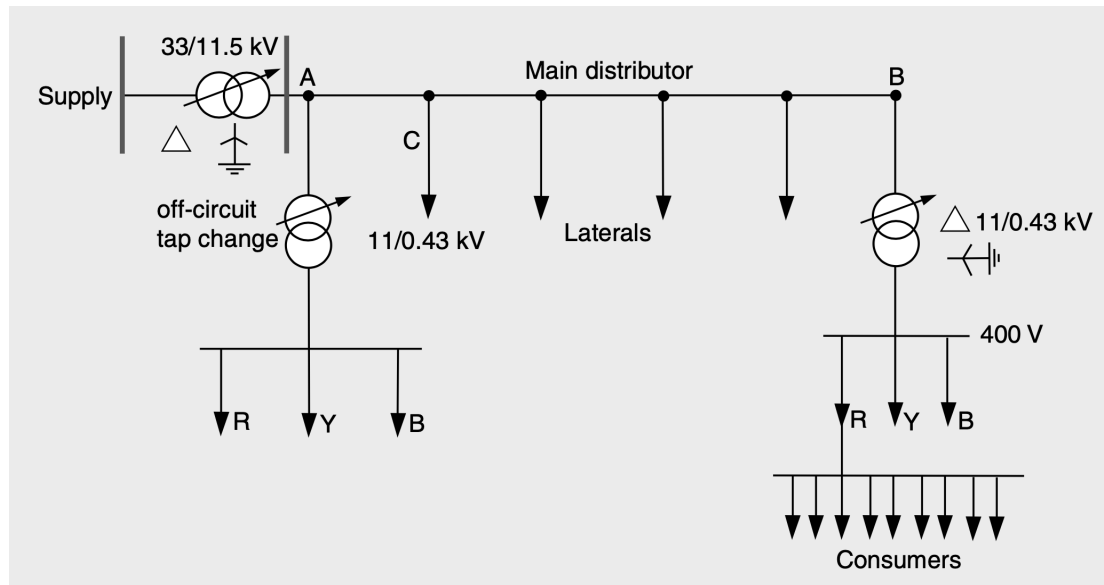


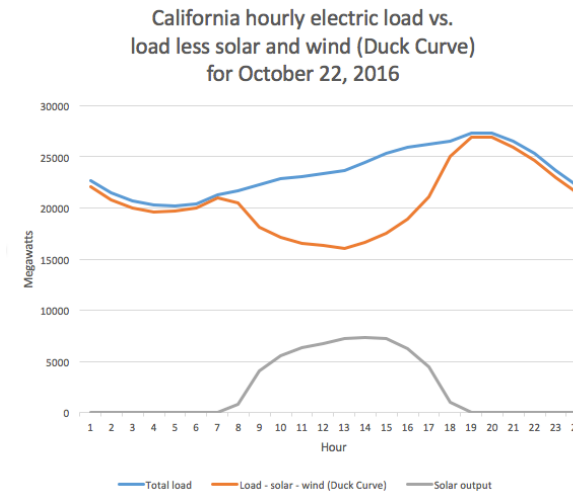
Figure from: Electric power systems, Weedy, B.M. et al. John Wiley & Sons, 2012

Notice that in MV-LV (distribution systems) at 200V-20kV: $X_L/R_L \approx 0.2 - 1$

Likely impact of the energy transition

A think tank

- Increasing difficulties
 - Fewer synchronous generators in operation at the transmission level
 - More and more pronounced 'Duck'-curve



- Higher variability of flows and flow-directions at the distribution and transmission level
- New 'high-tech' opportunities
 - Power electronics
 - Smart-grid technologies

References

- Mohan, Ned. Electric power systems: a first course. John Wiley & Sons, 2012.
- Van Cutsem, Thierry and Vournas, Costas. Voltage stability of electric power systems. Kluwer Academic Publishers, 1998
- Weedy, B.M. et al. Electric power systems. John Wiley & Sons, 2012

