Revisiting phenomena and instability mechanisms

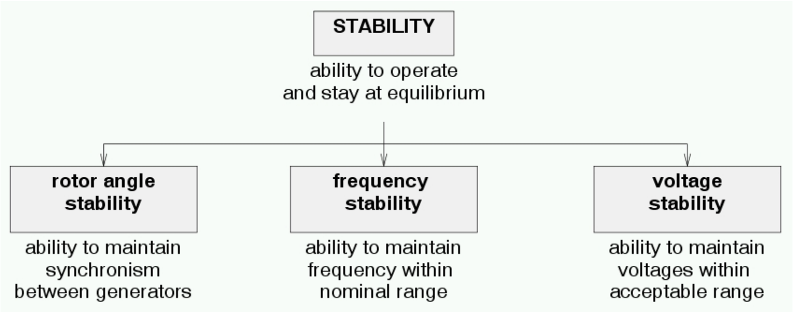
Thierry Van Cutsem

Department of Electrical Engineering and Computer Science
University of Liège - Belgium

Objectives

- definition and classification of power system stability notions
- qualitative explanation of instability mechanisms
- emphasis put on instability triggered by a large disturbance
- illustration from time simulations of a simple system

Main classification of stability problems



(Rotor) angle stability

- most of the electrical energy is generated by synchronous machines
- in normal system operation:
  - all synchronous machines have the same electrical speed $2\pi f$
  - the mechanical and electromagnetic torques acting on the rotating masses of each generator balance each other
  - the difference between the rotor angles of any two machines is constant = *synchronism*
- following a disturbance, there is an imbalance between the two torques and the rotor speed varies
- *rotor angle stability deals with the ability to keep synchronism after being subject to a disturbance*

Small-disturbance angle stability

- *small-signal (or small-disturbance) angle stability deals with the ability of the system to keep synchronism after being subject to small disturbances*
- "small disturbances" are those for which the system equations can be linearized (around an equilibrium point)
- following small disturbances, the change in electromagnetic torque has two components:
  - *synchronizing torque* proportional to rotor angle deviation
  - *damping torque* proportional to rotor speed deviation
- a decrease in synchronizing torque will eventually lead to aperiodic instability (machine "going out of step")
- a decrease in damping torque will eventually lead to oscillatory instability (growing oscillations)

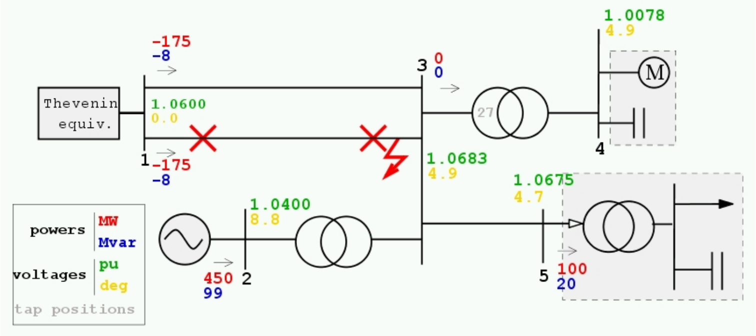
Transient (angle) stability

- *transient (angle) stability deals with the ability of the system to keep synchronism after being subject to a large disturbance*
- typical "large" disturbances:
  - short-circuit cleared by opening of circuit breakers
  - more complex sequences in case of breaker failure, line autoreclosing, etc.
- synchronizing torque T_s is nonlinear function of rotor angle δ: the larger $\Delta\delta$, the lower $\dfrac{\Delta T_s}{\Delta\delta}$ ("stiffness")
- for large disturbances, this nonlinear effect must be taken into account
- unacceptable consequences of transient instability:
  - generators losing synchronism are tripped by protections
  - large angle swings create voltage dips disturbing customers

Remarks

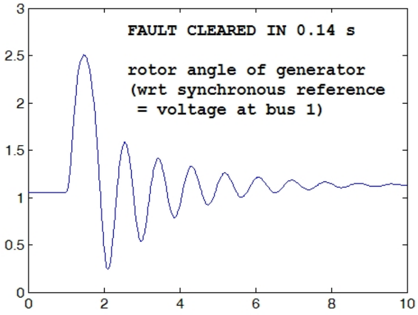
- small-signal angle stability:
  - depends on operating point and system parameters
  - does not depend on the disturbance (assumed infinitesimal and arbitrary)
  - is a necessary condition for operating a power system (small disturbances are always present !)
- transient stability:
  - depends on operating point, system parameters, AND the disturbance:
    - the system may be stable wrt disturbance D1 but not disturbance D2
    - if so, the system is *insecure* wrt D2, but as long as D2 does not happen, it can operate...

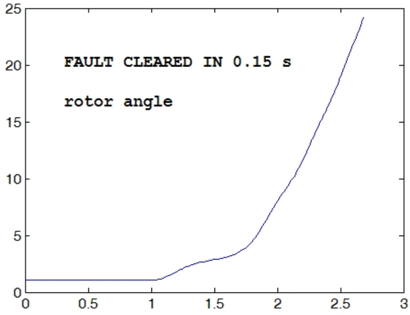
Transient stability - example

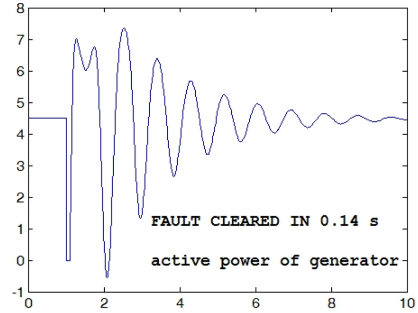


- synchronous generator (6th-order model) with Automatic Voltage Regulator (AVR), steam turbine and speed governor
- external system represented by Thévenin equivalent

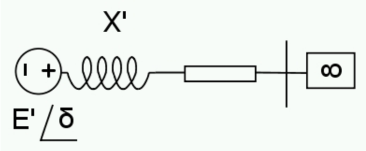
short-circuit at $t = 1$ s, on line 1-3, near bus 3
cleared by opening one circuit, after 0.14 and 0.15 s, respectively


FAULT CLEARED IN 0.14 s
rotor angle of generator
(wrt synchronous reference
= voltage at bus 1)

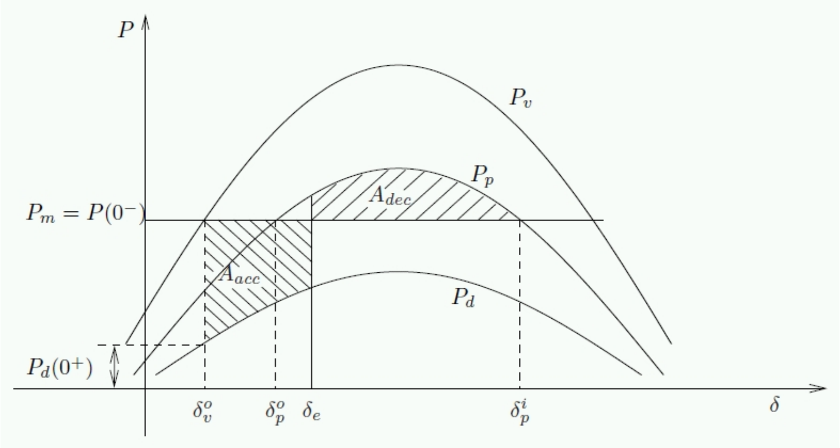

FAULT CLEARED IN 0.15 s
rotor angle


FAULT CLEARED IN 0.14 s
active power of generator

Transient instability mechanism - equal-area criterion

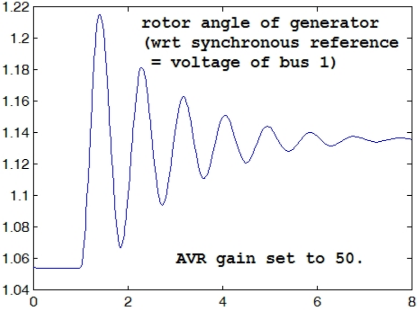


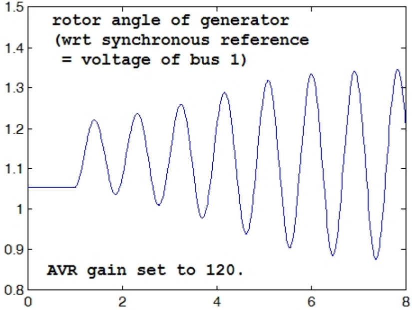
$$M\frac{d^2\delta}{dt^2} = P_m - P(\delta)$$



Small-signal angle stability - example

same initial power flow
tripping of the line without short-circuit





with the AVR gain increased to 120, the post-disturbance equilibrium is almost the same but is oscillatory unstable

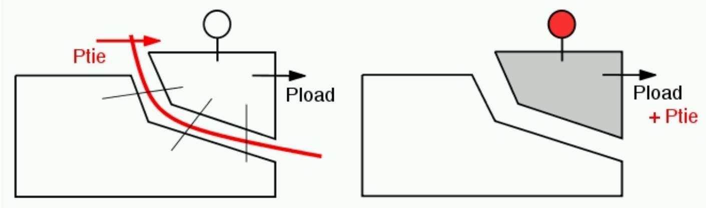
Not shown by this simple example: interarea oscillations

Frequency stability

- Electricity cannot be stored as such (in significant amount). It has to be converted into/from other forms of energy
- the active power balance $P_{gener} = P_{load} + P_{losses}$ must be satisfied at any time
- immediately after a disturbance:
  - generation deficit taken from kinetic energy of rotating masses in power plants $\longrightarrow$ speed decrease $\longrightarrow$ drop in frequency
  - generation excess given to rotating masses $\longrightarrow$ speed increase $\longrightarrow$ rise in frequency
- fastly, the speed deviation is corrected by *speed governors* adjusting the turbine control valves (to change the steam/water flow) = *primary frequency control*
- later on, frequency deviations left by primary control are corrected by *secondary frequency* (or *load frequency*) *control*
- together with deviations of tie-line power flows from schedule

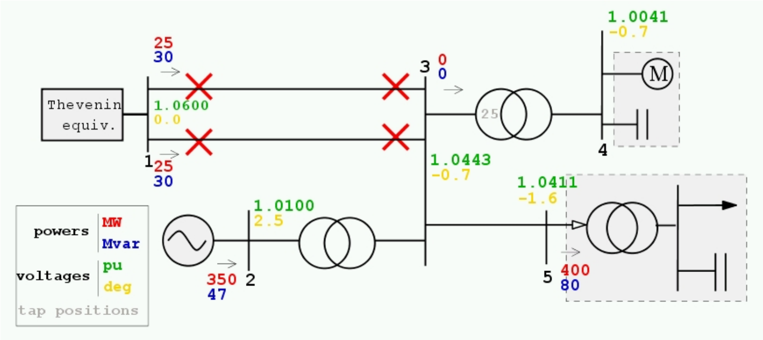
Frequency stability

- *Frequency stability deals with the ability of the system to keep frequency near its nominal value after a severe disturbance, with or without system split*
- in large interconnections:
  - frequency is controlled accurately
    Example: sensitivity of UCTE system $\simeq$ 18,000 MW/Hz
  - frequency instability of concern after:
    - a system split causing large power imbalance



    - a severe loss of generation
      Example: UCTE: maximum 3,000 MW

Frequency stability - example 1

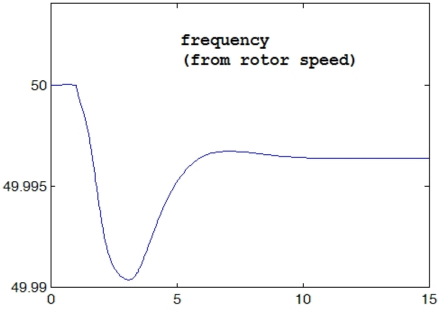


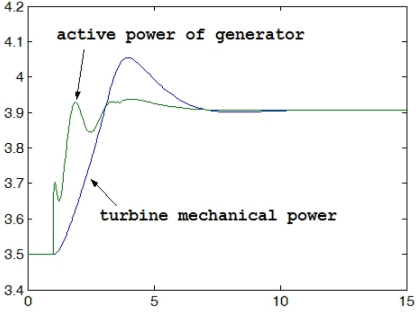
50 MW imported from equivalent system

at $t = 1$ s, tripping of the double line

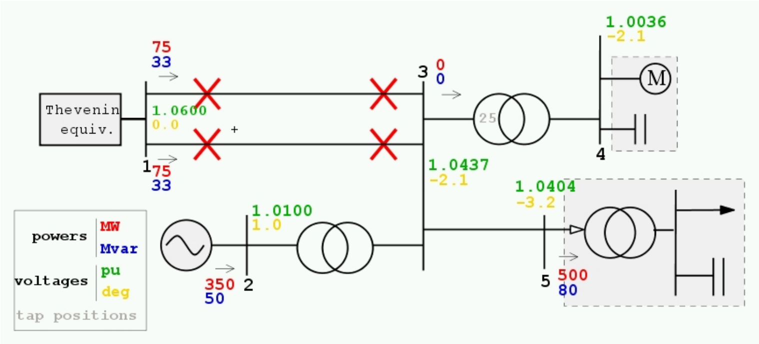
$\Rightarrow$ generator and load left isolated

generator driven by a turbine with 450 MW nominal power


frequency
(from rotor speed)
50
49.995
49.99
0
5
10
15


active power of generator
turbine mechanical power
4.2
4.1
4
3.9
3.8
3.7
3.6
3.5
3.4
0
5
10
15

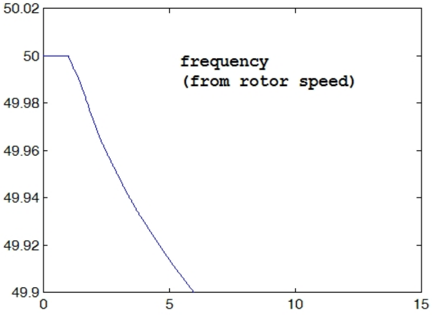
Frequency stability - example 2



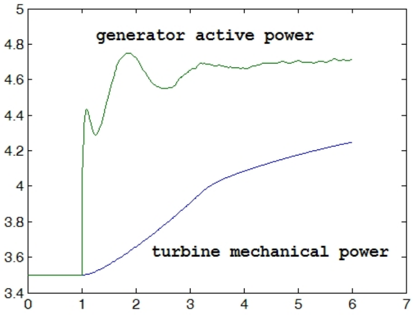
same disturbance

different operating point:

larger load and larger power import from equivalent system



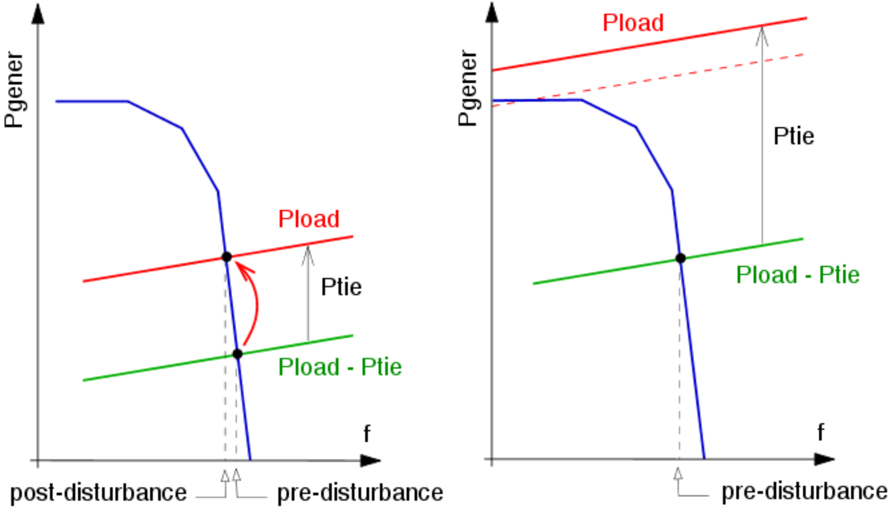
frequency
(from rotor speed)
50.02
50
49.98
49.96
49.94
49.92
49.9
0
5
10
15



generator active power
turbine mechanical power
5
4.8
4.6
4.4
4.2
4
3.8
3.6
3.4
0
1
2
3
4
5
6
7

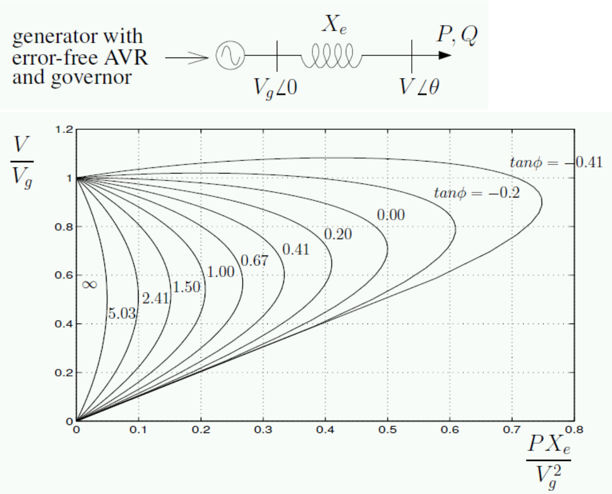
Frequency instability mechanism

combined steady-state characteristics
of turbines and speed governors in islanded network



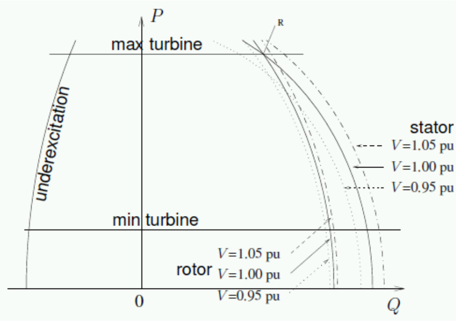
Voltage stability

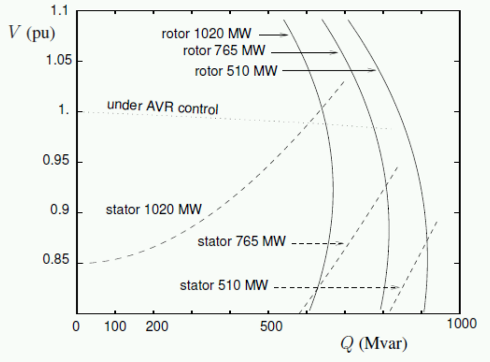
- There is a maximum power that generators can deliver to loads through the network



Voltage stability

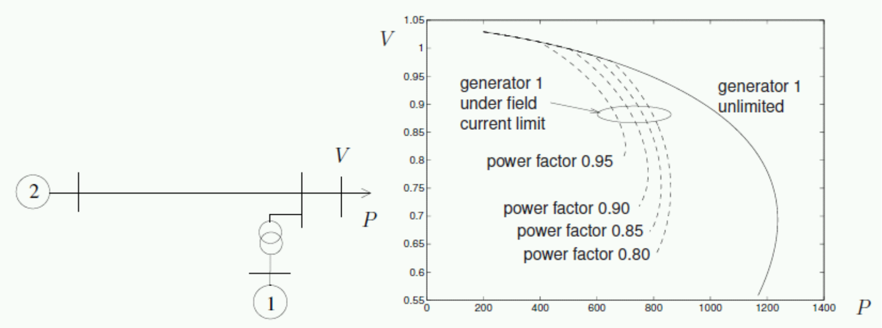
- the reactive power production of a generator is limited by the thermal overload of the field winding
- when the OvereXcitation limiter (OXL) is active the generator voltage is no longer controlled
- the stator (or armature) current may be also limiting





Voltage stability

- the reactive power limits of generators strongly impact the maximum power that can be delivered to loads



Voltage stability

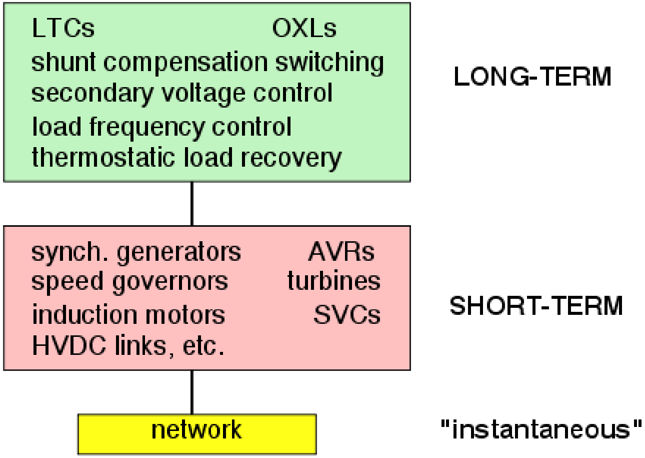
- after being subject to a voltage drop, some loads tend to restore their power consumption (close) to their pre-disturbance value

component	time scale	internal variable	equilibrium condition
induction motor	$\simeq$ 1 second	motor speed	mechan. torque = electrom. torque
load tap changer	$\simeq$ few minutes	transformer ratio	controlled voltage within deadband
thermostatically controlled load	$\simeq$ few tens of minutes	amount of connected load	temperature within deadband

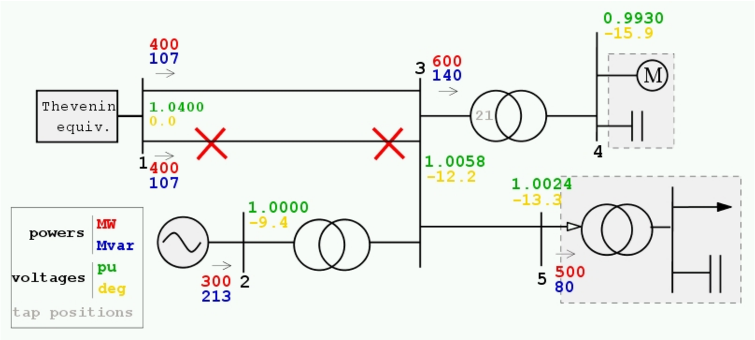
Voltage stability

- *Voltage stability deals with the ability of the system to keep voltages near their nominal values after a disturbance*
- voltage instability results from the inability of the combined transmission-generation system to provide the power requested by loads
- it is usually characterized by a monotonic decrease of system voltages
- it may develop in the short- as well as in the long-term time scale.

Time-scale decomposition

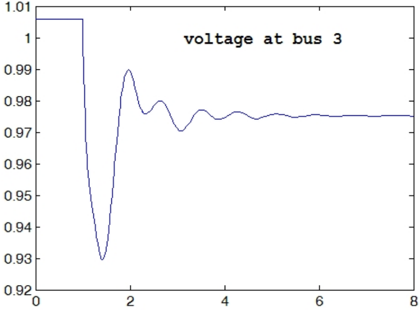


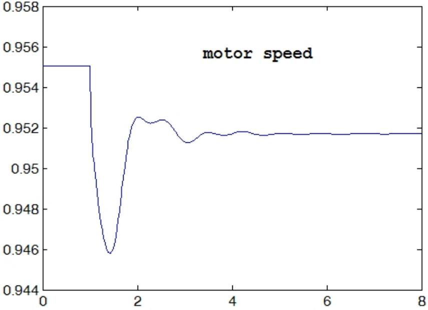
Short-term voltage stability - example 1

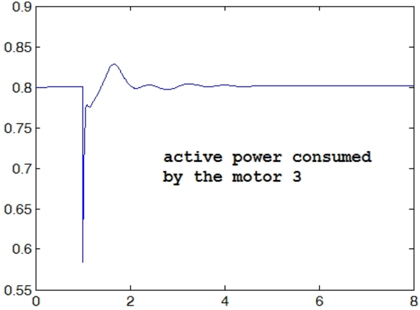


55 % induction motor load (single-motor equivalent)

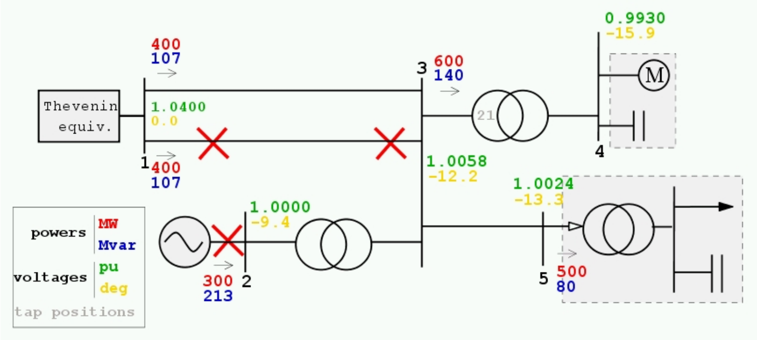
at $t = 1$ s, tripping of one circuit of the line


voltage at bus 3
1.01
1
0.99
0.98
0.97
0.96
0.95
0.94
0.93
0.92
0
2
4
6
8

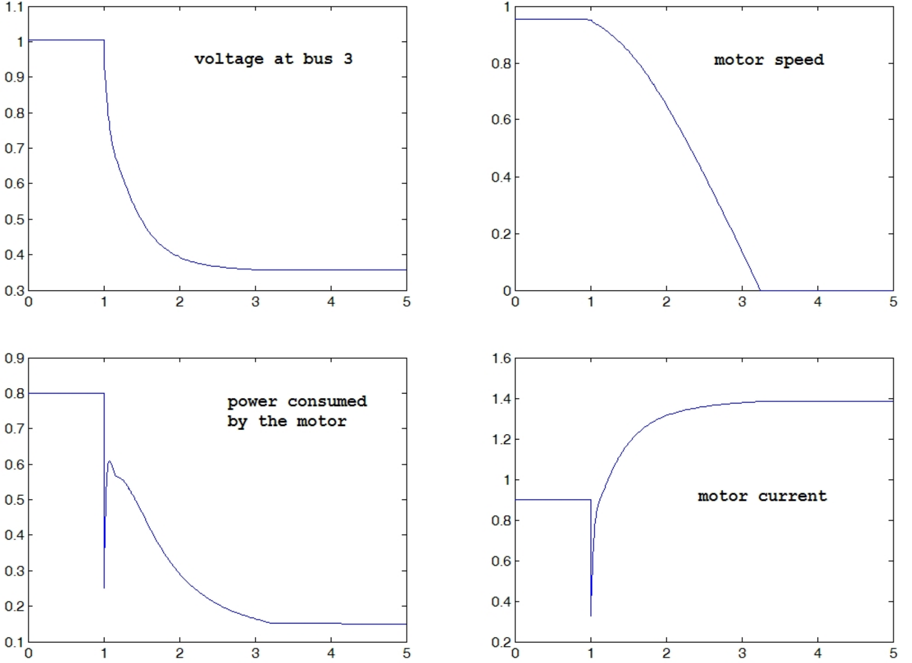

motor speed
0.958
0.956
0.954
0.952
0.95
0.948
0.946
0.944
0
2
4
6
8


active power consumed
by the motor 3
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0
2
4
6
8

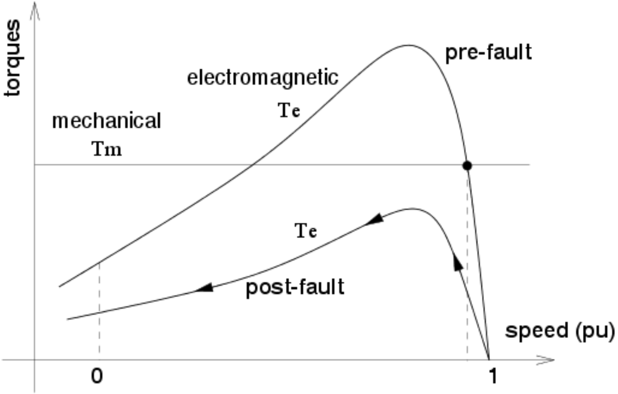
Short-term voltage stability - example 2



at $t = 1$ s, tripping of both the generator and one circuit of the line

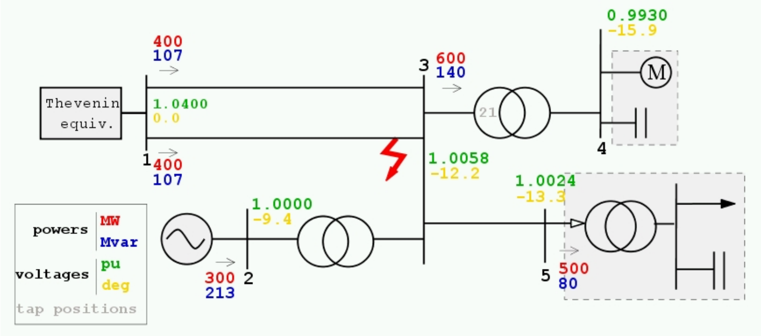

voltage at bus 3
motor speed
power consumed
by the motor
motor current

instability mechanism shown by motor speed-torque curves

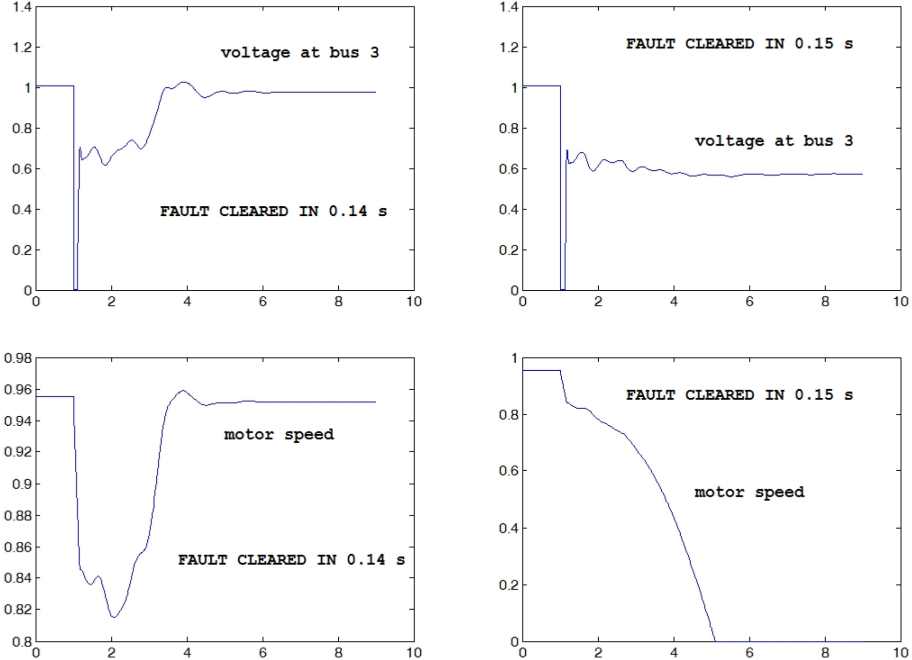


loss of short-term equilibrium

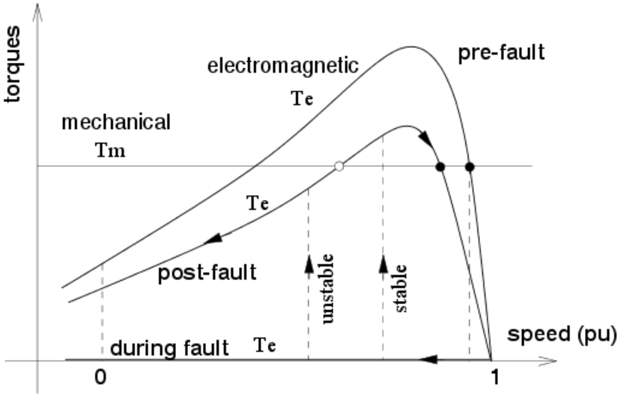
Short-term voltage stability - example 3



short-circuit at $t = 1$ s, on line 1-3, near bus 3
cleared by opening one circuit, after 0.14 and 0.15 s, respectively

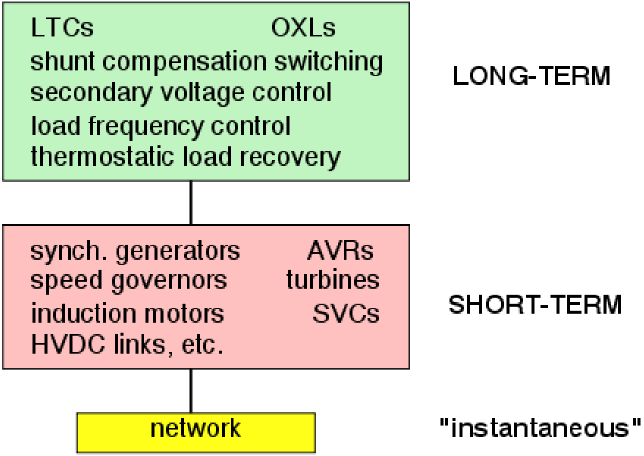

voltage at bus 3
FAULT CLEARED IN 0.14 s
FAULT CLEARED IN 0.15 s
voltage at bus 3
motor speed
FAULT CLEARED IN 0.14 s
FAULT CLEARED IN 0.15 s
motor speed

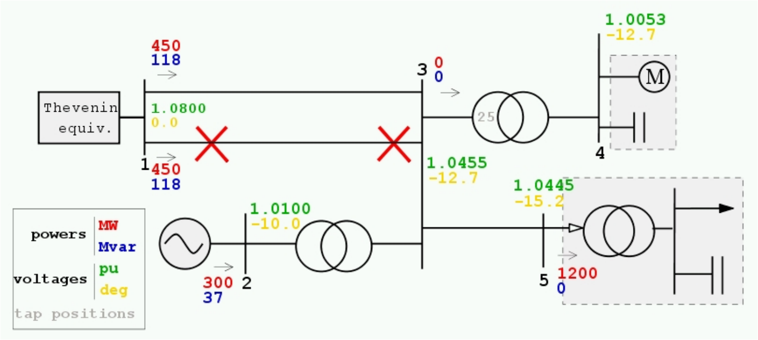
instability mechanism shown by motor speed-torque curves



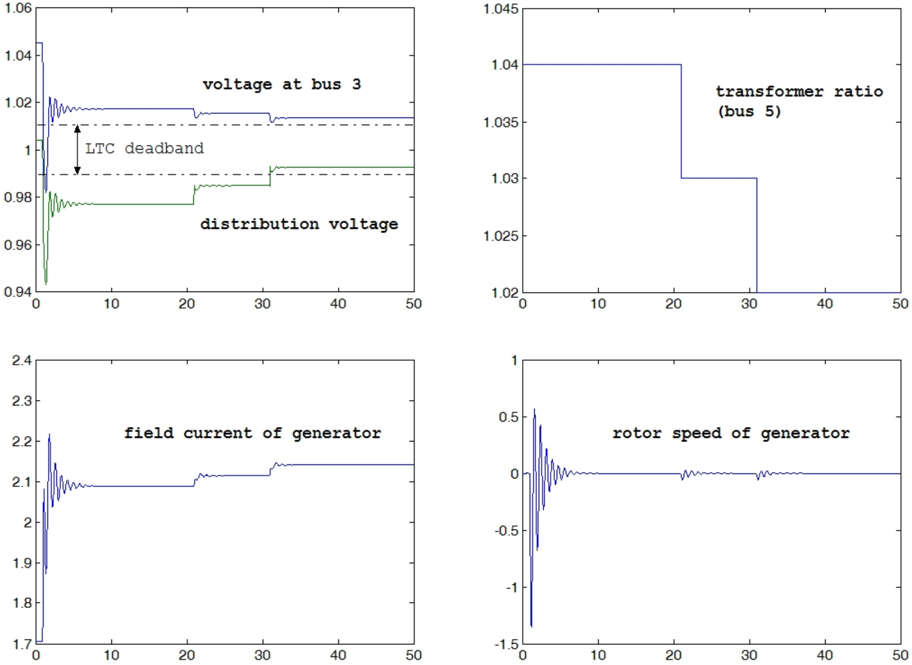
lack of attraction to post-fault stable equilibrium

Time-scale decomposition

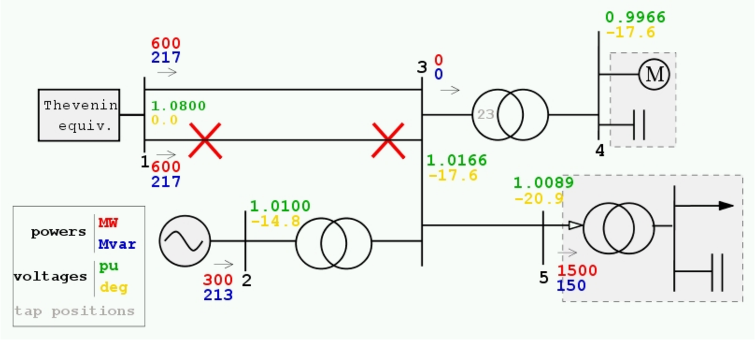




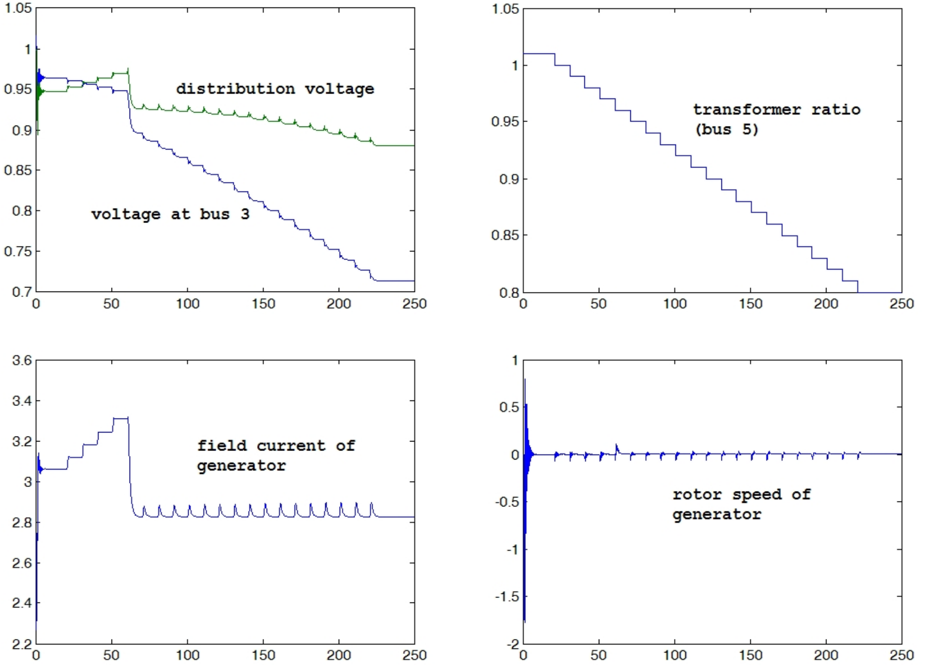
whole load with exponential model $P = \left(\frac{V}{V^o}\right)^{1.5}$ $Q = \left(\frac{V}{V^o}\right)^{2.5}$
Load Tap Changer (LTC) controlling distribution voltage
generator equipped with field current limiter
at $t = 1$ s, tripping of one circuit of the line


voltage at bus 3
LTC deadband
distribution voltage
transformer ratio
(bus 5)
field current of generator
rotor speed of generator

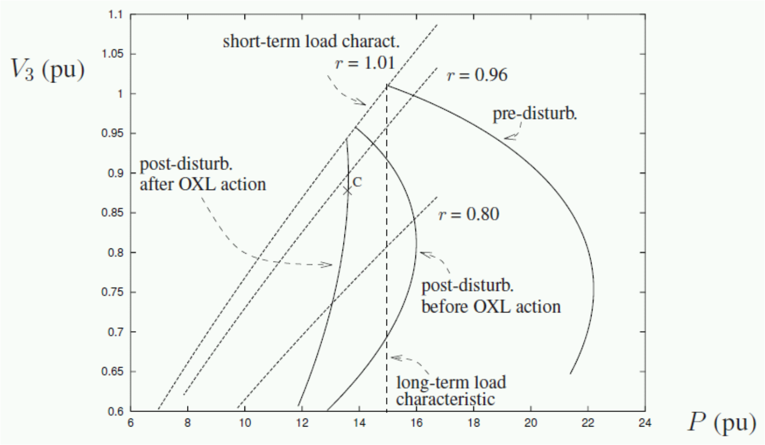
Long-term voltage stability - example 2



larger load
same disturbance

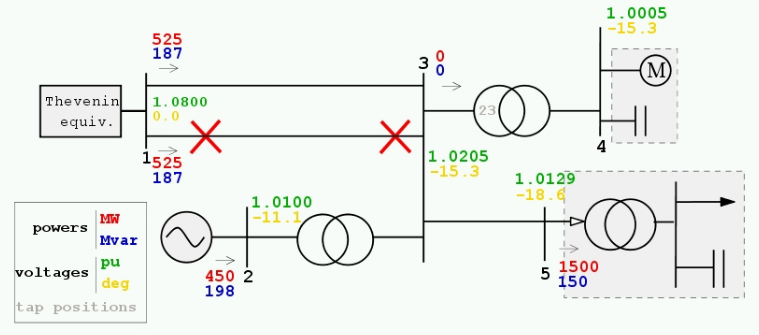

distribution voltage
voltage at bus 3
transformer ratio
(bus 5)
field current of
generator
rotor speed of
generator

instability mechanism shown by PV curves

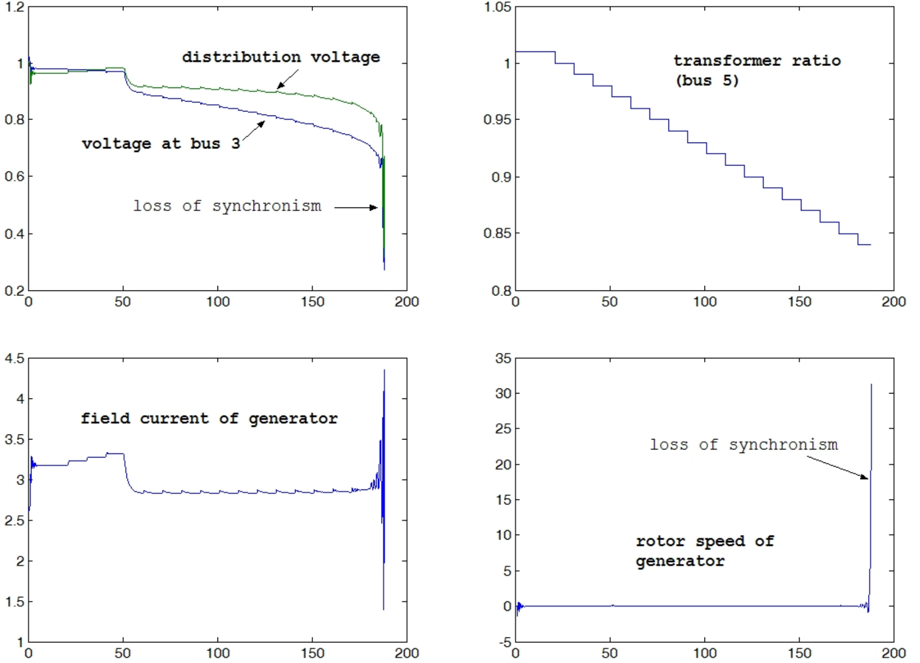


loss of equilibrium of long-term dynamics
pseudo-stabilization when LTC hits its limit
a case of “pure” long-term voltage instability

Long-term voltage stability - example 3

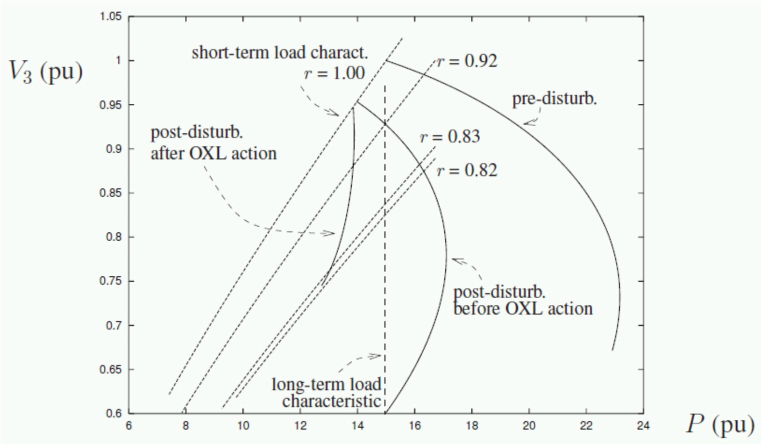


same load, larger production of generator
same disturbance



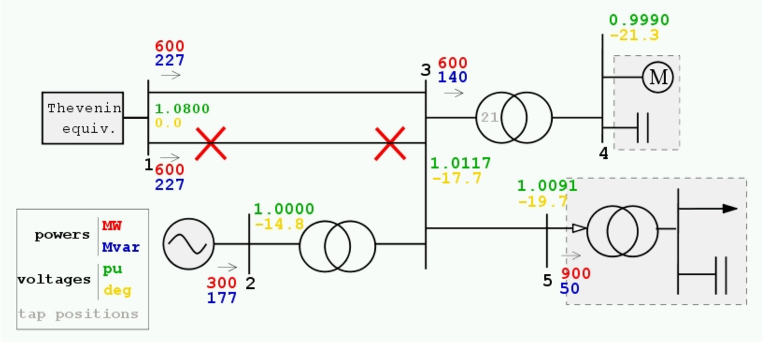
distribution voltage
voltage at bus 3
loss of synchronism
transformer ratio
(bus 5)
field current of generator
loss of synchronism
rotor speed of
generator

instability mechanism shown by PV curves



long-term instability $\rightarrow$ slow system degradation $\rightarrow$ instability of short-term dynamics (loss of synchronism) $\rightarrow$ system collapse

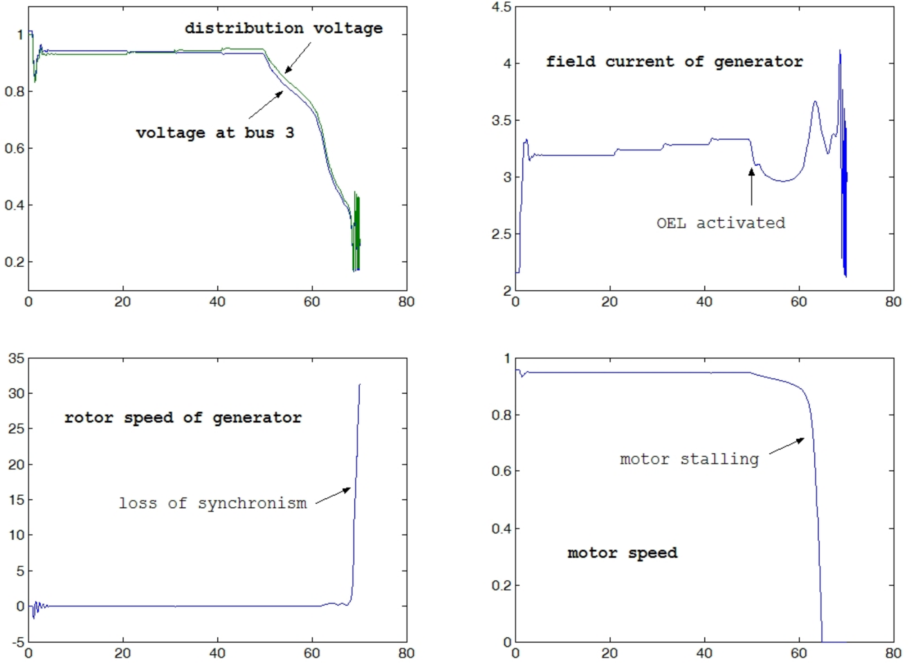
Long-term voltage stability - example 4



50 % induction motor load

same disturbance

long-term instability → slow system degradation → instability of short-term dynamics (motor stalling, followed by loss of synchronism) → system collapse


distribution voltage
voltage at bus 3
field current of generator
OEL activated
rotor speed of generator
loss of synchronism
motor stalling
motor speed