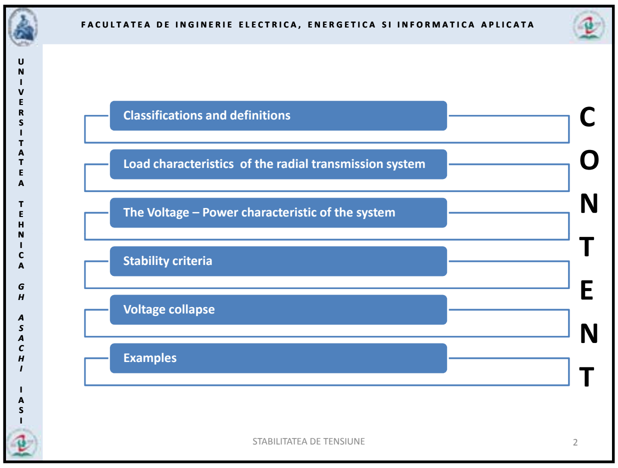
# STABILITATEA SISTEMELOR ELECTROENERGETICE

## STABILITATEA DE TENSIUNE
(Voltage Stability)



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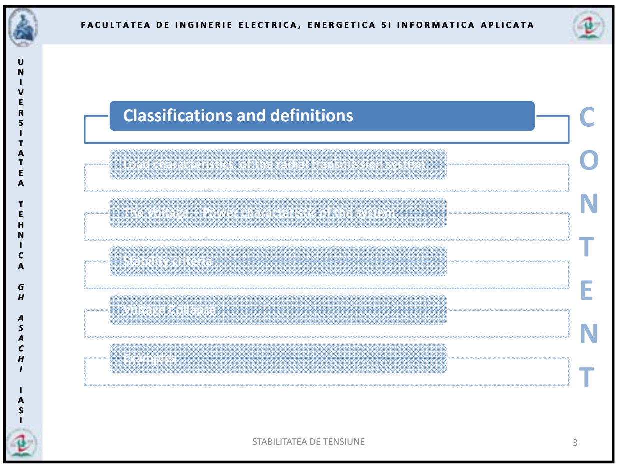
CONTENT

- Classifications and definitions
- Load characteristics of the radial transmission system
- The Voltage – Power characteristic of the system
- Stability criteria
- Voltage collapse
- Examples

STABILITATEA DE TENSIUNE 2



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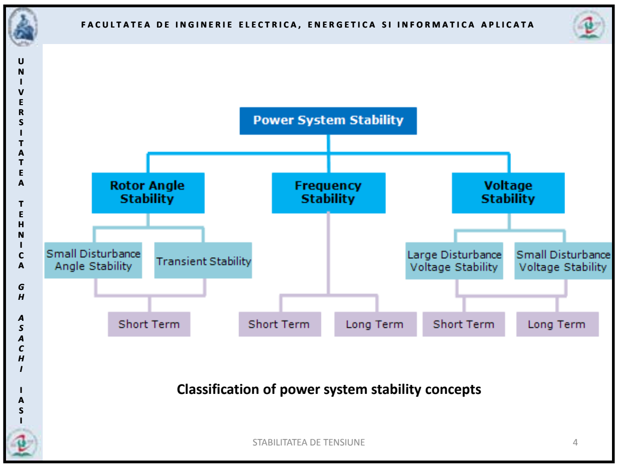

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Power System Stability

Rotor Angle Stability

Frequency Stability

Voltage Stability

Small Disturbance Angle Stability

Transient Stability

Large Disturbance Voltage Stability

Small Disturbance Voltage Stability

Short Term

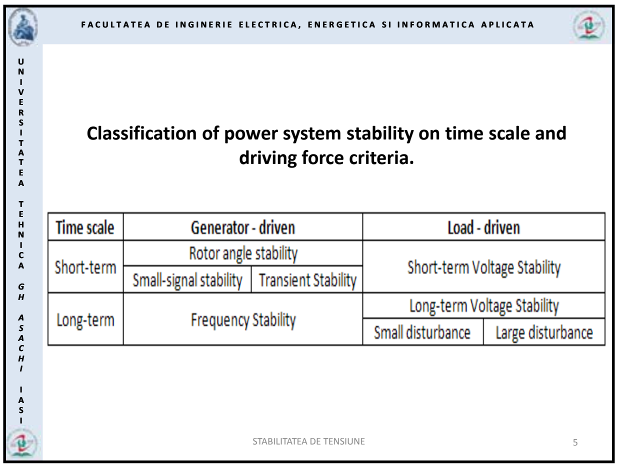
Short Term

Long Term

Short Term

Long Term

Classification of power system stability concepts



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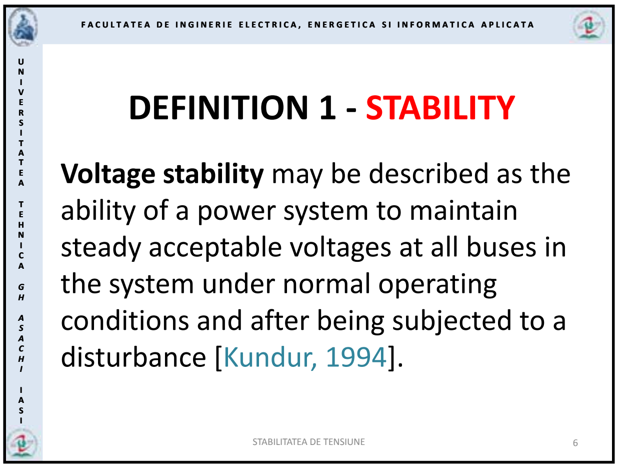
**Classification of power system stability on time scale and driving force criteria.**

| Time scale | Generator - driven | | Load - driven | |
|---|---|---|---|---|
| Short-term | Rotor angle stability | | Short-term Voltage Stability | |
| | Small-signal stability | Transient Stability | | |
| Long-term | Frequency Stability | | Long-term Voltage Stability | |
| | | | Small disturbance | Large disturbance |



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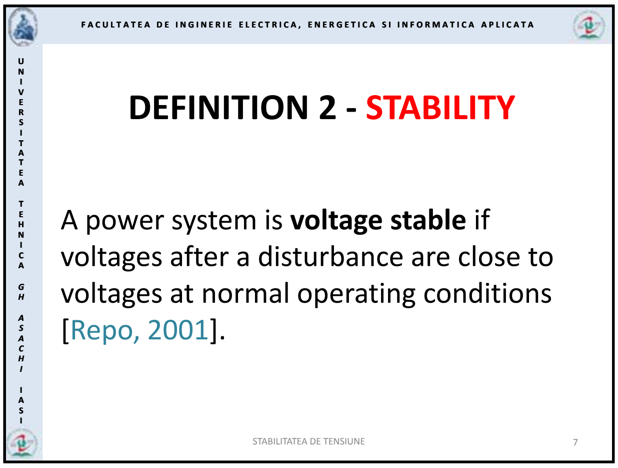
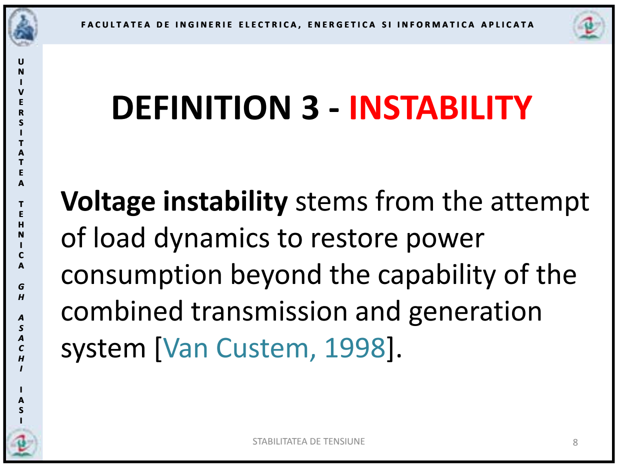
## DEFINITION 1 - STABILITY

**Voltage stability** may be described as the ability of a power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance [Kundur, 1994].



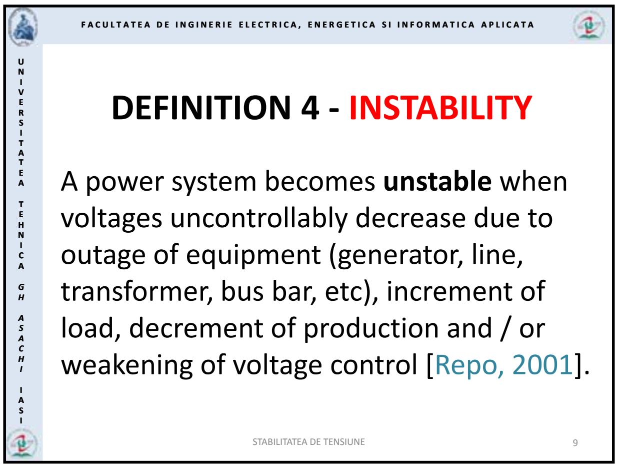
## DEFINITION 2 - STABILITY

A power system is **voltage stable** if voltages after a disturbance are close to voltages at normal operating conditions [Repo, 2001].



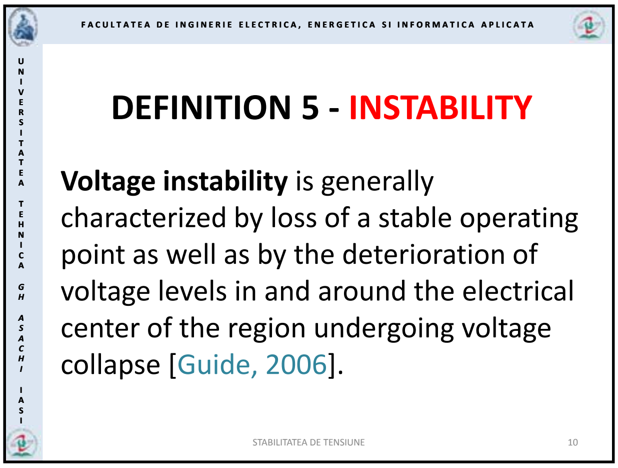
## DEFINITION 3 - INSTABILITY

**Voltage instability** stems from the attempt of load dynamics to restore power consumption beyond the capability of the combined transmission and generation system [Van Custem, 1998].



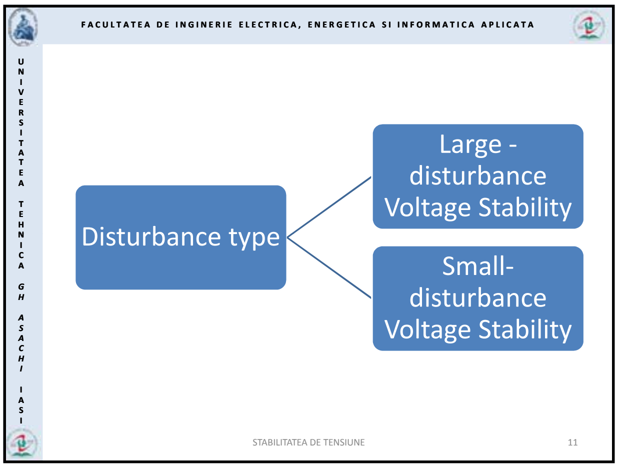
## DEFINITION 4 - INSTABILITY

A power system becomes **unstable** when voltages uncontrollably decrease due to outage of equipment (generator, line, transformer, bus bar, etc), increment of load, decrement of production and / or weakening of voltage control [Repo, 2001].



## DEFINITION 5 - INSTABILITY

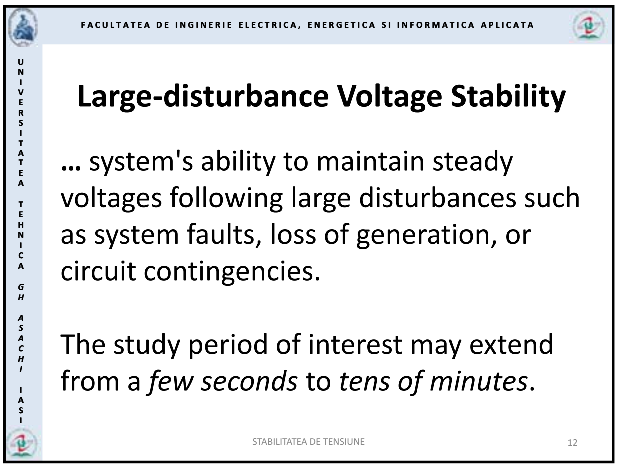
**Voltage instability** is generally characterized by loss of a stable operating point as well as by the deterioration of voltage levels in and around the electrical center of the region undergoing voltage collapse [Guide, 2006].



Disturbance type

Large - disturbance Voltage Stability

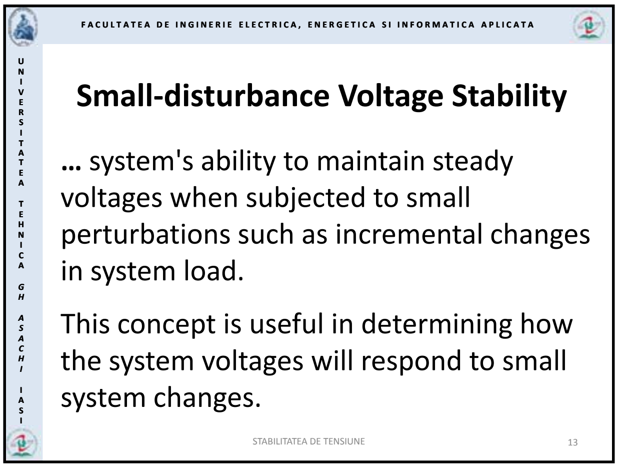
Small- disturbance Voltage Stability



## Large-disturbance Voltage Stability

**…** system's ability to maintain steady voltages following large disturbances such as system faults, loss of generation, or circuit contingencies.

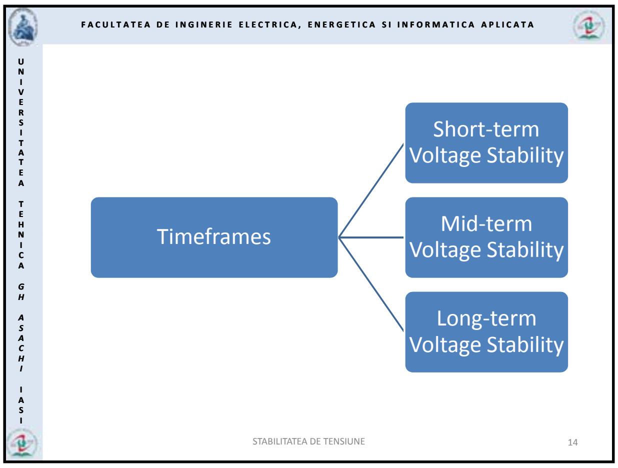
The study period of interest may extend from a *few seconds* to *tens of minutes*.



## Small-disturbance Voltage Stability

**…** system's ability to maintain steady voltages when subjected to small perturbations such as incremental changes in system load.

This concept is useful in determining how the system voltages will respond to small system changes.

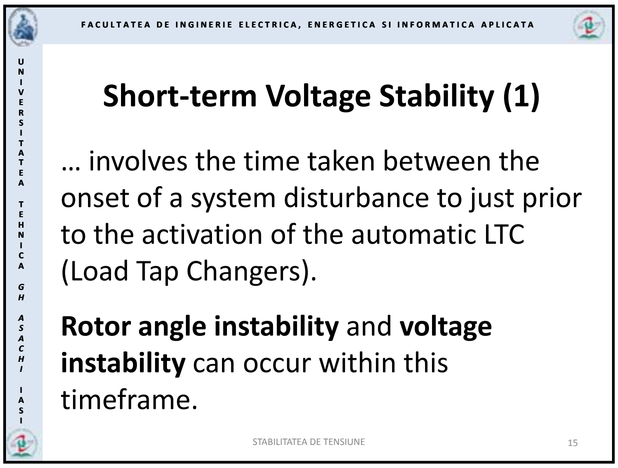


Timeframes

Short-term Voltage Stability

Mid-term Voltage Stability

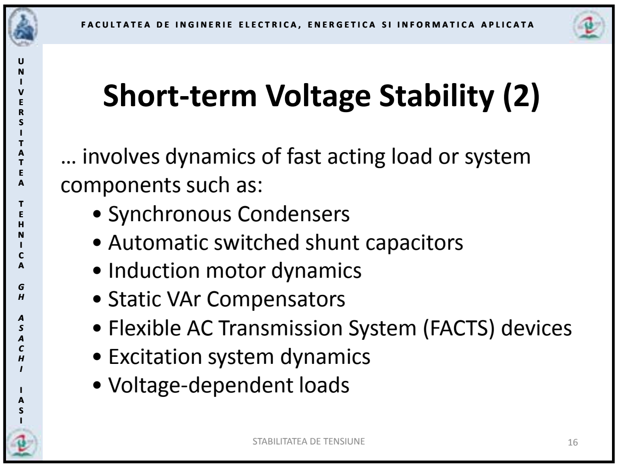
Long-term Voltage Stability



## Short-term Voltage Stability (1)

… involves the time taken between the onset of a system disturbance to just prior to the activation of the automatic LTC (Load Tap Changers).

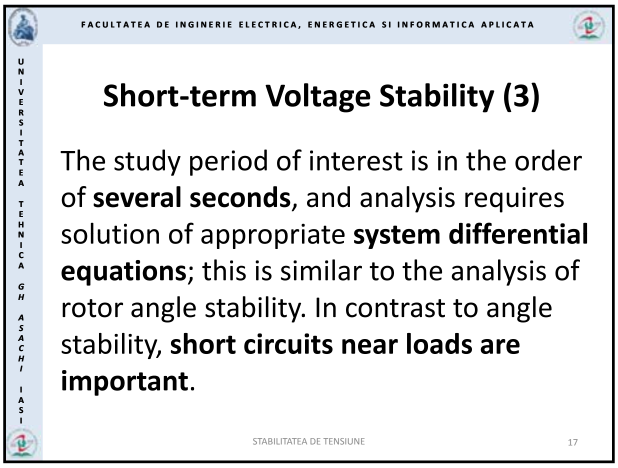
**Rotor angle instability** and **voltage instability** can occur within this timeframe.



## Short-term Voltage Stability (2)

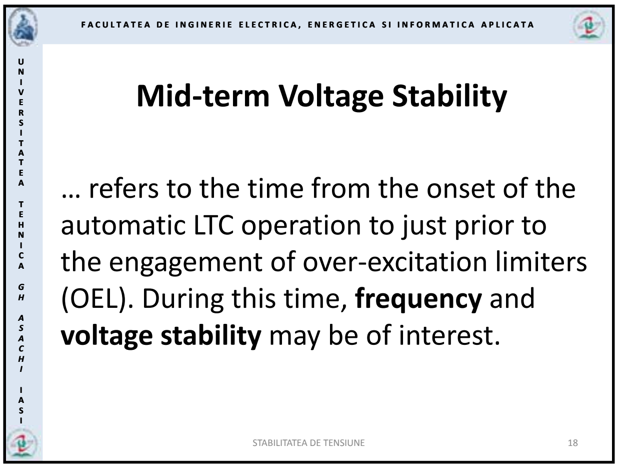
… involves dynamics of fast acting load or system components such as:

- Synchronous Condensers
- Automatic switched shunt capacitors
- Induction motor dynamics
- Static VAr Compensators
- Flexible AC Transmission System (FACTS) devices
- Excitation system dynamics
- Voltage-dependent loads



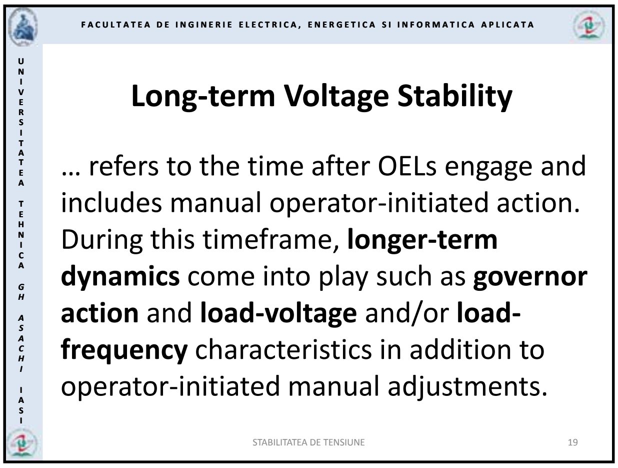
## Short-term Voltage Stability (3)

The study period of interest is in the order of **several seconds**, and analysis requires solution of appropriate **system differential equations**; this is similar to the analysis of rotor angle stability. In contrast to angle stability, **short circuits near loads are important**.



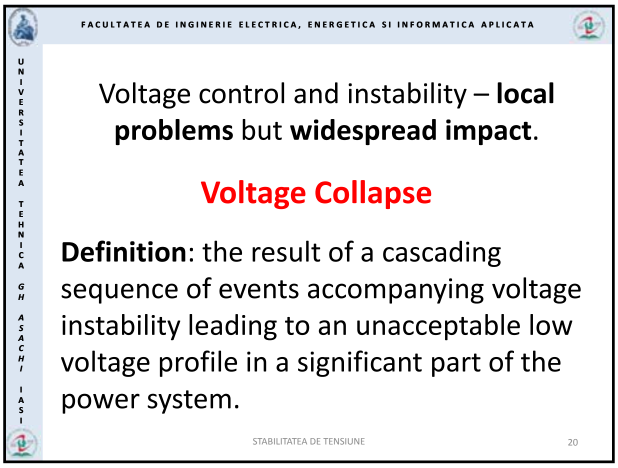
## Mid-term Voltage Stability

… refers to the time from the onset of the automatic LTC operation to just prior to the engagement of over-excitation limiters (OEL). During this time, **frequency** and **voltage stability** may be of interest.



## Long-term Voltage Stability

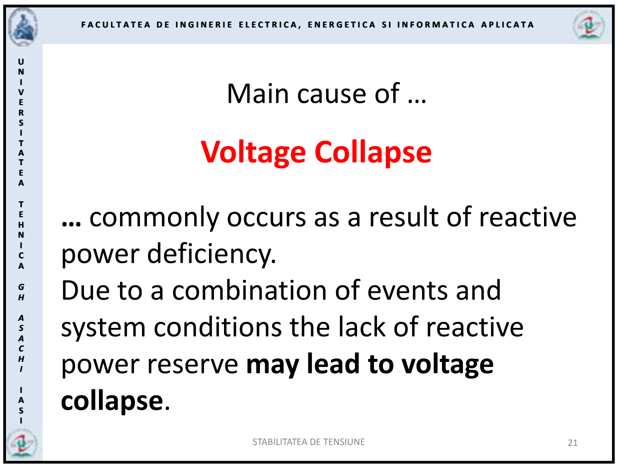
… refers to the time after OELs engage and includes manual operator-initiated action. During this timeframe, **longer-term dynamics** come into play such as **governor action** and **load-voltage** and/or **load-frequency** characteristics in addition to operator-initiated manual adjustments.



Voltage control and instability – **local problems** but **widespread impact**.

## Voltage Collapse

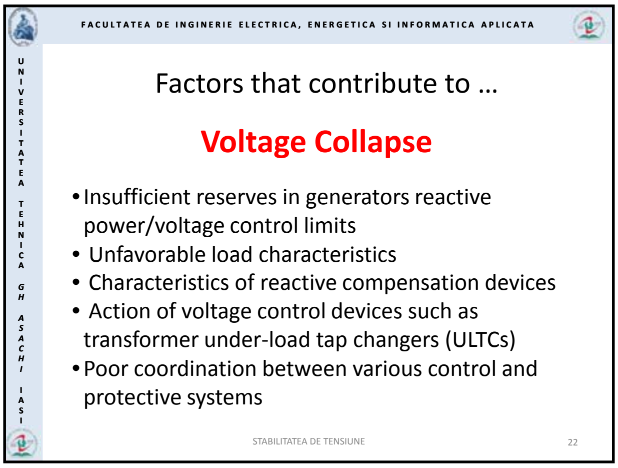
**Definition**: the result of a cascading sequence of events accompanying voltage instability leading to an unacceptable low voltage profile in a significant part of the power system.



Main cause of …

## Voltage Collapse

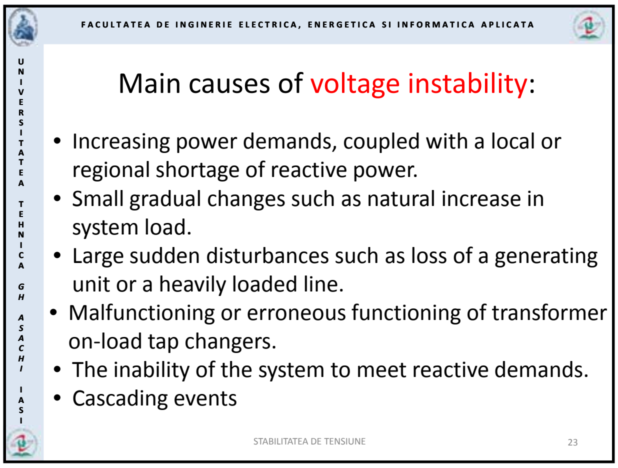
**…** commonly occurs as a result of reactive power deficiency.
Due to a combination of events and system conditions the lack of reactive power reserve **may lead to voltage collapse**.



## Factors that contribute to …

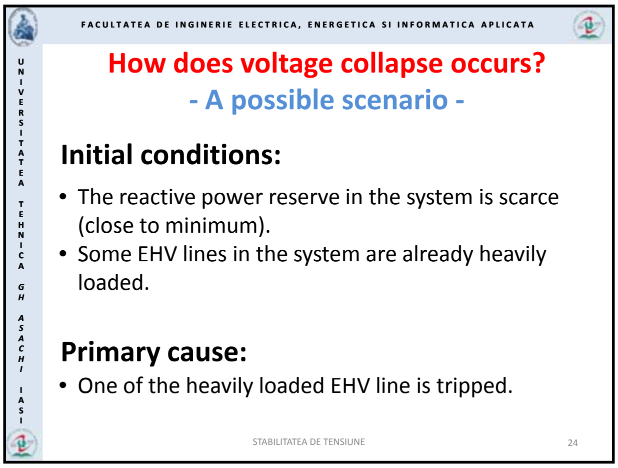
## Voltage Collapse

- Insufficient reserves in generators reactive power/voltage control limits
- Unfavorable load characteristics
- Characteristics of reactive compensation devices
- Action of voltage control devices such as transformer under-load tap changers (ULTCs)
- Poor coordination between various control and protective systems



## Main causes of voltage instability:

- Increasing power demands, coupled with a local or regional shortage of reactive power.
- Small gradual changes such as natural increase in system load.
- Large sudden disturbances such as loss of a generating unit or a heavily loaded line.
- Malfunctioning or erroneous functioning of transformer on-load tap changers.
- The inability of the system to meet reactive demands.
- Cascading events



## How does voltage collapse occurs?

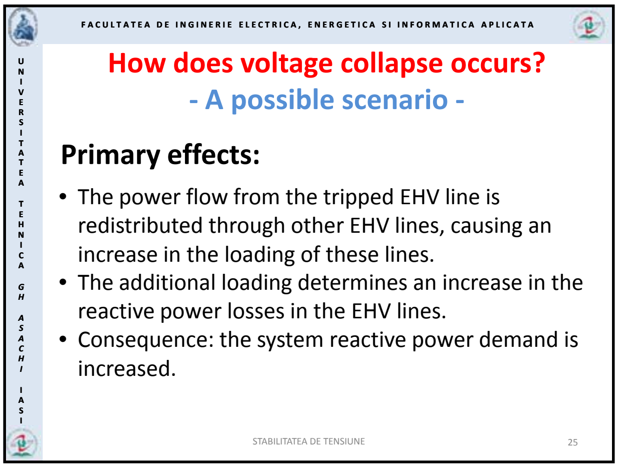
### - A possible scenario -

**Initial conditions:**

- The reactive power reserve in the system is scarce (close to minimum).
- Some EHV lines in the system are already heavily loaded.

**Primary cause:**

- One of the heavily loaded EHV line is tripped.

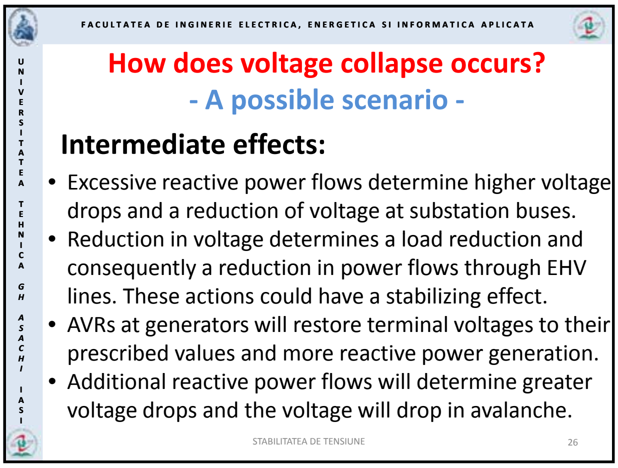


## How does voltage collapse occurs?

### - A possible scenario -

**Primary effects:**

- The power flow from the tripped EHV line is redistributed through other EHV lines, causing an increase in the loading of these lines.
- The additional loading determines an increase in the reactive power losses in the EHV lines.
- Consequence: the system reactive power demand is increased.

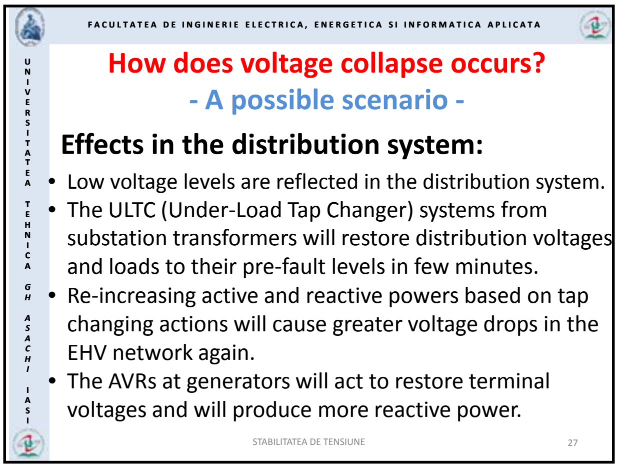


## How does voltage collapse occurs?

### - A possible scenario -

**Intermediate effects:**

- Excessive reactive power flows determine higher voltage drops and a reduction of voltage at substation buses.
- Reduction in voltage determines a load reduction and consequently a reduction in power flows through EHV lines. These actions could have a stabilizing effect.
- AVRs at generators will restore terminal voltages to their prescribed values and more reactive power generation.
- Additional reactive power flows will determine greater voltage drops and the voltage will drop in avalanche.



## How does voltage collapse occurs?

### - A possible scenario -

**Effects in the distribution system:**

- Low voltage levels are reflected in the distribution system.
- The ULTC (Under-Load Tap Changer) systems from substation transformers will restore distribution voltages and loads to their pre-fault levels in few minutes.
- Re-increasing active and reactive powers based on tap changing actions will cause greater voltage drops in the EHV network again.
- The AVRs at generators will act to restore terminal voltages and will produce more reactive power.

## How does voltage collapse occurs?

### - A possible scenario -

### Cascading effect:

- Gradually all or part of the generators in the system will reach their reactive power limits (the maximum field current).
- Suppose the first generator has reached its limits. At this moment the AVR could no more maintain the prescribed value of the terminal voltage, which will drop down.
- To continue to produce the same power with lower voltages, the armature current will increase causing additional reduction in the generator's reactive power.

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## How does voltage collapse occurs?

### - A possible scenario -

### Cascading effect - continued:

- Hence the initial share of reactive power of this generator will be transferred to other generators, leading to overloading more and more generators.
- This process will eventually lead to voltage collapse and possibly to loss of synchronism of generating units.

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CONTENT

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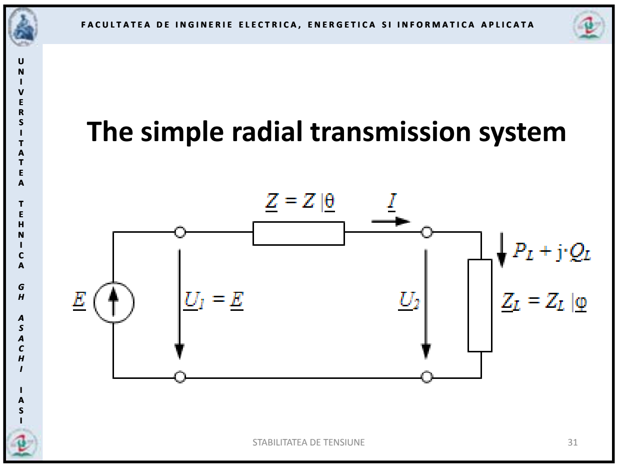
The Voltage – Power characteristic of the system

Stability criteria

Voltage collapse

Examples



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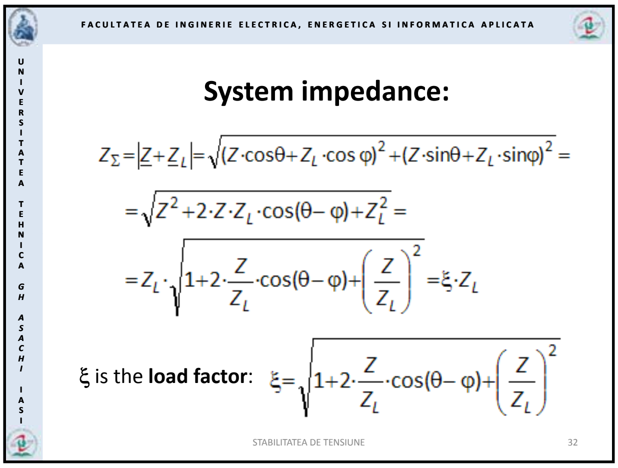
## The simple radial transmission system



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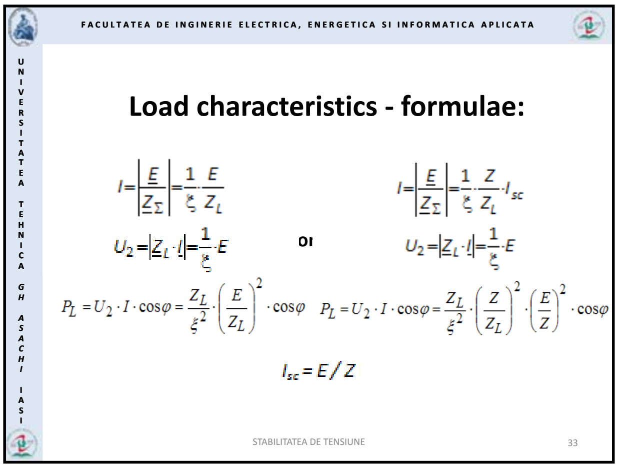
## System impedance:

$$Z_\Sigma = |\underline{Z}+\underline{Z}_L| = \sqrt{(Z\cdot\cos\theta + Z_L\cdot\cos\varphi)^2 + (Z\cdot\sin\theta + Z_L\cdot\sin\varphi)^2} =$$

$$= \sqrt{Z^2 + 2\cdot Z\cdot Z_L\cdot\cos(\theta-\varphi) + Z_L^2} =$$

$$= Z_L\cdot\sqrt{1 + 2\cdot\frac{Z}{Z_L}\cdot\cos(\theta-\varphi) + \left(\frac{Z}{Z_L}\right)^2} = \xi\cdot Z_L$$

ξ is the **load factor**: $\xi = \sqrt{1 + 2\cdot\frac{Z}{Z_L}\cdot\cos(\theta-\varphi) + \left(\frac{Z}{Z_L}\right)^2}$



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## Load characteristics - formulae:

$$I = \left|\frac{\underline{E}}{\underline{Z}_\Sigma}\right| = \frac{1}{\xi}\cdot\frac{E}{Z_L} \qquad I = \left|\frac{\underline{E}}{\underline{Z}_\Sigma}\right| = \frac{1}{\xi}\cdot\frac{Z}{Z_L}\cdot I_{sc}$$

$$U_2 = |\underline{Z}_L\cdot\underline{I}| = \frac{1}{\xi}\cdot E \qquad \text{or} \qquad U_2 = |\underline{Z}_L\cdot\underline{I}| = \frac{1}{\xi}\cdot E$$

$$P_L = U_2\cdot I\cdot\cos\varphi = \frac{Z_L}{\xi^2}\cdot\left(\frac{E}{Z_L}\right)^2\cdot\cos\varphi \qquad P_L = U_2\cdot I\cdot\cos\varphi = \frac{Z_L}{\xi^2}\cdot\left(\frac{Z}{Z_L}\right)^2\cdot\left(\frac{E}{Z}\right)^2\cdot\cos\varphi$$

$$I_{sc} = E/Z$$

# Load characteristics - formulae:

Active power **maximum value**: $P_{L,\max}=\dfrac{E^2\cdot\cos\varphi}{Z_L\cdot\sqrt{2\cdot[1+\cos(\theta-\varphi)]}}=\dfrac{E^2\cdot\cos\varphi}{4\cdot Z_L\cdot\cos\dfrac{\theta-\varphi}{2}}$

Voltage **critical value**: $U_{cr}=\dfrac{E}{\sqrt{2\cdot[1+\cos(\theta-\varphi)]}}=\dfrac{E}{2\cdot\cos\dfrac{\theta-\varphi}{2}}$

Changing from **absolute units** to **p.u.** – reference values:

$I_{sc}$ - the short-circuit current;
$U_1 = E$ - the sending end voltage;
$P_{L,max}$ - the maximum active power at the receiving end

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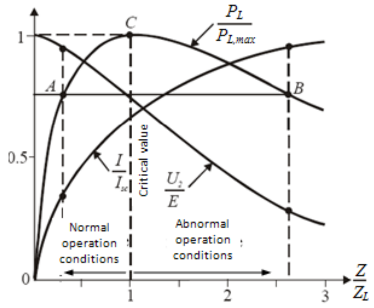
# Load characteristics - graphics



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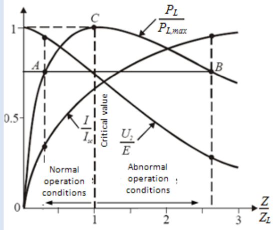
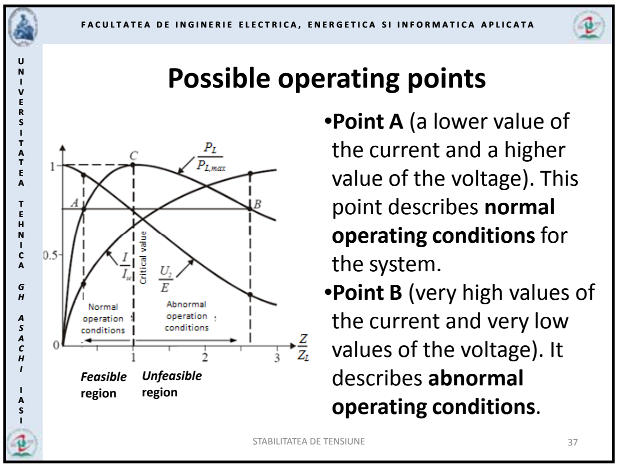
# Variation of active power



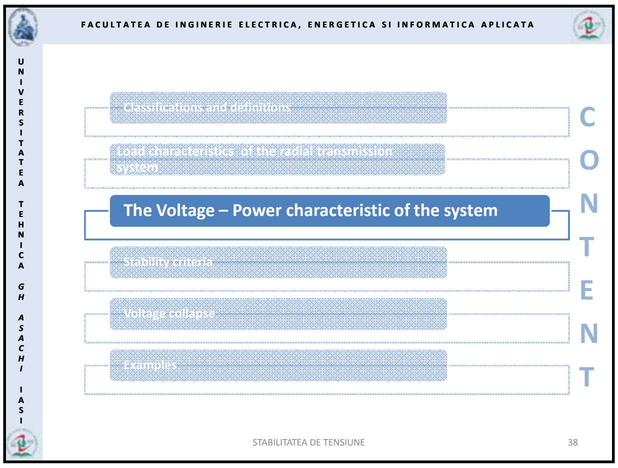
- For $Z_L > Z$ the increase in current is dominant $\Rightarrow P_L = U_2 \cdot I \cdot \cos\varphi$ will increase too;
- For $Z_L < Z$ the decrease in voltage is dominant $\Rightarrow P_L = U_2 \cdot I \cdot \cos\varphi$ will decrease too;
- When $Z_L = Z$, $P_L \rightarrow P_{L,max}$ and $U_2 \rightarrow U_{cr}$.



## Possible operating points

***Feasible*** **region** ***Unfeasible*** **region**

- **Point A** (a lower value of the current and a higher value of the voltage). This point describes **normal operating conditions** for the system.
- **Point B** (very high values of the current and very low values of the voltage). It describes **abnormal operating conditions**.



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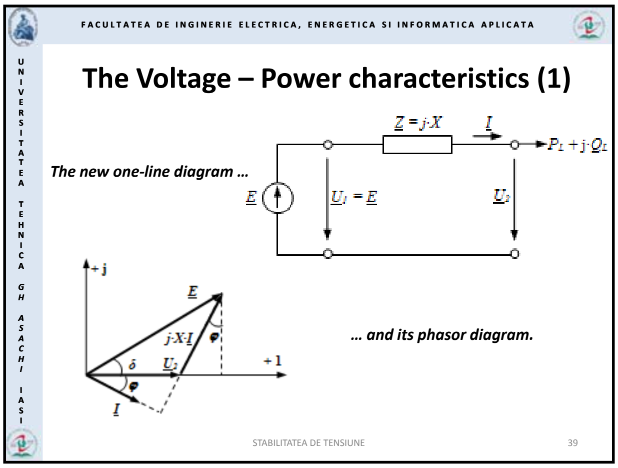
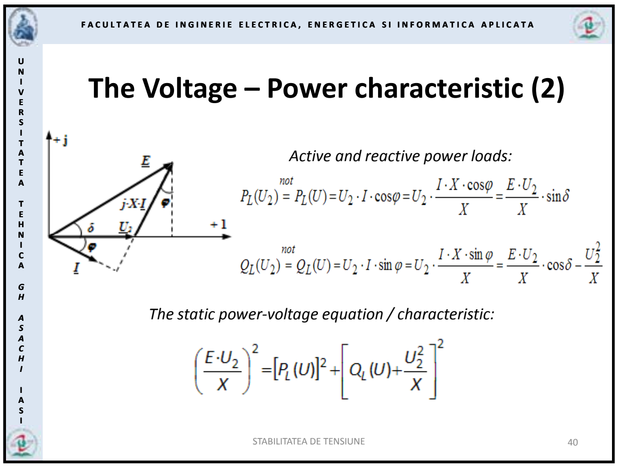


## The Voltage – Power characteristics (1)

*The new one-line diagram …*

*… and its phasor diagram.*



## The Voltage – Power characteristic (2)

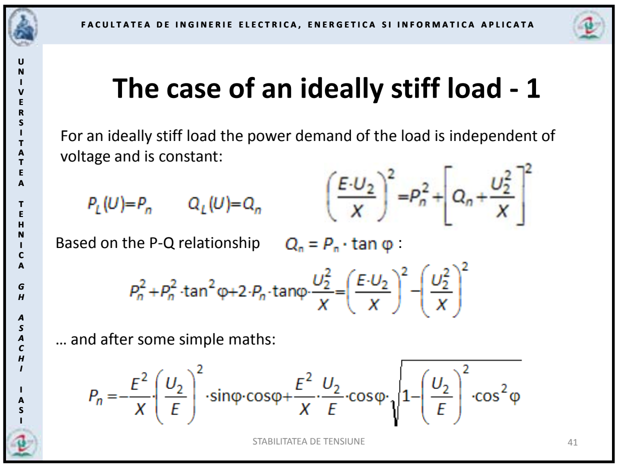
*Active and reactive power loads:*

$$P_L(U_2) \overset{not}{=} P_L(U) = U_2 \cdot I \cdot \cos\varphi = U_2 \cdot \frac{I \cdot X \cdot \cos\varphi}{X} = \frac{E \cdot U_2}{X} \cdot \sin\delta$$

$$Q_L(U_2) \overset{not}{=} Q_L(U) = U_2 \cdot I \cdot \sin\varphi = U_2 \cdot \frac{I \cdot X \cdot \sin\varphi}{X} = \frac{E \cdot U_2}{X} \cdot \cos\delta - \frac{U_2^2}{X}$$

*The static power-voltage equation / characteristic:*

$$\left(\frac{E \cdot U_2}{X}\right)^2 = [P_L(U)]^2 + \left[Q_L(U) + \frac{U_2^2}{X}\right]^2$$



## The case of an ideally stiff load - 1

For an ideally stiff load the power demand of the load is independent of voltage and is constant:

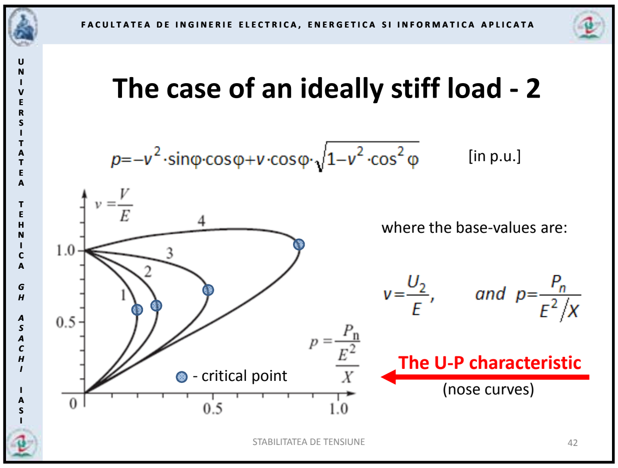
$$P_L(U) = P_n \qquad Q_L(U) = Q_n \qquad \left(\frac{E \cdot U_2}{X}\right)^2 = P_n^2 + \left[Q_n + \frac{U_2^2}{X}\right]^2$$

Based on the P-Q relationship $Q_n = P_n \cdot \tan\varphi$ :

$$P_n^2 + P_n^2 \cdot \tan^2\varphi + 2 \cdot P_n \cdot \tan\varphi \cdot \frac{U_2^2}{X} = \left(\frac{E \cdot U_2}{X}\right)^2 - \left(\frac{U_2^2}{X}\right)^2$$

… and after some simple maths:

$$P_n = -\frac{E^2}{X} \cdot \left(\frac{U_2}{E}\right)^2 \cdot \sin\varphi \cdot \cos\varphi + \frac{E^2}{X} \cdot \frac{U_2}{E} \cdot \cos\varphi \cdot \sqrt{1 - \left(\frac{U_2}{E}\right)^2 \cdot \cos^2\varphi}$$



## The case of an ideally stiff load - 2

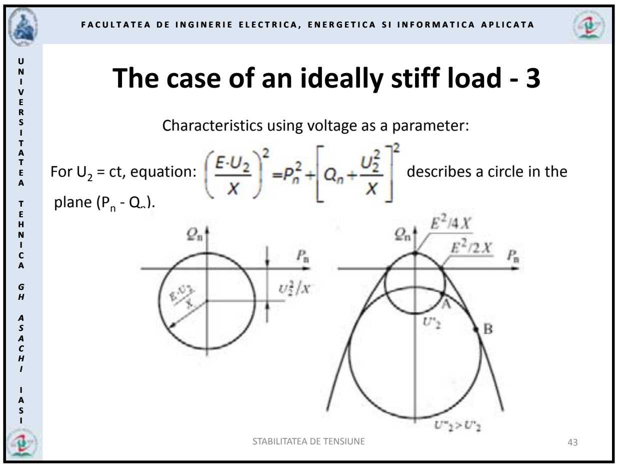
$$p = -v^2 \cdot \sin\varphi \cdot \cos\varphi + v \cdot \cos\varphi \cdot \sqrt{1 - v^2 \cdot \cos^2\varphi}$$ [in p.u.]

where the base-values are:

$$v = \frac{U_2}{E}, \qquad and \quad p = \frac{P_n}{E^2/X}$$

**The U-P characteristic**

(nose curves)



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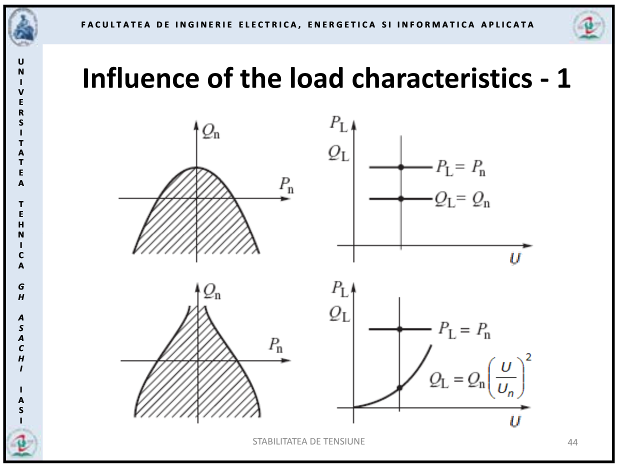
## The case of an ideally stiff load - 3

Characteristics using voltage as a parameter:

For $U_2$ = ct, equation: $\left(\frac{E \cdot U_2}{X}\right)^2 = P_n^2 + \left[Q_n + \frac{U_2^2}{X}\right]^2$ describes a circle in the plane ($P_n$ - $Q_n$).



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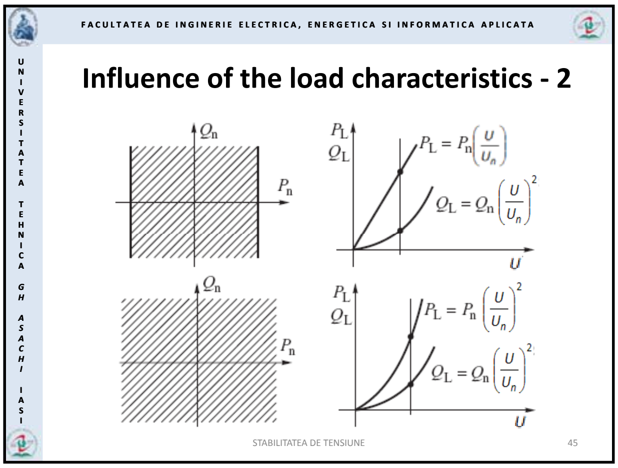
## Influence of the load characteristics - 1



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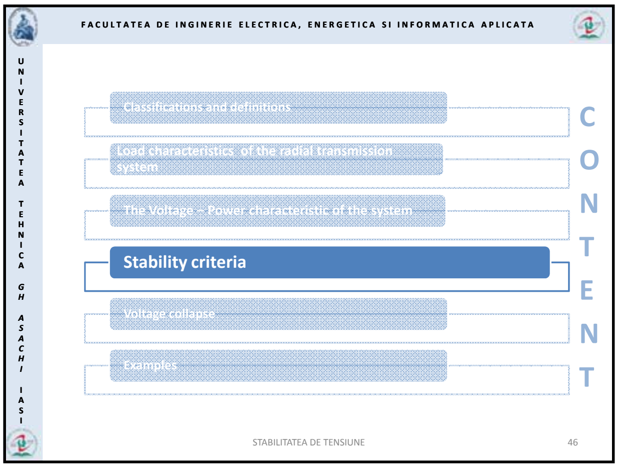
## Influence of the load characteristics - 2



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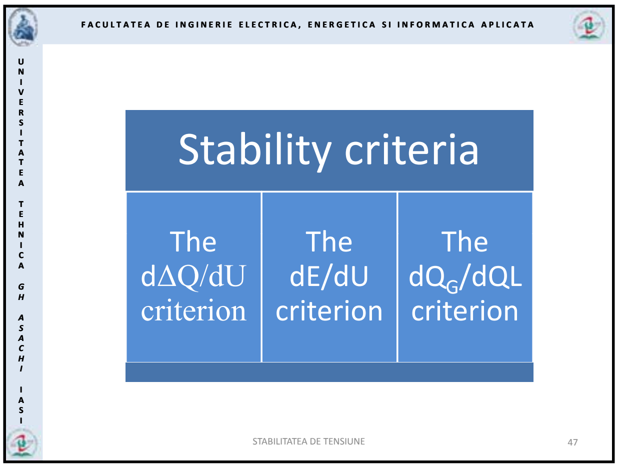
CONTENT

- Classifications and definitions
- Load characteristics of the radial transmission system
- The Voltage – Power characteristic of the system
- **Stability criteria**
- Voltage collapse
- Examples



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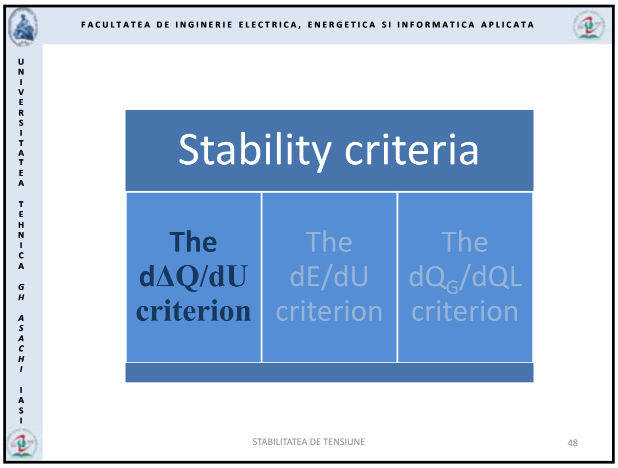
## Stability criteria

| The $d\Delta Q/dU$ criterion | The $dE/dU$ criterion | The $dQ_G/dQL$ criterion |
|---|---|---|



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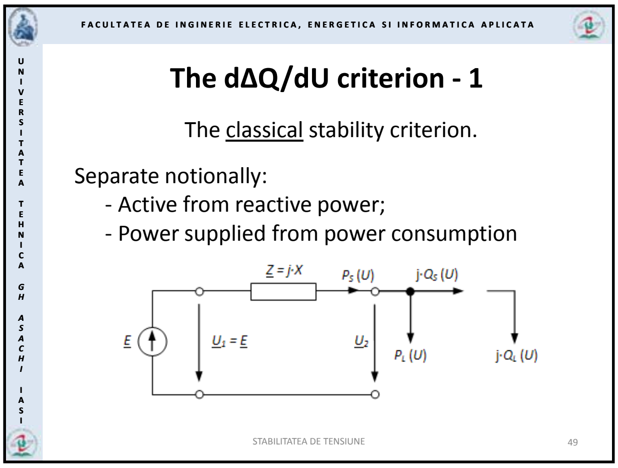
## Stability criteria

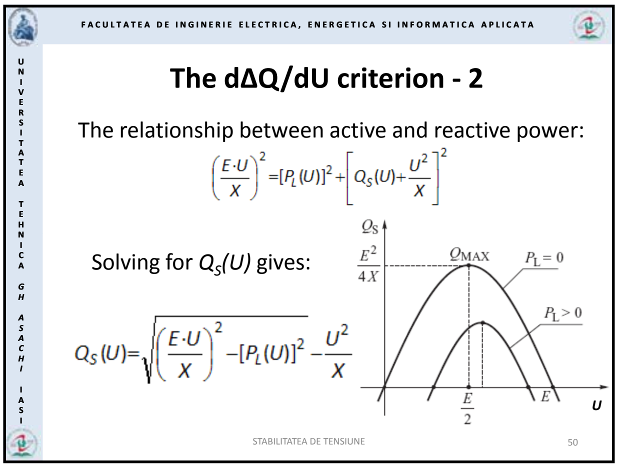
| **The $d\Delta Q/dU$ criterion** | The $dE/dU$ criterion | The $dQ_G/dQL$ criterion |
|---|---|---|



## The dΔQ/dU criterion - 1

The classical stability criterion.

Separate notionally:
- Active from reactive power;
- Power supplied from power consumption



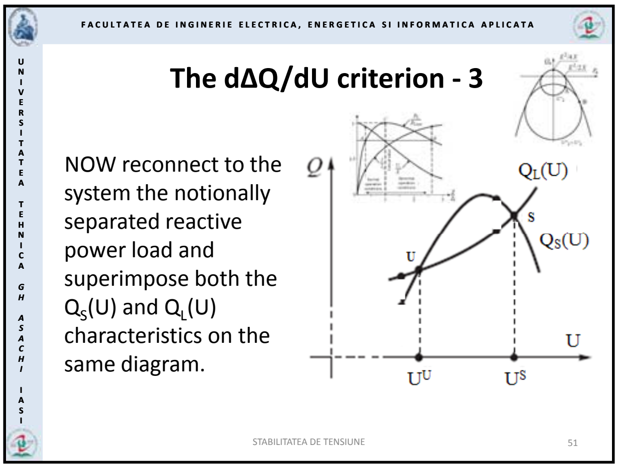
## The dΔQ/dU criterion - 2

The relationship between active and reactive power:

$$\left(\frac{E \cdot U}{X}\right)^2 = [P_L(U)]^2 + \left[Q_S(U) + \frac{U^2}{X}\right]^2$$

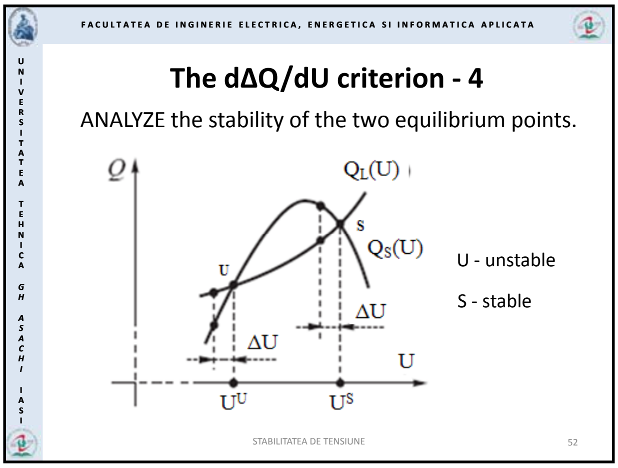
Solving for $Q_S(U)$ gives:

$$Q_S(U) = \sqrt{\left(\frac{E \cdot U}{X}\right)^2 - [P_L(U)]^2} - \frac{U^2}{X}$$



## The dΔQ/dU criterion - 3

NOW reconnect to the system the notionally separated reactive power load and superimpose both the $Q_S(U)$ and $Q_L(U)$ characteristics on the same diagram.

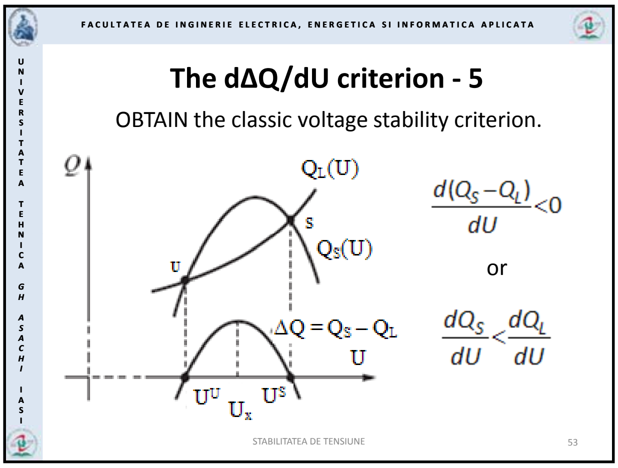


## The dΔQ/dU criterion - 4

ANALYZE the stability of the two equilibrium points.

U - unstable

S - stable



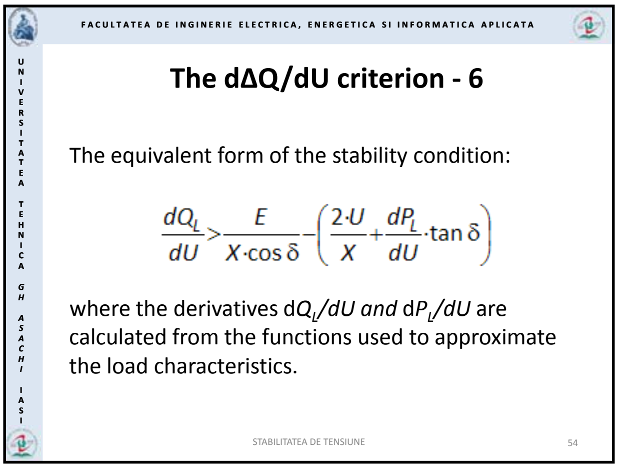
## The dΔQ/dU criterion - 5

OBTAIN the classic voltage stability criterion.

$$\frac{d(Q_S - Q_L)}{dU} < 0$$

or

$$\frac{dQ_S}{dU} < \frac{dQ_L}{dU}$$

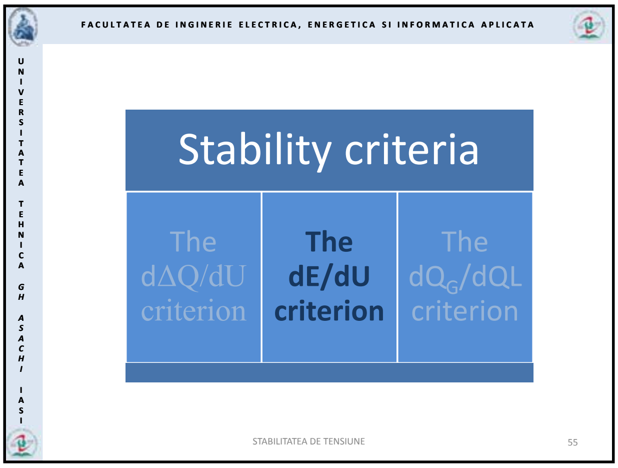


## The dΔQ/dU criterion - 6

The equivalent form of the stability condition:

$$\frac{dQ_L}{dU} > \frac{E}{X \cdot \cos\delta} - \left( \frac{2 \cdot U}{X} + \frac{dP_L}{dU} \cdot \tan\delta \right)$$

where the derivatives $dQ_L/dU$ and $dP_L/dU$ are calculated from the functions used to approximate the load characteristics.



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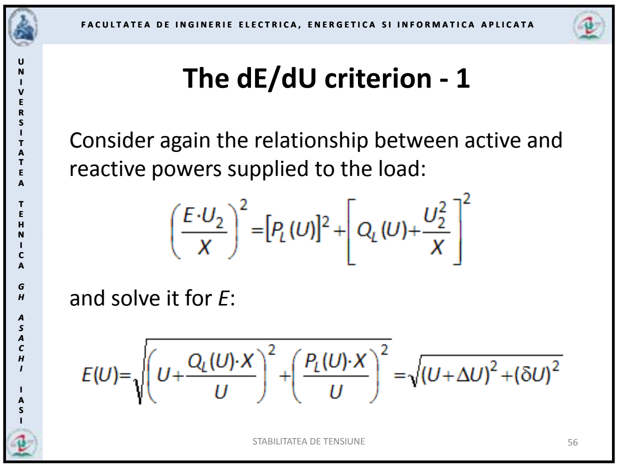
## Stability criteria

| The $d\Delta Q/dU$ criterion | **The dE/dU criterion** | The $dQ_G/dQL$ criterion |
|---|---|---|



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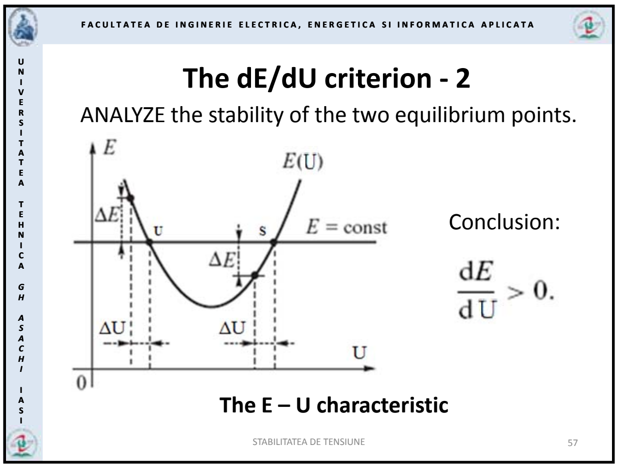
## The dE/dU criterion - 1

Consider again the relationship between active and reactive powers supplied to the load:

$$\left(\frac{E\cdot U_2}{X}\right)^2 = [P_L(U)]^2 + \left[Q_L(U) + \frac{U_2^2}{X}\right]^2$$

and solve it for *E*:

$$E(U) = \sqrt{\left(U + \frac{Q_L(U)\cdot X}{U}\right)^2 + \left(\frac{P_L(U)\cdot X}{U}\right)^2} = \sqrt{(U+\Delta U)^2 + (\delta U)^2}$$



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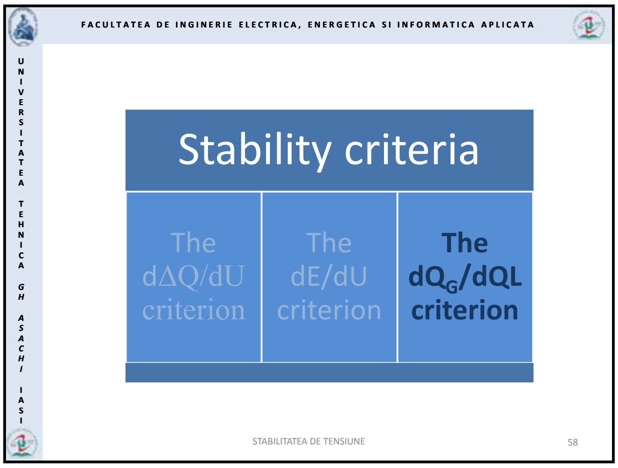
## The dE/dU criterion - 2

ANALYZE the stability of the two equilibrium points.

Conclusion:

$$\frac{dE}{dU} > 0.$$

**The E – U characteristic**

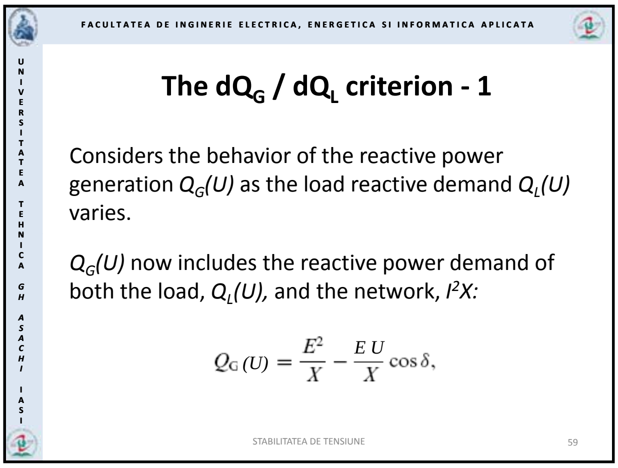


## Stability criteria

The $d\Delta Q/dU$ criterion

The $dE/dU$ criterion

**The $dQ_G/dQL$ criterion**

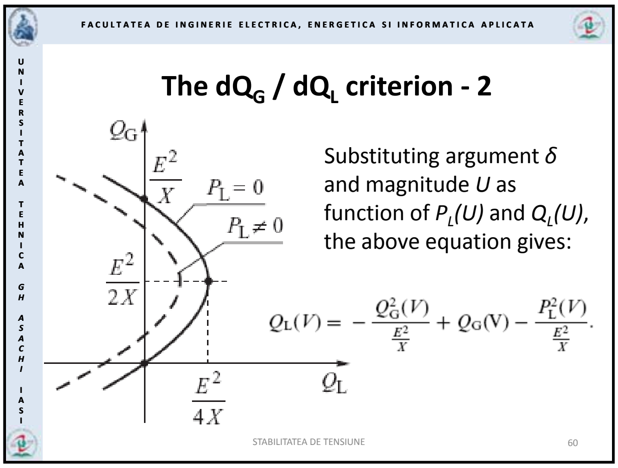


## The $dQ_G$ / $dQ_L$ criterion - 1

Considers the behavior of the reactive power generation $Q_G(U)$ as the load reactive demand $Q_L(U)$ varies.

$Q_G(U)$ now includes the reactive power demand of both the load, $Q_L(U)$, and the network, $I^2X$:

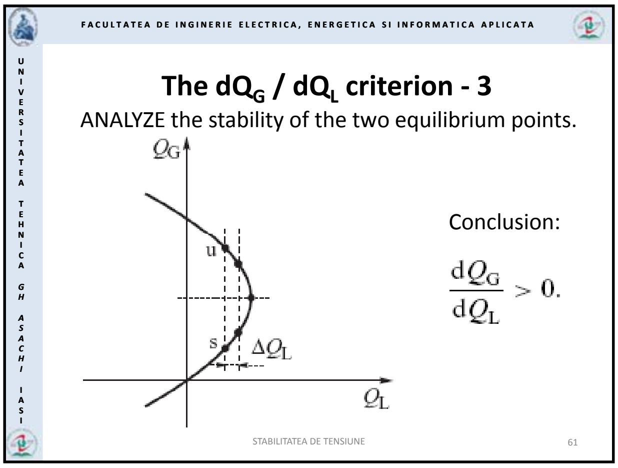
$$Q_G(U) = \frac{E^2}{X} - \frac{EU}{X}\cos\delta,$$



## The $dQ_G$ / $dQ_L$ criterion - 2

Substituting argument $\delta$ and magnitude $U$ as function of $P_L(U)$ and $Q_L(U)$, the above equation gives:

$$Q_L(V) = -\frac{Q_G^2(V)}{\frac{E^2}{X}} + Q_G(V) - \frac{P_L^2(V)}{\frac{E^2}{X}}.$$

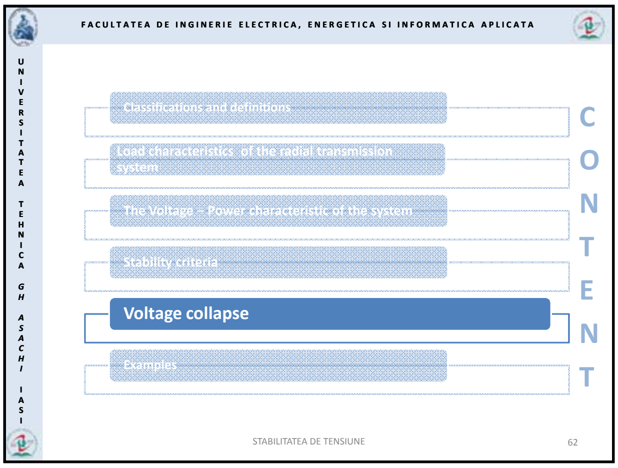


## The $dQ_G$ / $dQ_L$ criterion - 3

ANALYZE the stability of the two equilibrium points.

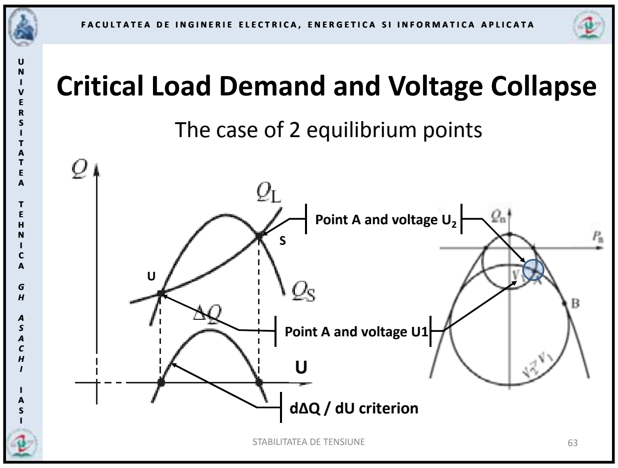
Conclusion:

$$\frac{dQ_G}{dQ_L} > 0.$$



Classifications and definitions
Load characteristics of the radial transmission system
The Voltage – Power characteristic of the system
Stability criteria
**Voltage collapse**
Examples

CONTENT



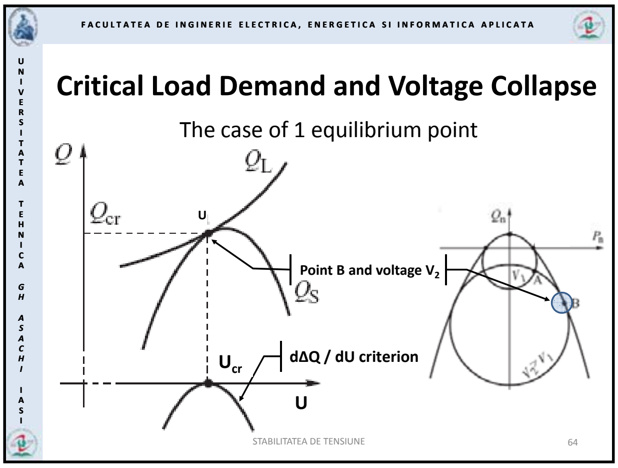
## Critical Load Demand and Voltage Collapse

The case of 2 equilibrium points

**Point A and voltage $U_2$**

**Point A and voltage U1**

**dΔQ / dU criterion**



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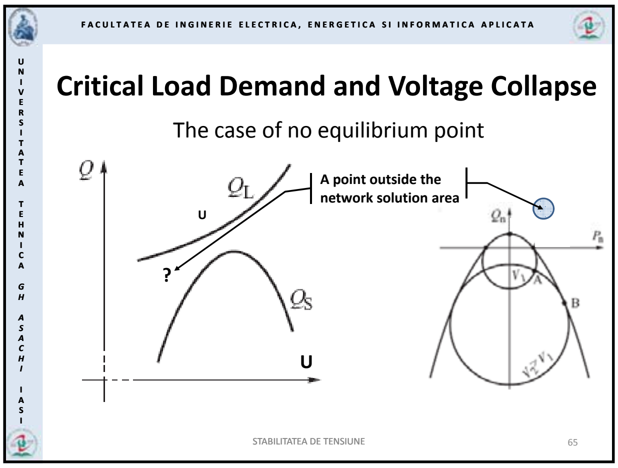
## Critical Load Demand and Voltage Collapse

The case of 1 equilibrium point

Point B and voltage $V_2$

$d\Delta Q / dU$ criterion



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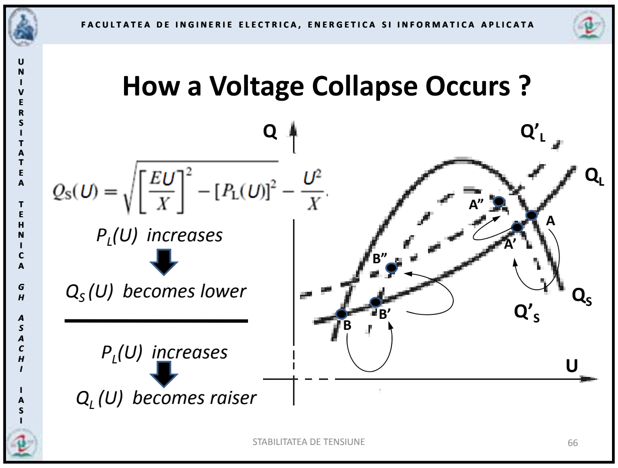
## Critical Load Demand and Voltage Collapse

The case of no equilibrium point

A point outside the network solution area



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## How a Voltage Collapse Occurs ?

$$Q_S(U) = \sqrt{\left[\frac{EU}{X}\right]^2 - [P_L(U)]^2} - \frac{U^2}{X}.$$

*$P_L(U)$ increases*

⬇

*$Q_S(U)$ becomes lower*

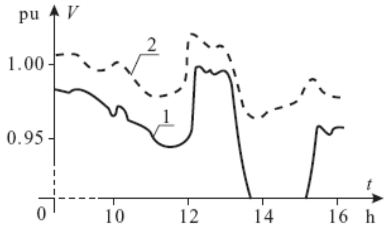
---

*$P_L(U)$ increases*

⬇

*$Q_L(U)$ becomes raiser*

## How Does a Voltage Collapse Looks Like?



(1) voltage variations during the day of the voltage collapse;
(2) voltage variations during the previous day (Nagao, 1975).

## Estimating critical power and voltage (1)

It’s impossible to derive a general formula, due to nonlinearities of voltage characteristics.

An iterative approach is possible if the following assumptions are made:

- The power factor of the consumer load is maintained constant when the load demand increase.
- The composite load has a parabola form for the reactive power characteristic and a linear form for the active power characteristic.
- The load composition is constant.

## Estimating critical power and voltage (2)

The load model:

$$Q_L = \xi \cdot [\alpha_2 \cdot U^2 - \alpha_1 \cdot U + \alpha_0] \qquad P_L = \xi \cdot \beta_1 \cdot U$$

$$\alpha_2 = \frac{Q_0}{U_n^2} \cdot a_2, \quad \alpha_1 = \frac{Q_0}{U_n} \cdot a_1, \quad \alpha_0 = Q_0 \cdot a_0, \quad \beta_1 = \frac{P_0}{U_n} \cdot b_1$$

$$\frac{Q_L}{Q_n} = a_2 \cdot \left(\frac{U}{U_n}\right)^2 - a_1 \cdot \left(\frac{U}{U_n}\right) + a_0, \qquad \frac{P_L}{P_n} = b_1 \cdot \left(\frac{U}{U_n}\right)$$

Critical values:

$$U_{cr} = \frac{\sqrt{\left(\frac{E}{\beta_1 \cdot X}\right)^2 - \xi_{cr}^2 + \frac{\alpha_1}{\beta_1} \cdot \xi_{cr}}}{2 \cdot \frac{\alpha_2}{\beta_1} \cdot \xi_{cr} + \frac{2}{\beta_1 \cdot X}} \qquad \xi_{cr} = \frac{1}{\frac{\alpha_0 \cdot X}{U_{cr}^2} - \alpha 2 \cdot X}$$

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- **Examples**

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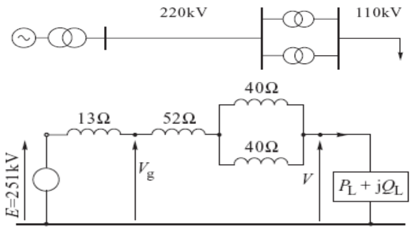
# Example 1

## Effect of Increasing the Load

--------- The network ---------



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## Effect of Increasing the Load

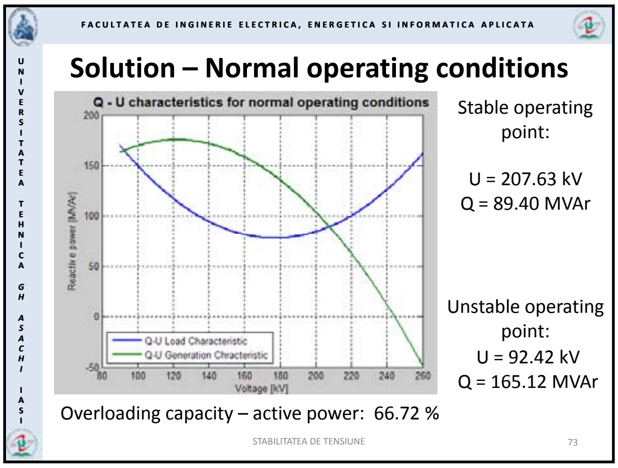
--------- The load---------

Active power:

$$P_L = 0.682 \cdot \xi \cdot U$$

Reactive power:

$$Q_L = \xi \cdot (0.0122 \cdot U^2 - 4.318 \cdot U + 460)$$



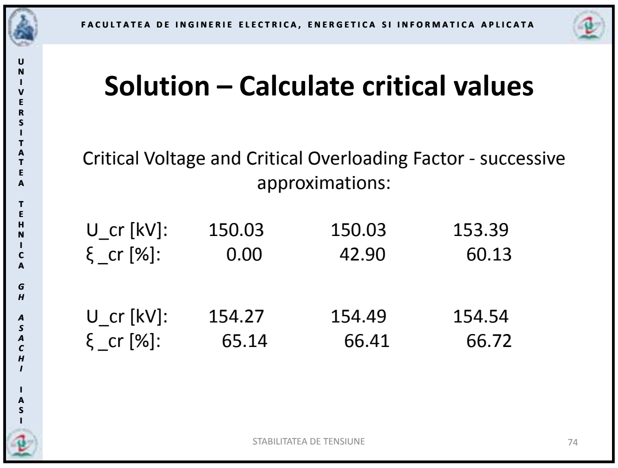
## Solution – Normal operating conditions

Stable operating point:

U = 207.63 kV
Q = 89.40 MVAr

Unstable operating point:
U = 92.42 kV
Q = 165.12 MVAr

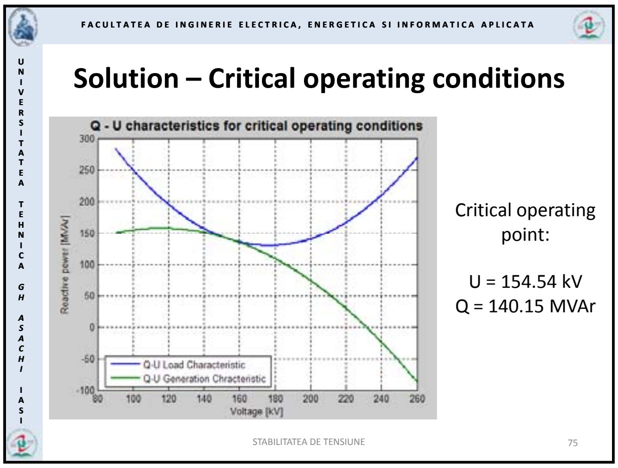
Overloading capacity – active power: 66.72 %



## Solution – Calculate critical values

Critical Voltage and Critical Overloading Factor - successive approximations:

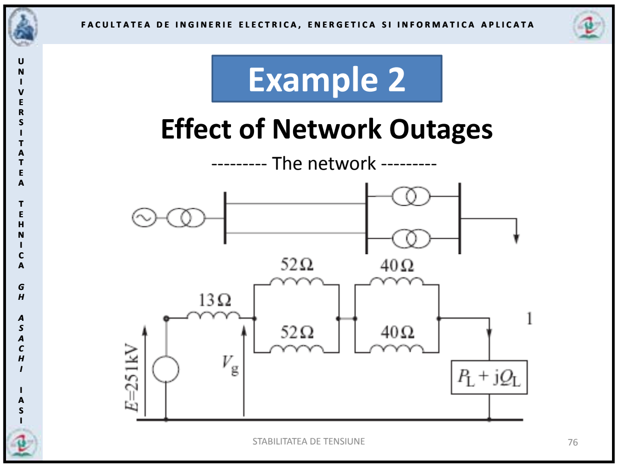
| | | | |
|---|---|---|---|
| U_cr [kV]: | 150.03 | 150.03 | 153.39 |
| ξ _cr [%]: | 0.00 | 42.90 | 60.13 |
| U_cr [kV]: | 154.27 | 154.49 | 154.54 |
| ξ _cr [%]: | 65.14 | 66.41 | 66.72 |



## Solution – Critical operating conditions

Critical operating point:

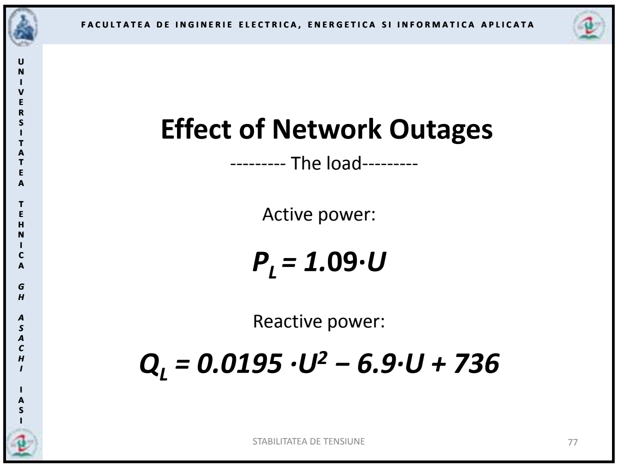
U = 154.54 kV
Q = 140.15 MVAr



## Example 2

### Effect of Network Outages

--------- The network ---------



### Effect of Network Outages

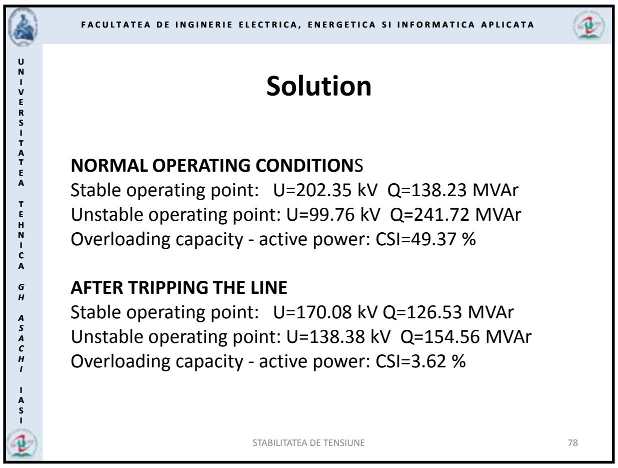
--------- The load---------

Active power:

$$P_L = 1.09 \cdot U$$

Reactive power:

$$Q_L = 0.0195 \cdot U^2 - 6.9 \cdot U + 736$$

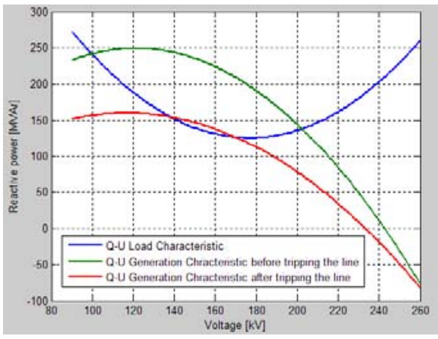


### Solution

**NORMAL OPERATING CONDITIONS**
Stable operating point: U=202.35 kV Q=138.23 MVAr
Unstable operating point: U=99.76 kV Q=241.72 MVAr
Overloading capacity - active power: CSI=49.37 %

**AFTER TRIPPING THE LINE**
Stable operating point: U=170.08 kV Q=126.53 MVAr
Unstable operating point: U=138.38 kV Q=154.56 MVAr
Overloading capacity - active power: CSI=3.62 %

## Solution – graphic representation



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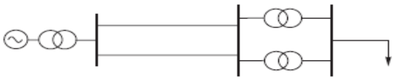
## Example 3

## Effect of the Shape of the Load Characteristics

--------- The network ---------

**The same network data from Example 2.**



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## Effect of the Shape of the Load Characteristics

--------- The load---------

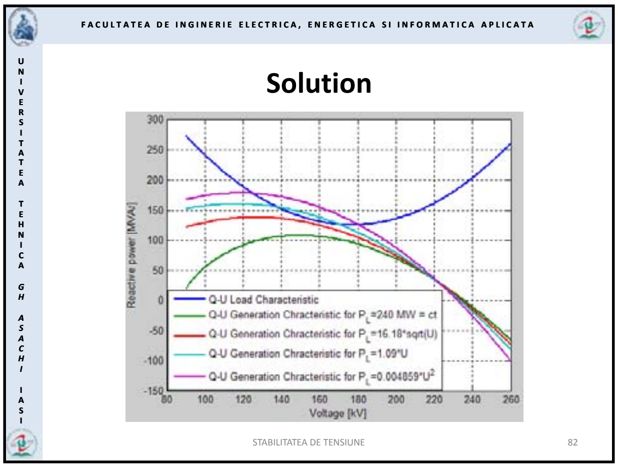
Active power:

(1) $P_L = 240 = ct$ (2) $P_L = 16.18 \cdot sqrt(U)$

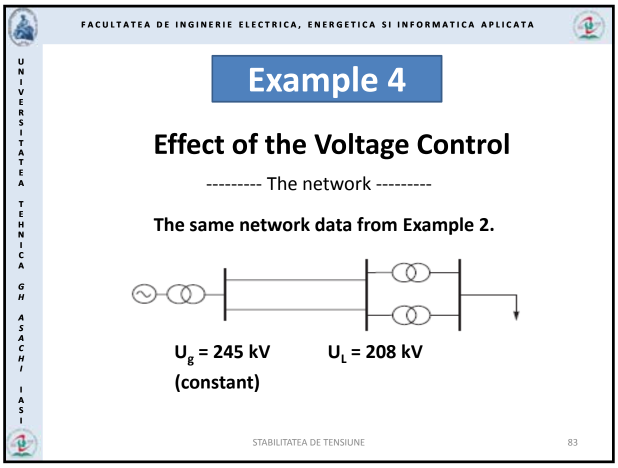
(3) $P_L = 1.09 \cdot U$ (4) $P_L = 0.004859 \cdot U^2$

Reactive power:

$$Q_L = 0.0195 \cdot U^2 - 6.9 \cdot U + 736$$



## Solution



## Example 4

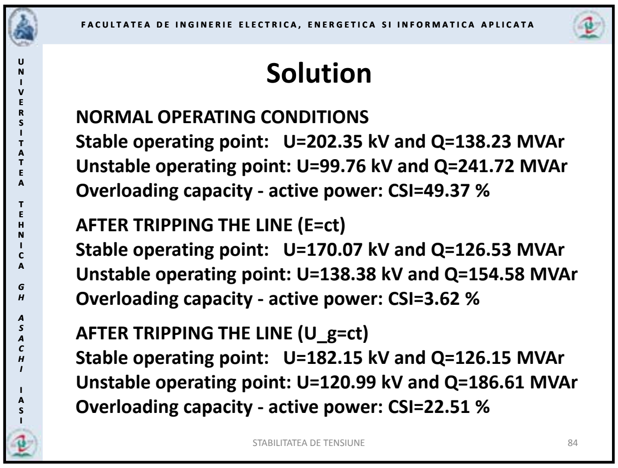
## Effect of the Voltage Control

--------- The network ---------

**The same network data from Example 2.**

**$U_g$ = 245 kV**
**(constant)**

**$U_L$ = 208 kV**



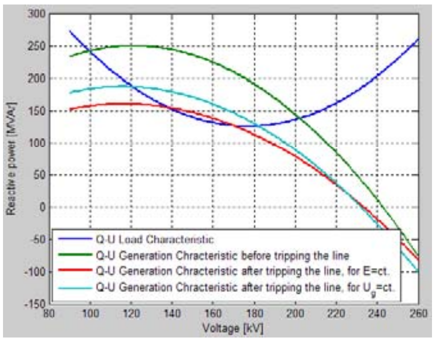
## Solution

**NORMAL OPERATING CONDITIONS**
**Stable operating point: U=202.35 kV and Q=138.23 MVAr**
**Unstable operating point: U=99.76 kV and Q=241.72 MVAr**
**Overloading capacity - active power: CSI=49.37 %**

**AFTER TRIPPING THE LINE (E=ct)**
**Stable operating point: U=170.07 kV and Q=126.53 MVAr**
**Unstable operating point: U=138.38 kV and Q=154.58 MVAr**
**Overloading capacity - active power: CSI=3.62 %**

**AFTER TRIPPING THE LINE (U_g=ct)**
**Stable operating point: U=182.15 kV and Q=126.15 MVAr**
**Unstable operating point: U=120.99 kV and Q=186.61 MVAr**
**Overloading capacity - active power: CSI=22.51 %**

## Solution



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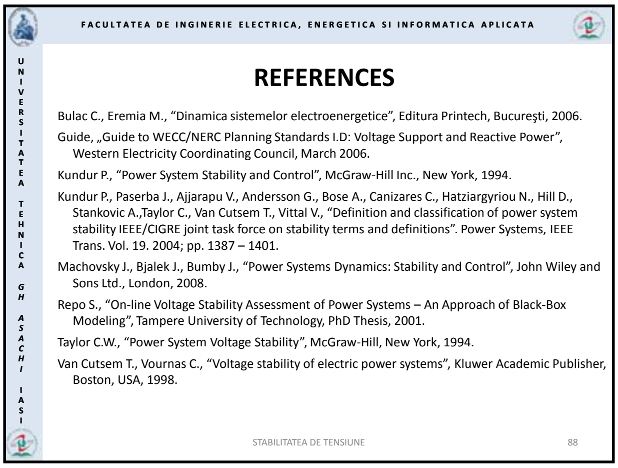
## Why Voltage Stability is Important Today ?

- Generation **centralized** in fewer, larger power plants:
  - o fewer voltage controlled buses
  - o longer electrical distances between generation and load
- Generation **decentralized** in more, smaller power plants:
  - o difficulties to take part in the voltage control process
  - o growing complexity in voltage control coordination.

---

## Why Voltage Stability is Important Today ?

- Extensive use of shunt capacitor compensation.
- Voltage instability caused by line and generator outages
- Many incidents throughout the world (USA and Canada - 2003, Denmark and Sweden - 2003, Greece - 2004 etc.)
- Operation of systems closer to their limits



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