Analysis of electric power and energy systems

Lecture 7: Voltage regulation and voltage instability

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What will we learn today?

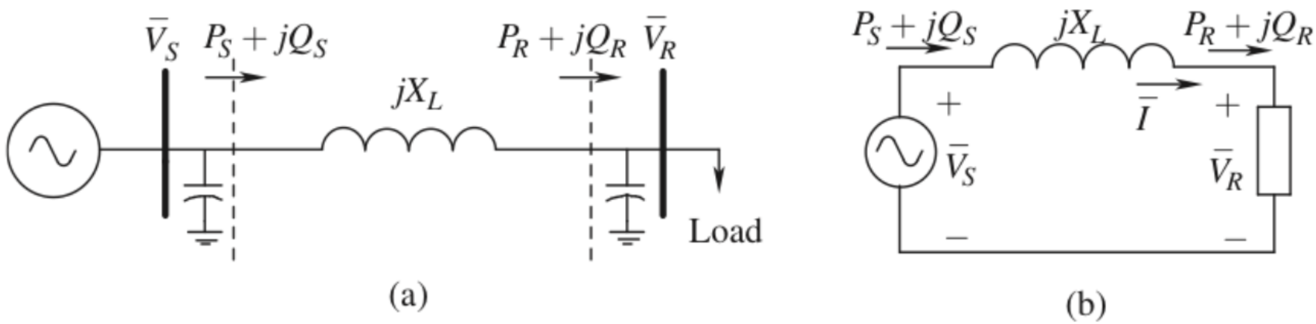
- Voltage regulation and reactive power compensation in EHV grids
- Voltage instability and voltage collapse
- Voltage control and reactive power compensation devices
- Likely impact of the energy transition, and distribution grid voltage control

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

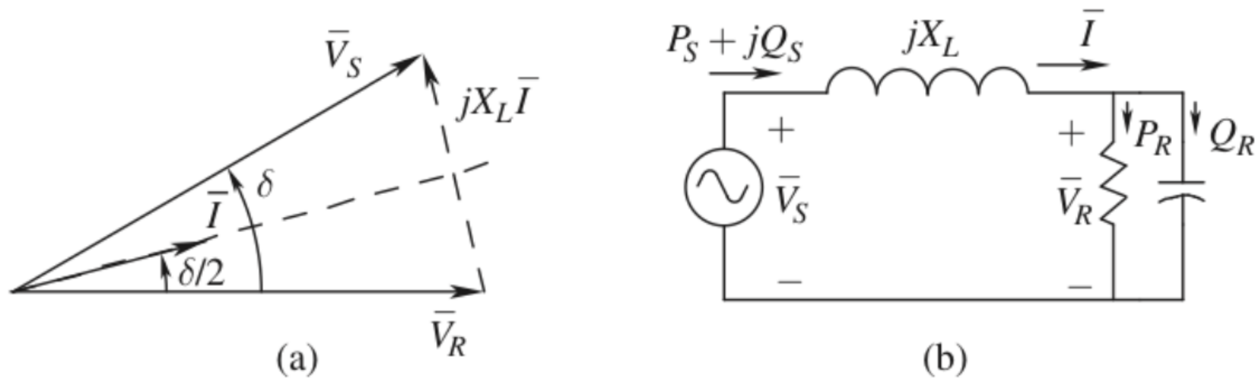
$$P_R = \frac{V_R V_S}{X_L}\sin\delta = P_S$$

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

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

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

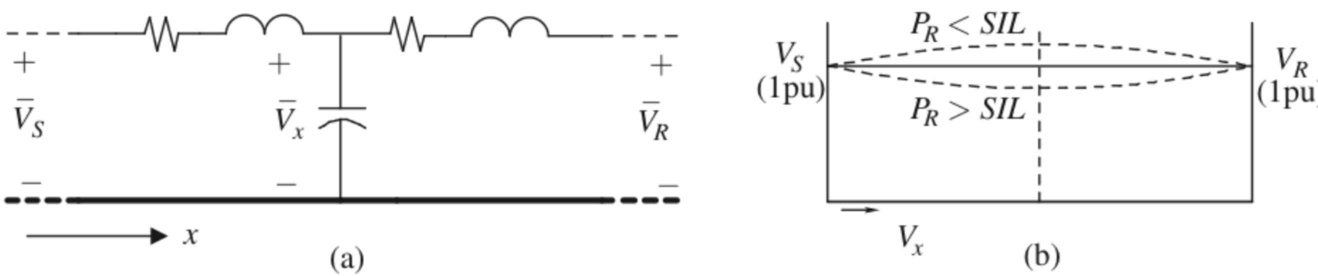
$$Q_S = -Q_R = \frac{X_L I^2}{2}$$

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 transfered 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 transfered P_R, in comparison with the surge impendance 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 $V_x < V_S$.

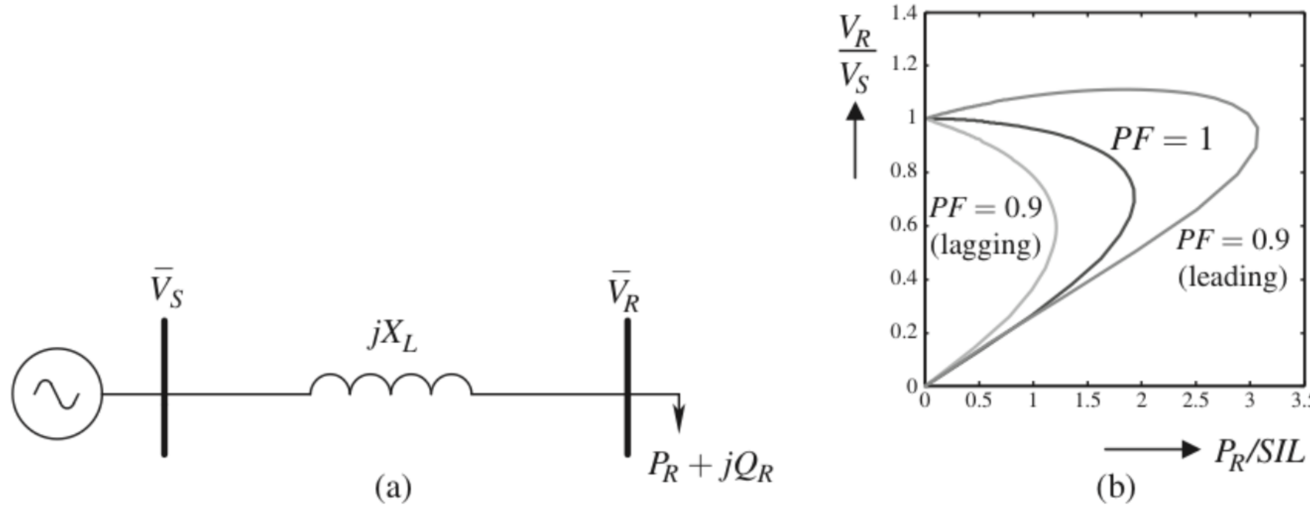
If $P_R < SIL$, the line produces reactive power and we have to absorb the surplus at its ends. The voltage profile along the line will be $V_x > V_S$.

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 $P - V$ curve (aka 'nose curve')

Consider the case of Figure (a) below, assuming an ideal voltage source:



From Figure (b), we see that there (for each PF) is a maximum value of P_R that can be transfered 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

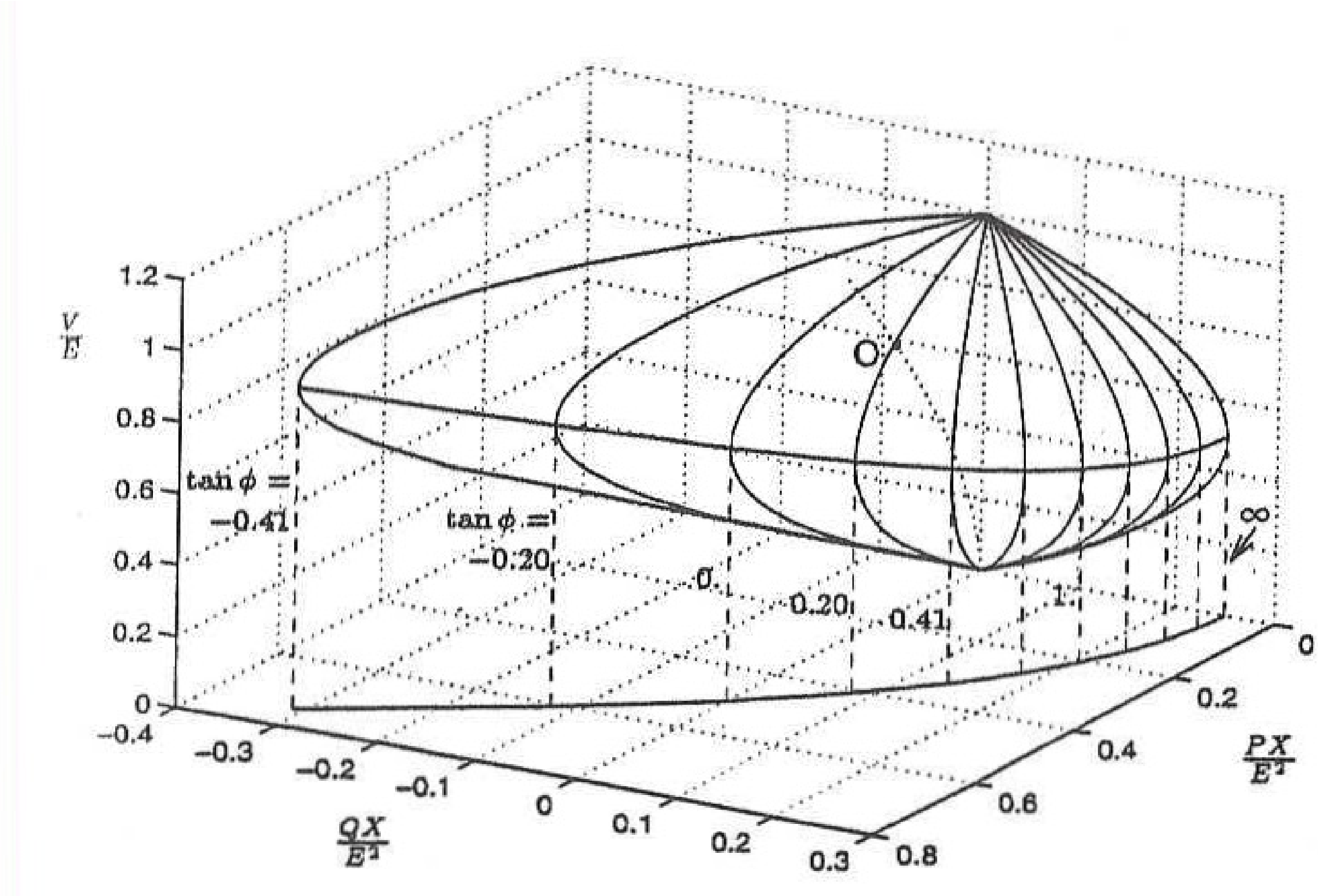


Figure from: Voltage stability of electric power systems. T. Van Cutsem & C. Vournas, KAP 1998

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

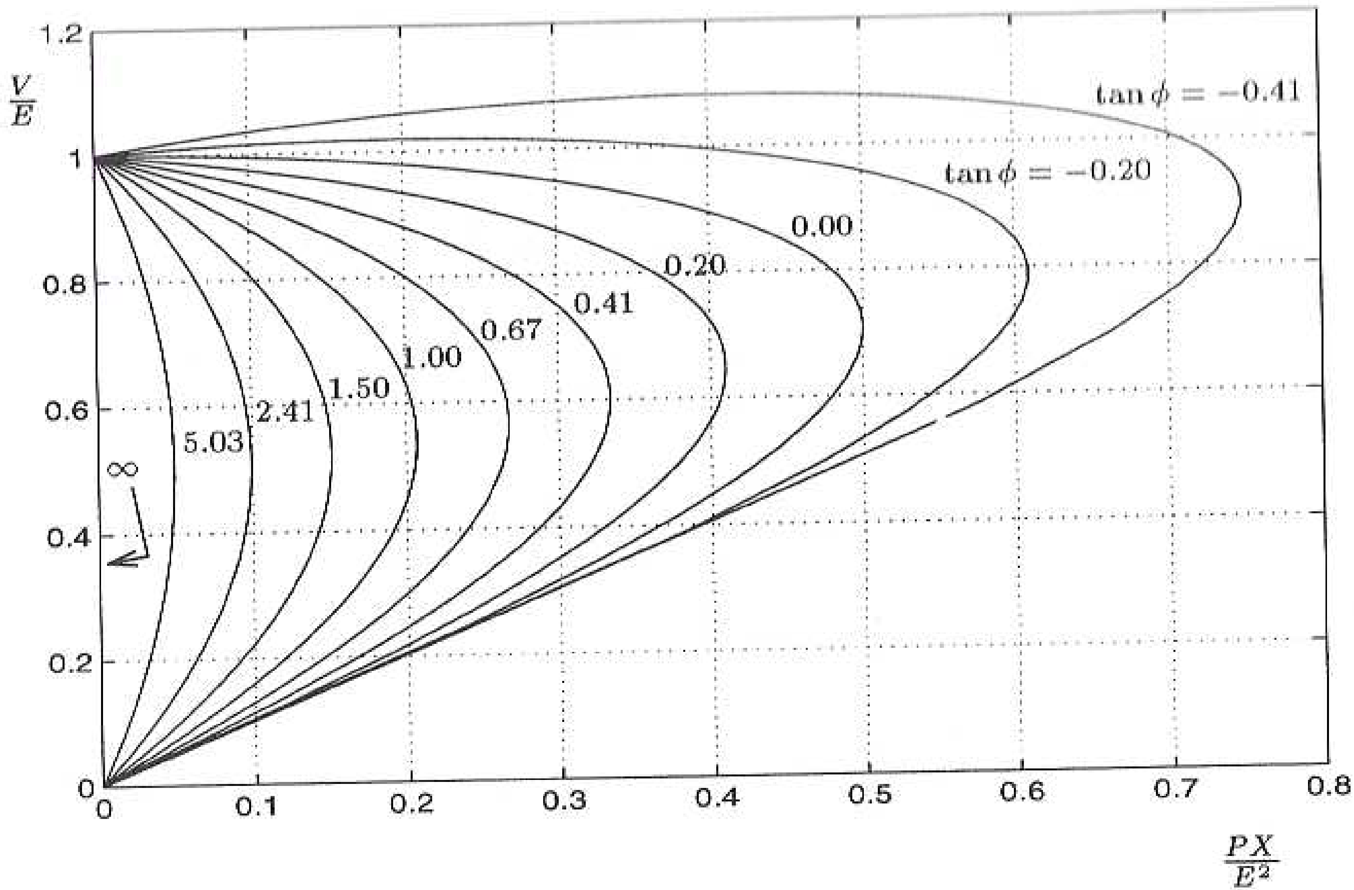


Figure from: Voltage stability of electric power systems. T. Van Cutsem & C. Vournas, KAP 1998

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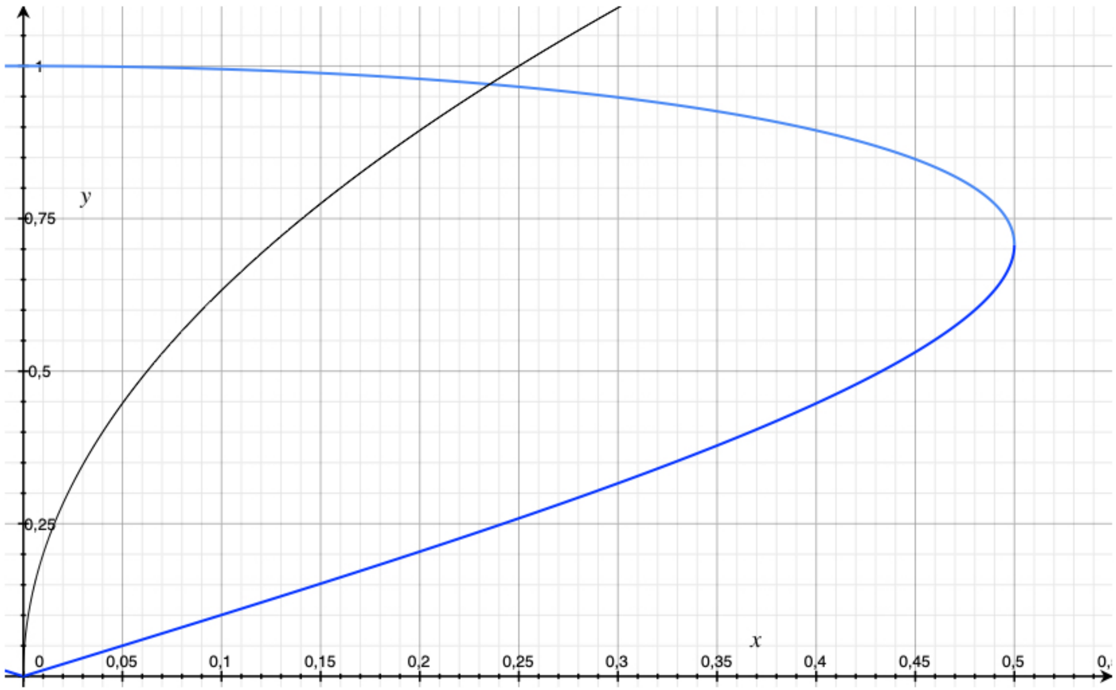
Assume a purely resistive load, i.e. PF=1 (i.e. $\tan\phi = 0$)

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

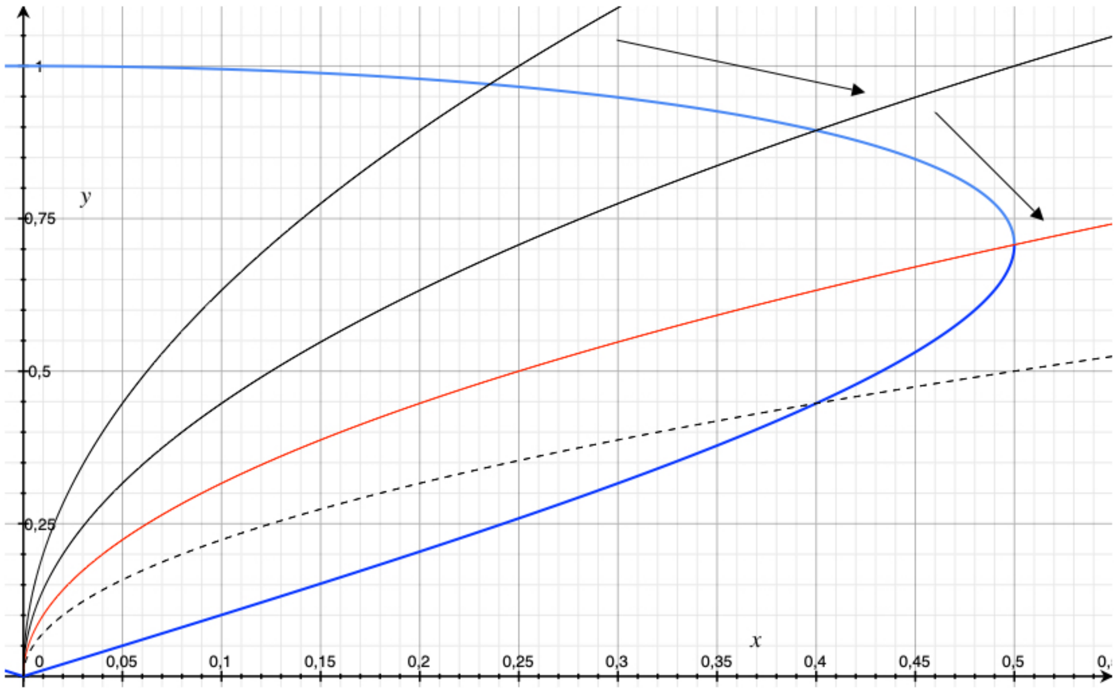


The load chacteristic (black curve) is defined by $P_R = \frac{V_R^2}{R_R}$, i.e. $y = \sqrt{x \frac{R_R}{X_L}}$

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 existings ones, and thus results in a decrease of the total load resistance.

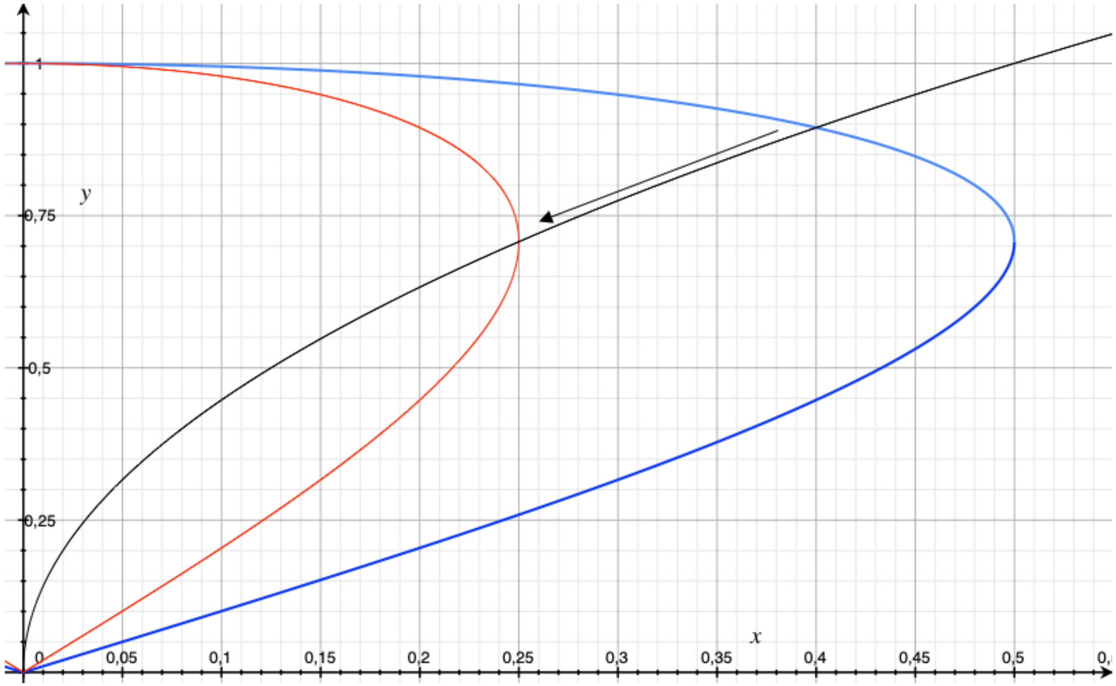


The red curve corresponds to $R_R = X_L, V_R = V_S/\sqrt{2}$ and $P_R = V_S^2/(2X_L)$.

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.

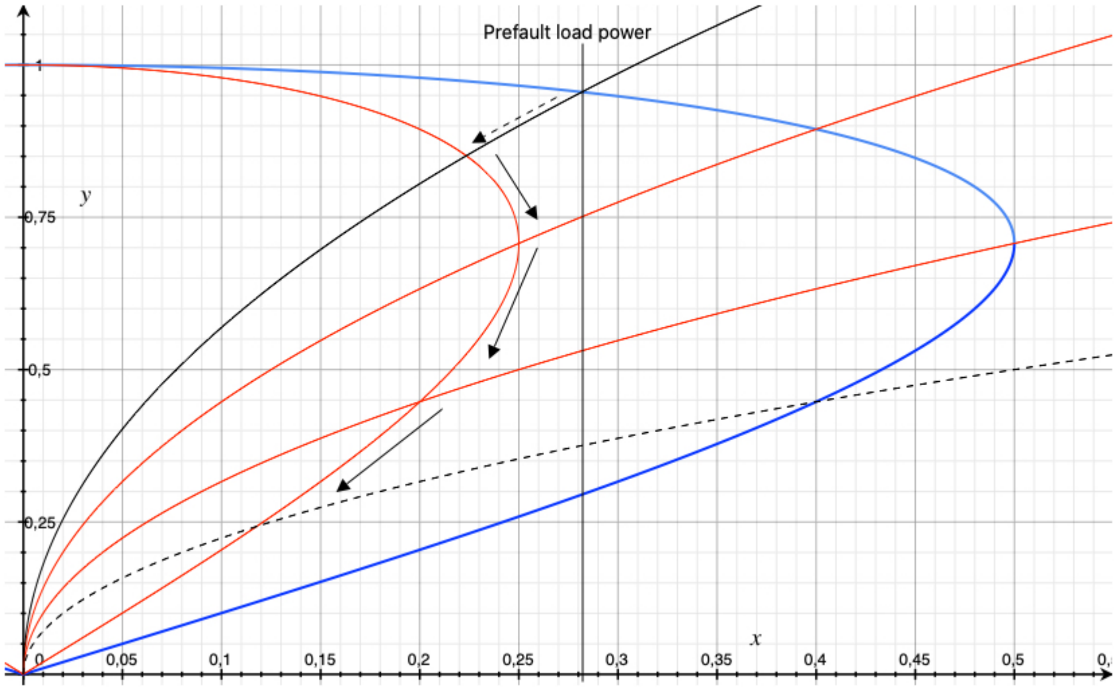
Voltage instability mechanism 2: line tripping

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 3: load restoration

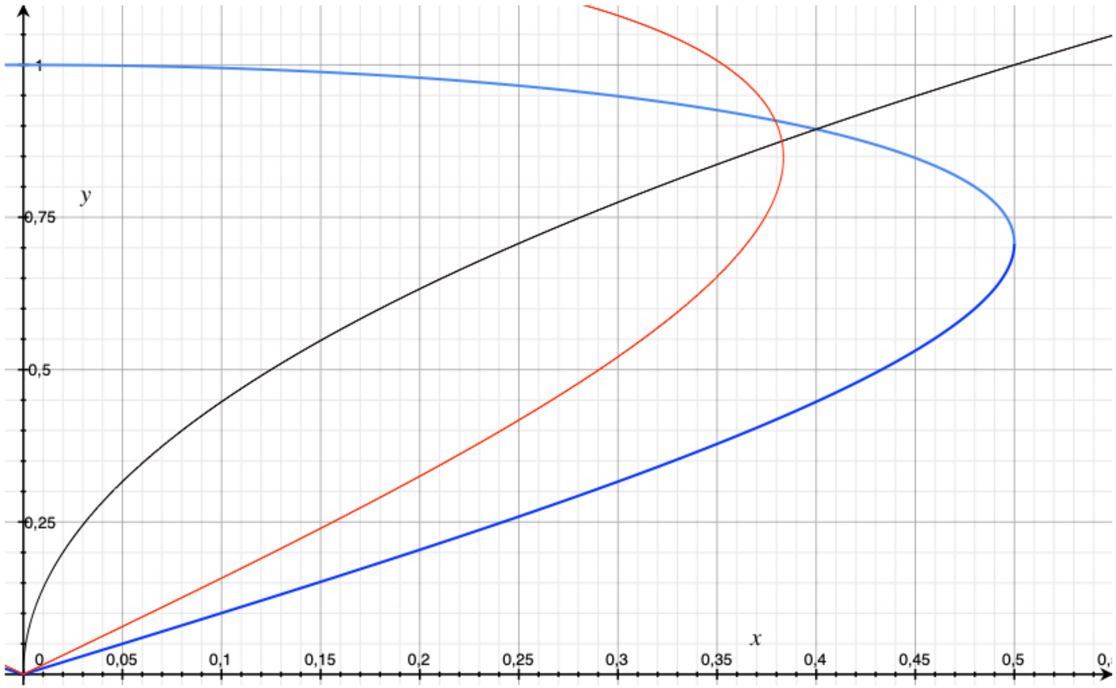


After the "instantaneous" (dashed arrow) switch of the operating point, the load power has well redecreased.

Subsequently, the load 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.

Voltage instability mechanism 4: reactive power limit of generators



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

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

NB: in practice all voltage instability mechanisms can combine.

Load restoration mechanisms

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

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

- Reactive power compensation (series and shunt capacitors) but caveat
- Ensure availability of local reactive power reserves
- Ad hoc under-voltage load-shedding schemes and clever power electronics

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
- Corrective control
- Emergency control

Likely impact of the energy transition

A think tank

- Less synchronous generators in operation at the transmission level
- Duck curve
- Higher variability of flows and flow-directions at the distribution level
- Tech opportunities

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

The end.