LIÈGE université
Sciences Appliquées

Voltage regulation and voltage instability

ELEC0447 - Analysis of electric power and energy systems

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Overview

1. The concept of stability
2. Why do we need stability?
3. Voltage instability and voltage collapse
4. Why do we need to control power systems?

Overview

- Concept of stability
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  - In power systems
- Why do we need stability?
- Voltage instability and voltage collapse
  - Impact of power flows on voltages
  - Concept of nose curve
  - Examples of voltage instabilities
- (Some) counter-measures
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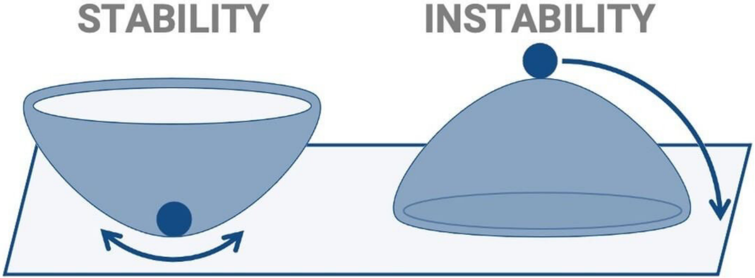
  - Voltage regulation
- Impact of renewable energy resources (RES)
  - Reverse power flows in distribution systems
  - Duck curve
- What did we learn?

The concept of stability

General concept

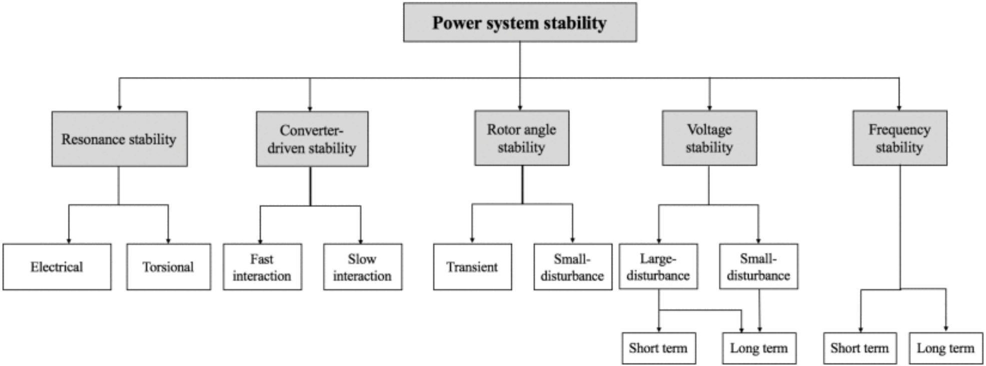
If a system has the property that it will get back into the equilibrium state again after moving away from its equilibrium state, then it is stable. [1]



In power systems I

Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact. *[2]*

In power systems II



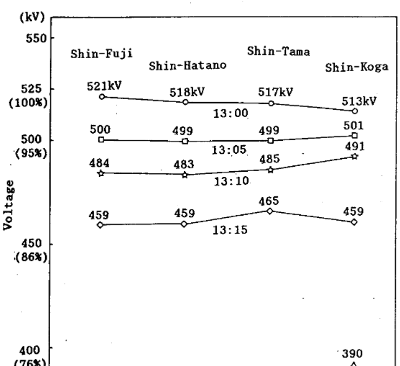
Why do we need stability?

Key points

- We often take electricity as a simple commodity.
- But the electric power system is one of the most complex and largest man-made system.
- The chances of system failures are very high taking into account the impact of external factors and rapid changes in system's state.
- However, power systems are very reliable (operated 24h/24h 7d/7d and only a few hours of power outages per year!).
- But when instabilities occur, it can lead to blackouts with huge financial and societal consequences.

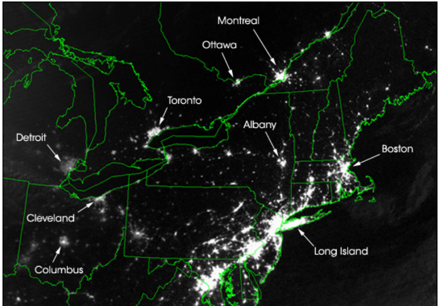
Tokyo 1987

- Unexpected load increase and presence of constant power devices (air conditioners) led to a voltage collapse.



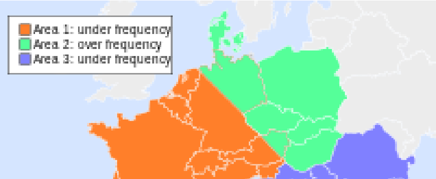
Canada/Northeast USA 2003

- Initial problem: not enough reactive power reserve. Hot weather and large consumption led to transmission lines overloading and eventually sagging into trees, further deteriorating the initial problem.
- A cascading event caused the tripping of hundreds of lines and generating units.



Europe 2006

- Disconnection of a transmission line in Germany for the transport of a ship approved by the local TSO.
- The local TSO approved to advance the disconnection later that day, but the commercial flows remained unchanged.
- Some lines were critically loaded because of the line disconnection and a fast increase of load consumption led to a cascading event.
- European interconnected network has been split into 3 islands.



Brazil 2023

- False operation of a relay protection system led to a 500kV line disconnection.
- The Energy Management System did not operate properly.

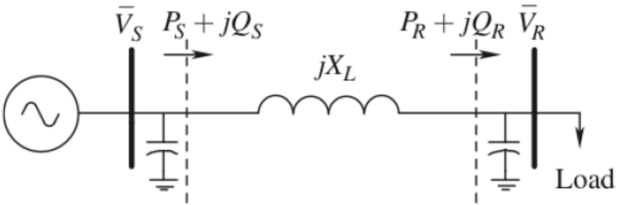
19 GW lost

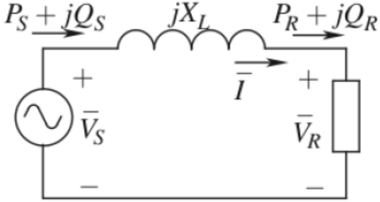
- Every time a black-out happened, lessons have been learned, and new rules have been put in place.
- Nonetheless, due to the system complexity, new complex phenomena occur that power system engineers try to understand.
- In the following, we'll dive into the mechanisms of voltage instability.

Voltage instability and voltage collapse

Impact of power flows on voltages

Consider a simple radial system.





Assuming no transmission-line losses:

$$S_S = P_S + jQ_S = V_S e^{j\delta_S} \left(\frac{V_S e^{-j\delta_S} - V_R e^{-j\delta_R}}{X} \right) e^{j\frac{\pi}{2}}$$

Impact of power flows on voltages

If we define $\delta = \delta_S - \delta_R$, we have:

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

$$Q_R = \frac{V_S V_R \cos\delta}{X_L} - \frac{V_R^2}{X_L}$$

$$Q_S = \frac{V_S^2}{X_L} - \frac{V_S V_R \cos\delta}{X_L}$$

<u>**Question:** What is the sign of Q_S if $V_S > V_R$. What about Q_R?</u>

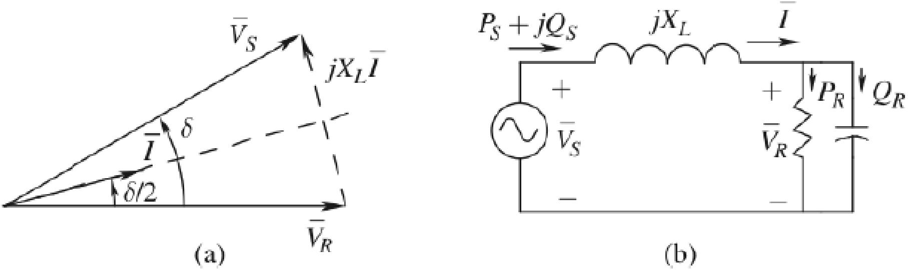
From the expression of Q_R, dividing both sides by $\frac{V_R^2}{X_L}$, we get:

$$\frac{V_R}{V_S} = \cos\delta \left(\frac{1}{1 + \frac{Q_R}{V_R^2/X_L}} \right)$$

Assuming $P_R >> 0$ and $V_R \simeq V_S \simeq 1$, it leads to $\delta >> 0 \Rightarrow \cos\delta << 1$. **Question:** What

Impact of power flows on voltages

Consider the following radial system, and the associated phasor diagram for which we consider $V_R = 1e^{j0}, V_S = 1e^{j\delta}$.



Considering Kirchhoff's Laws, one has:

Impact of power flows on voltages

Question: Where does the reactive power go?

- Total reactive power loss:

$$Q_S - (-Q_S) = 2Q_S$$

- Line current:

$$\bar{I} = \frac{2\sin(\delta/2)}{X_L} e^{j(\delta/2)}$$

- Reactive power consumed by the line:

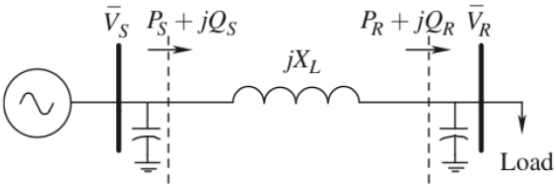
$$X_L |\bar{I}|^2 = \frac{4}{X_L} \sin(\delta/2)^2 = 2Q_S$$

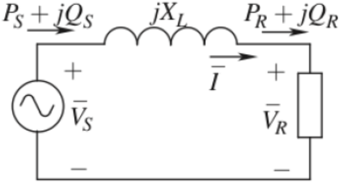
Key points

- For HV systems, we usually assume: $P_{s\to r} \propto (\delta_s - \delta_r)$
- And $Q_{s\to r} \propto (V_s - V_r)$
- Lines are mostly inductive so they consume reactive power.
- Therefore, voltage control is done locally to avoid transferring reactive power over long distances.

Concept of nose curve

Consider again the following simple radial system.





Consider $Q_R = 0 \Rightarrow \frac{V_S V_R \cos\delta}{X_L} - \frac{V_R^2}{X_L} = 0 \Rightarrow V_S \cos\delta = V_R$ We know $P_R = \frac{V_S V_R}{X_L} \sin\delta$, substituing the previous results in the expression of P_R gives:

$$P_R = \frac{V_S^2}{X_L} \sin\delta \cos\delta = \frac{V_S^2}{2X_L} \sin(2\delta)$$

We can determine the maximum transmissible power by setting the partial derivative to 0:

Concept of nose curve

Replacing δ by δ^* in the equation of P_R, we have:

$$P_R^{max} = \frac{V_S^2}{2X_L}$$

and

$$V_R \approx 0.7V_S$$

Question: How can we increase the maximum transmissible power through a line?

One can derive a relationship such that $\frac{V_R}{V_S} = f(\frac{P_R X_L}{V_S^2})$. Consider $y = \frac{V_R}{V_S}$ and $x = \frac{P_R X_L}{V_S^2}$, one has (trust me):

$$y = \sqrt{\frac{1}{2} \pm \sqrt{\frac{1}{4} - x^2}}$$

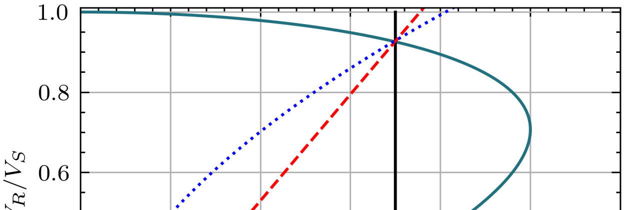
We verify that y has a unique solution when $x = \frac{1}{2} \Rightarrow P_R = \frac{V_S^2}{2X_L}$, which is the nose of the curve. There is no solution for $P_R > \frac{V_S^2}{2X_L}$ and two solutions for $P_R < \frac{V_S^2}{2X_L}$.

Concept of nose curve

Let us consider different load characteristics:

$$P_{constant} \Rightarrow P_R = C_P \Rightarrow x = c_P$$
$$I_{constant} \Rightarrow \frac{P_R}{V_R} = C_I \Rightarrow y = c_I x$$
$$Z_{constant} \Rightarrow \frac{P_R}{V_R^2} = C_Z \Rightarrow y = c_Z \sqrt{x}$$

The operating point is where the load characteristic crosses the *PV curve*.



Concept of nose curve

$$P_R = V_R I \cos\phi = \frac{V_S V_R}{X_L} \sin\delta$$

Let us consider $\cos\phi = 1$ (unity power factor), and $X_L = 1$ as well as $V_S = 1$.

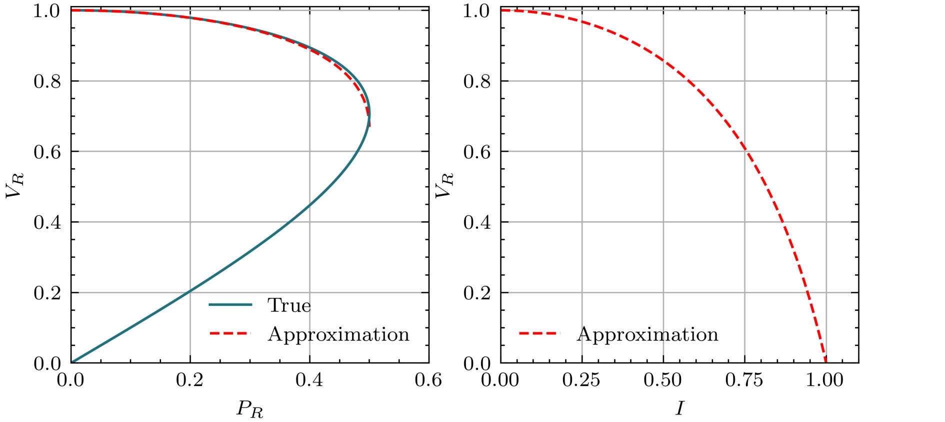
$$I = \frac{V_S}{X_L} \sin\delta = \sin\delta$$

$$Q_S = \frac{V_S^2}{X_L} - \frac{V_S V_R \cos\delta}{X_L} = 1 - V_R \cos\delta$$

Since $Q_R = 0$, you know that $Q_S = X_L I^2 = I^2 \Rightarrow \frac{-I^2+1}{\cos\delta} = V_R$. Consider the Taylor expansion of $\sin\delta \approx \delta$ and $\cos\delta \approx 1 - \frac{\delta^2}{2}$ for $\delta \approx 0$, we have

$$V_R \approx \frac{(1 - I^2)}{(1 - I^2) + I^2/2}$$

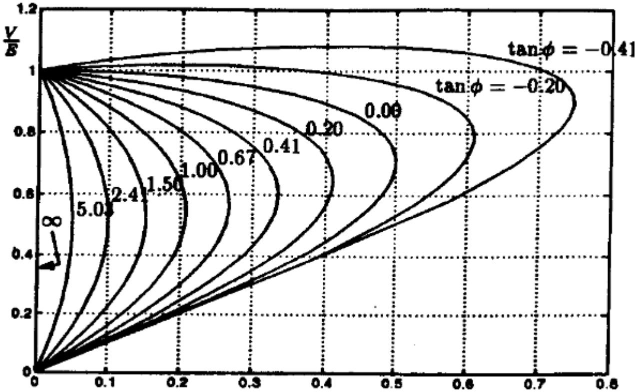
Concept of nose curve



Since $I = \sin\delta \leq 1$, which implies that $(1 - I^2) \geq 0$ and therefore V_R decreases when I increases. But after a given value of I, V_R decreases faster than I increases. Since

Concept of nose curve

NO When you consider $\cos\phi \neq 1$ (the load consumes or produces reactive power), you get more complex nose curves [**?**].



Key points

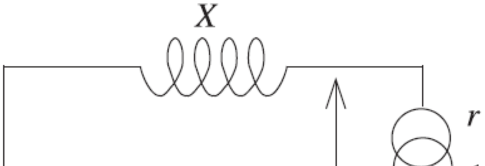
- There's a maximum transmissible power ($P_R^{max} = \frac{V_S^2}{2X_L}$ for load with $\cos\phi = 1$).
- Inductive character of the line which consumes reactive power (influence of X_L)

How to increase P_R^{max}?

- By increasing the source voltage V_S,
- By decreasing X_L (adding lines in parallel),
- By producing reactive power at the load side to compensate for the reactive power consumed by the line.

Examples of voltage instabilities

Long-term instabilities On-load tap changers (OLTCs) change the turn ratio of the transformers feeding the distribution systems to keep the voltages on the secondary side as close as possible to a given setpoint. Let us consider the following circuit, where the primary side of the transformer is the high voltage network, and the secondary side is the medium voltage network. The load on the secondary side is represented by a constant conductance G, consuming active power. The voltage on the primary side is controlled by a synchronous generator. V_g is kept constant as long as the reactive power limits of the generator are not reached.



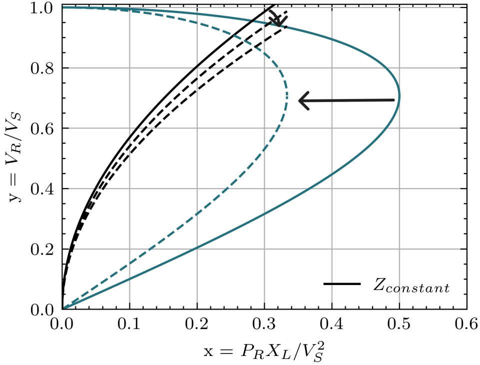
Examples of voltage instabilities

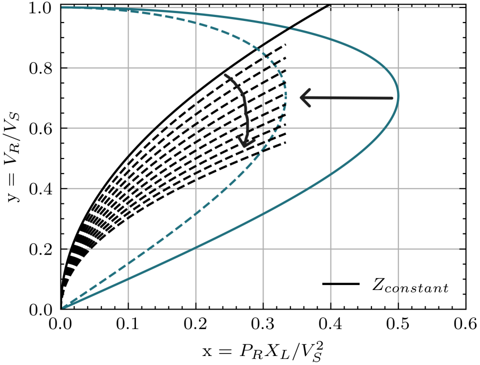
We assume an ideal transformer: $\frac{V}{V_2} = r$, $\frac{I_2}{I} = r$. The load characteristic seen from the primary side becomes $P_G = G\left(\frac{V}{r}\right)^2$, with P_G the power consumed by the conductance G. Now, imagine one wants to keep $V_2 = V_2^o$, if $V \searrow \Rightarrow r \searrow$. Indirectly, by decreasing r, the OLTC tries to restore the load (since it increases V_2 and $P_G = GV_2^2 = G\left(\frac{V}{r}\right)^2$). Two different scenarii:

- 1) $\frac{V}{r}$ converges towards V_2^o, the load is restored.
- 2) $\frac{V}{r}$ never converges towards V_2^o and V collapses.

Examples of voltage instabilities

Imagine a disturbance leading to a decrease in the maximum transmissible power.

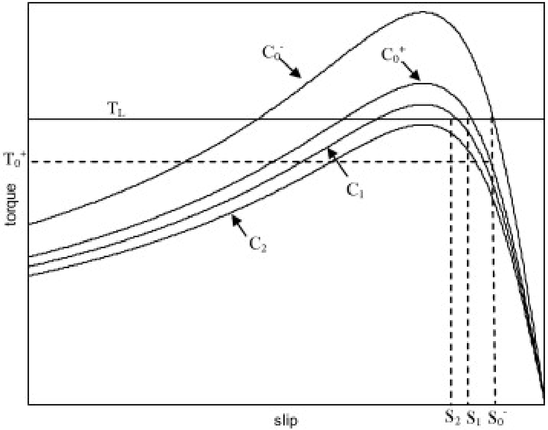




- 1) Left figure shows P_G is recovered after two tap changes.

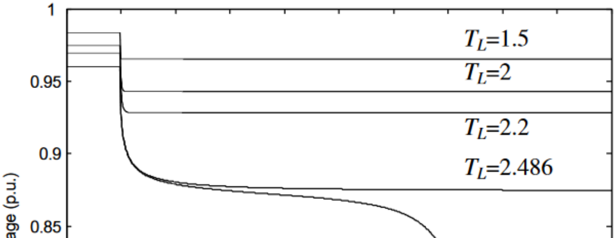
Examples of voltage instabilities

Short-term instabilities Consider an induction motor. The torque-speed curve is given below.



Examples of voltage instabilities

If now the voltage drops faster, and the new curve becomes C_2, the motor speed is reduced until it completely stops (since there is no intersection between C_2 and T_L). The induction motor acts as a large inductance, drawing reactive power. This is considered as a **Short-term Voltage Instability** as this phenomenon is much quicker than what we have with OLTCs (it takes several seconds to change tap positions). OLTCs are not able to restore the voltage.



Why do we need to control power systems?

Why to control power systems?

- Technical requirements: power system devices are designed so as to operate within well-defined "tolerance regions"
  - around nominal values of voltage V_n: 1 ± 0.1 pu in Europe
  - around nominal value of frequency f_n: 50 ± 0.2 Hz in Europe (in steady state)
  - within the P-Q capabilities of devices
  - under the current limits of lines and transformers
- Large/persistent deviations from nominal values could lead to
  - damages and safety problems (e.g. high voltage)
  - cascading phenomena
  - service interruptions

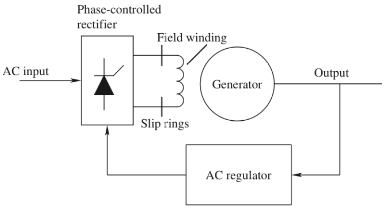
Exogeneous threats

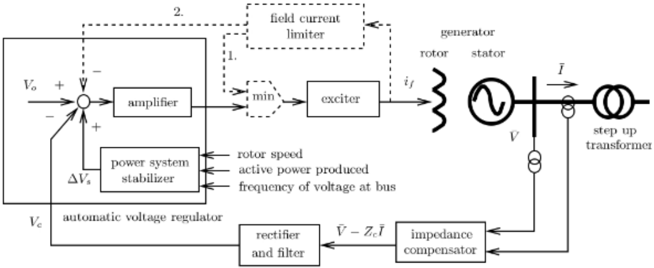
- Sudden disturbances, such as line or generator tripping
- Fast variations of the *net load* (cf. Duck curve)
  - the net load refers to the load "seen" by the transmission system, i.e. the load minus the non-controllable dispersed generation
- weather conditions, such as storms, which can impact the generation of renewable energy sources (RES) (e.g. wind turbines' cut-out speed)

Principle of Automatic Voltage Control

- *The main tool:* primary voltage control via *Automatic Voltage Regulators (AVRs)* of large synchronous generators and synchronous condensers
- Secondary voltage control and automatic switching of reactive compensation devices and transformer taps
- Tertiary voltage control and voltage profile optimization

Automatic voltage regulator of a synchronous machine (reminder)





Automatic Voltage Regulator (AVR)

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

- Notice that if several generators are connected in parallel (either at the MV or at the EHV bus), it is necessary to coordinate their AVRs so that they share the reactive power in an even way.
- The value of Z_c may be adjusted in order to ensure such a coordination.

Primary, secondary and tertiary voltage control

- When a disturbance occurs, or subsequently to following the change in load (cf. ’duck curve’), the *primary* voltage control loops maintain suitable voltage levels close to the large power plants equipped with AVRs.
  - However, voltages at other buses may move out of tolerance intervals (in either direction), and reactive power reserves may not be shared in an even way among generators.
- *Secondary* voltage control loops can be used at the zonal level, to adjust the set-points of AVRs so as to control the voltage at ’pilot nodes’ in the network while distributing the required reactive power evenly among generators.
  - Secondary voltage control loops can also be used to switch shunt reactive compensation devices (capacitors/inductors) in order to increase reactive power generation margins in their zone (among a few large power plants).
- *Tertiary* voltage control uses OPF solvers to calculate set-points at pilot nodes and possibly adjust some transformer ratios, so as to minimize losses and maximize MVar

Control resources

Which of these control resources are the main levers for freqency stability?

- Adjust synchronous generators’ field current
- Adjust synchronous generators’ mechanical power
- Change transformer taps
- Change shunt compensation
- Act on topology: switch lines and transformers in/out of service
- Fast start-up generator units
- In extremis load curtailment
- Control renewable generation (e.g. PV curtailment)
- Use batteries and other energy storage systems

References I

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- N. Hatziargyriou, J. Milanovic, C. Rahmann, V. Ajjarapu, C. Canizares, I. Erlich, D. Hill, I. Hiskens, I. Kamwa, B. Pal, *et al.*, "Definition and classification of power system stability–revisited & extended," *IEEE Transactions on Power Systems*, vol. 36, no. 4, pp. 3271–3281, 2020.