ELEC0047 - Power system dynamics, control and stability

Long-term voltage instability: dynamic aspects and countermeasures

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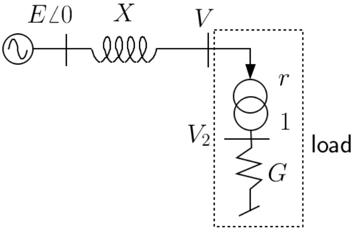
Instability mechanisms of a Load Tap Changer (LTC)

A simple model



We assume for simplicity that:

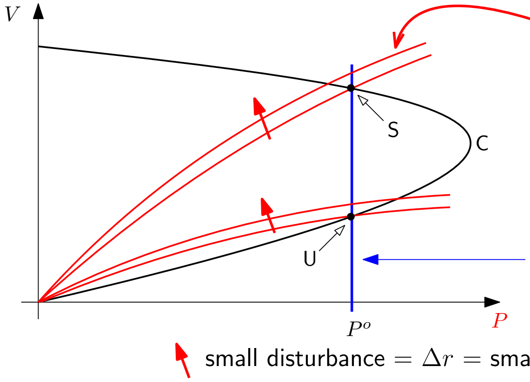
- the transformer is ideal :

$$V = r\,V_2$$

- the Load Tap Changer (LTC) adjusts r to have $V_2 = V_2^o$
    - if $V_2 < V_2^o$ then r is decreased
    - if $V_2 > V_2^o$ then r is increased
    - the voltage dead-band is neglected
- the load behaves as a constant admittance with unity power factor :

$$P = G\,V_2^2 = G\left(\frac{V}{r}\right)^2 \qquad Q = 0$$

Small-disturbance stability (of an operating point)



load for various values of r changed by LTC
$P = G(\frac{V}{r})^2$

load with voltage V_2 restored to V_2^o by LTC
$P = G(V_2^o)^2 = P^o$

small disturbance $= \Delta r =$ small increase of r

- equilibrium point S is stable:

$$\begin{array}{lllll} \Delta r > 0 & \Rightarrow \ \Delta P < 0 & \Rightarrow \ \Delta V_2 < 0 & \Rightarrow & \text{the LTC decreases } r \\ \Delta r < 0 & \Rightarrow \ \Delta P > 0 & \Rightarrow \ \Delta V_2 > 0 & \Rightarrow & \text{the LTC increases } r \end{array}$$

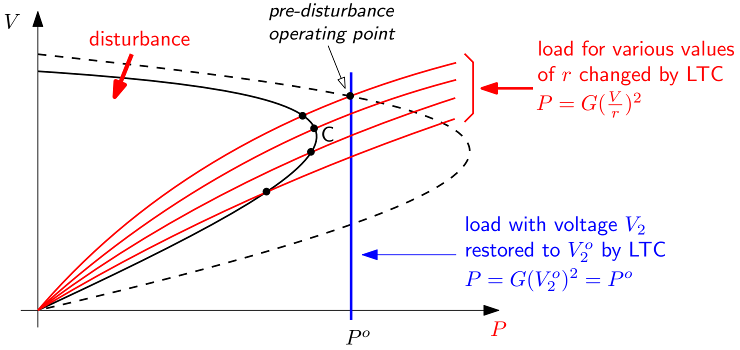
- equilibrium point U is unstable:

$$\begin{array}{lllll} \Delta r > 0 & \Rightarrow \ \Delta P > 0 & \Rightarrow \ \Delta V_2 > 0 & \Rightarrow & \text{the LTC further increases } r \\ \Delta r < 0 & \Rightarrow \ \Delta P < 0 & \Rightarrow \ \Delta V_2 < 0 & \Rightarrow & \text{the LTC further decreases } r \end{array}$$

- As the “demand” G increases, the stable and unstable operating points converge, coalesce and disappear at point C
- point C is a *bifurcation* point : a point where, for a small variation of one or several parameter(s), the qualitative behaviour of the dynamics changes with respect to :
  - the number of equilibrium points
  - or the number of limit cycles
  - or the stability of equilibrium points or limits cycles, etc.
- this particular bifurcation is called a *saddle-node bifurcation*
- the saddle-node bifurcation point is also the maximum load power point because the equilbrium characteristics of the load is a constant power, under the effect of the LTC.

Instability due to a large disturbance

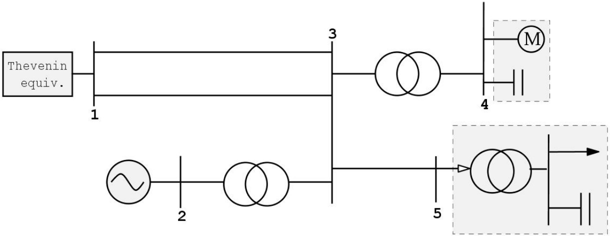
(outage of transmission lines or generators)



- the LTC attempts to restore $V_2 \rightarrow V_2^o$ and, hence, $P \rightarrow G\left(V_2^o\right)^2 = P^o$
- the disturbance causes the maximum load power to become smaller than P^o
- successive operating points shown with dots : in its attempt to restore V_2 the LTC depresses the transmission voltage V
- after crossing the critical point C, the tap changes produce reverse effects.

Dynamic simulations and analysis of a 5-bus system

System



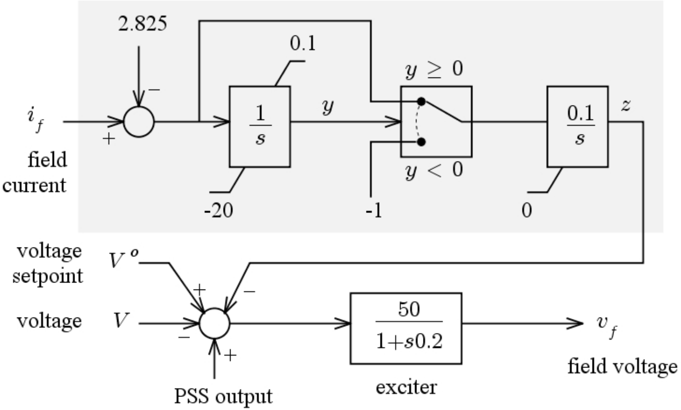
Load center:

- equivalent induction motor
- static load with exponential model $P = P^o(V/V^o)^{1.5}$ $Q = Q^o(V/V^o)^{2.5}$
- LTC controlling voltage of static load. Tap delays $= 20 + k.10$ s

fed by:

- external system (represented by Thévenin equivalent) through long line
- local synchronous generator equipped with AVR and OEL

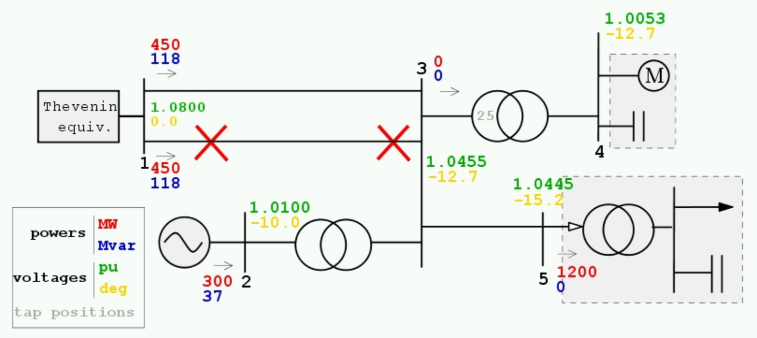
Model of overexcitation limiter



y initially at lower bound -20 *z initially at lower bound 0*

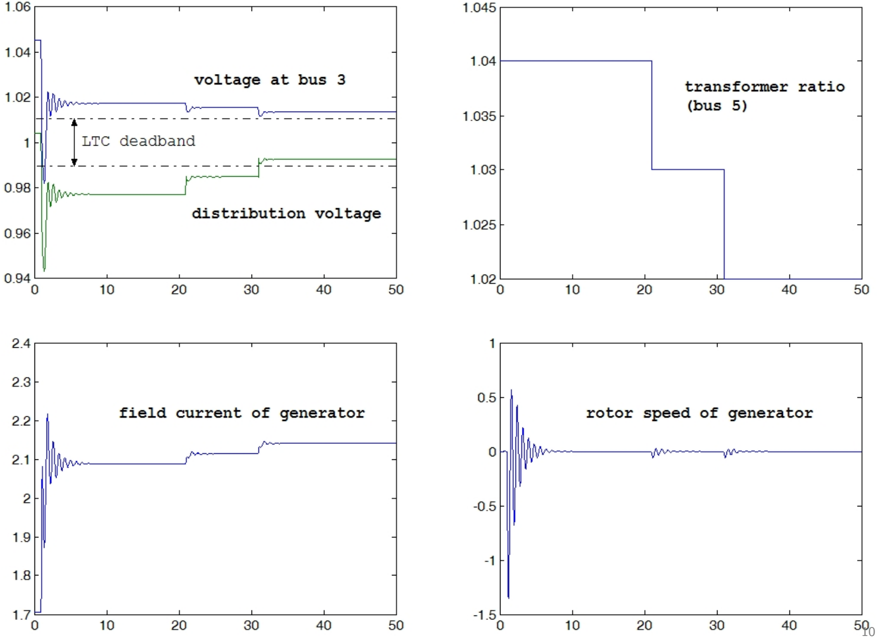
inverse-time characteristic: the smaller the field winding overload, the longer the delay before the field current is decreased to its limit (2.825 pu)

Case 1. Disturbance

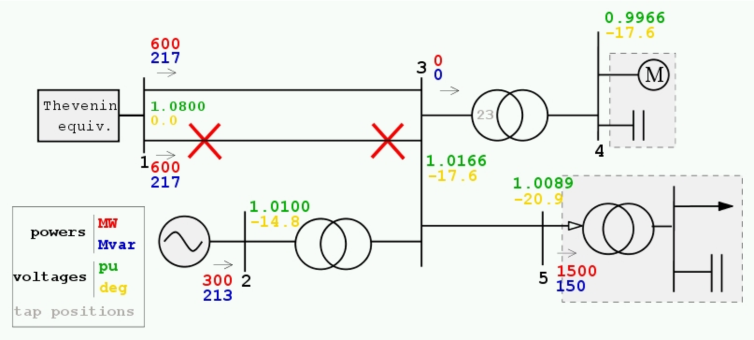


At $t = 1$ s, tripping of one circuit of the line

Case 1. Time responses

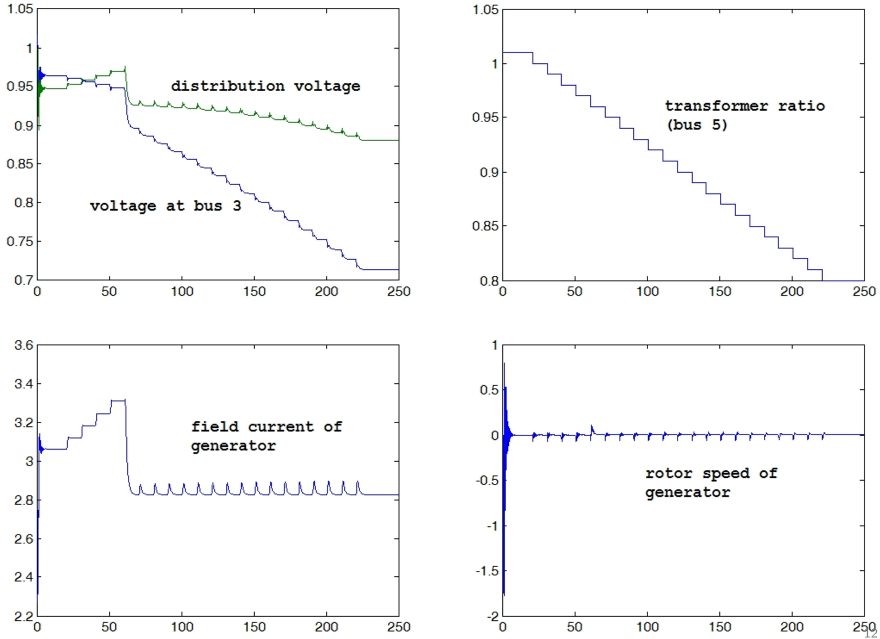


Case 2. Disturbance



same as Case 1 but exponential load increased to 1500 MW

Case 2. Time responses

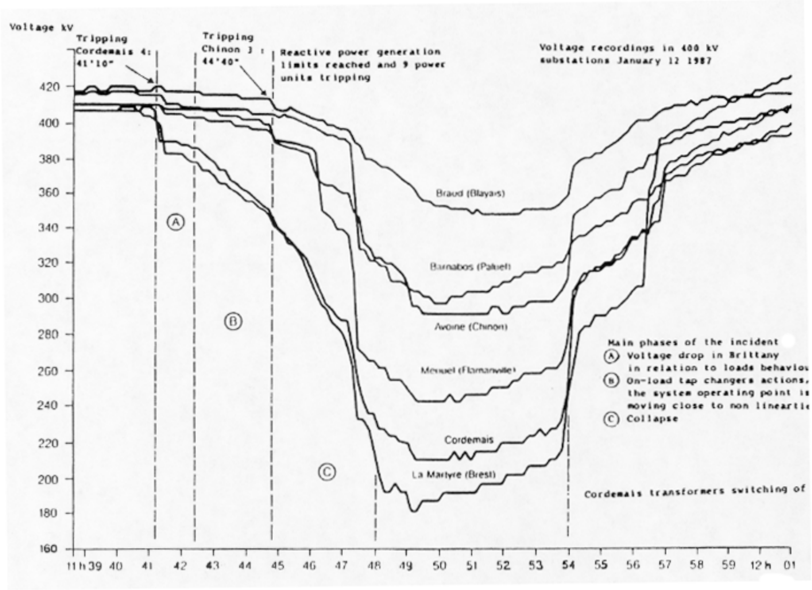


Case 2. Comments

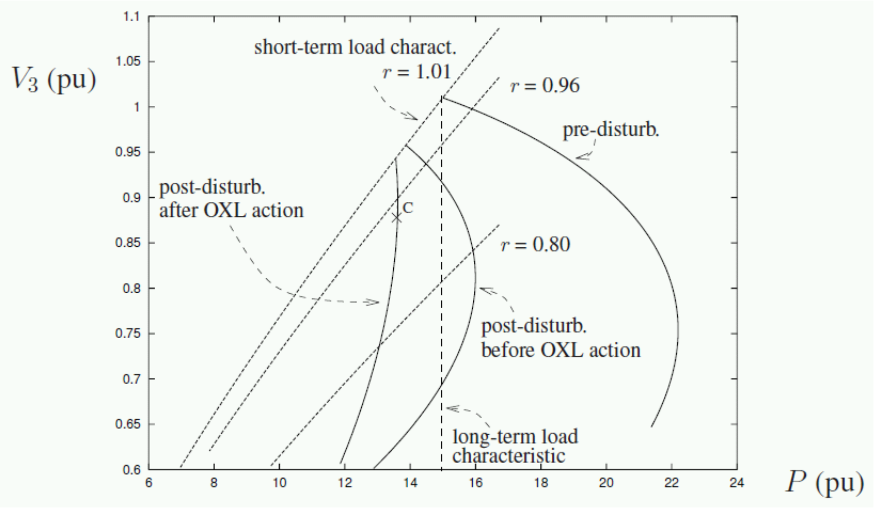
- field current of local generator limited by OEL at $t \simeq 70$ s
- from there on, the LTC fails restoring the distribution voltage; on the contrary, it has reverse effect on this voltage
- the transmission voltage drops under the effect of the LTC and the OEL
- the short-term dynamics of the generator, its regulators, etc. respond in a stable way
- there is a pseudo-stabilization when the LTC reaches its limit. This pseudo-equilibrium is not viable:
  - voltage is really low (in a real system, protections could trigger further trippings, with cascading effects)
  - any attempt to increase the demand will result in opposite effect.

A real incident with the same characteristics

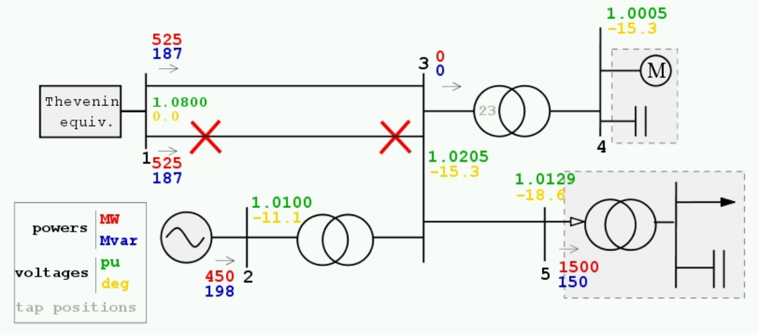
Incident in Brittany (Western France), January 12, 1987



Case 2. Instability mechanism shown by PV curves

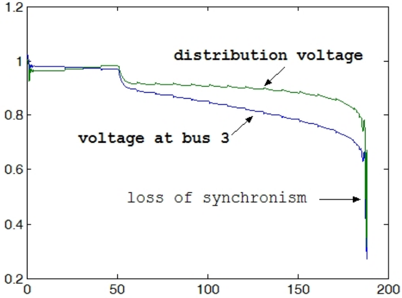


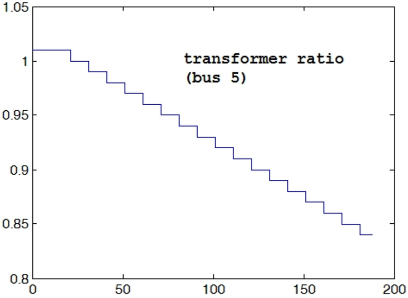
Case 3. Disturbance

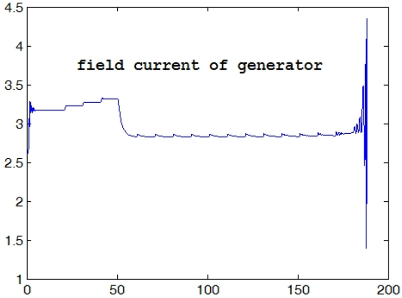


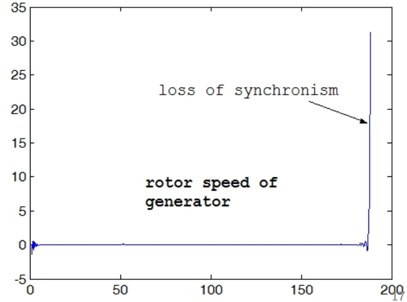
same as Case 2 but local generation increased to 450 MW

Case 3. Time responses





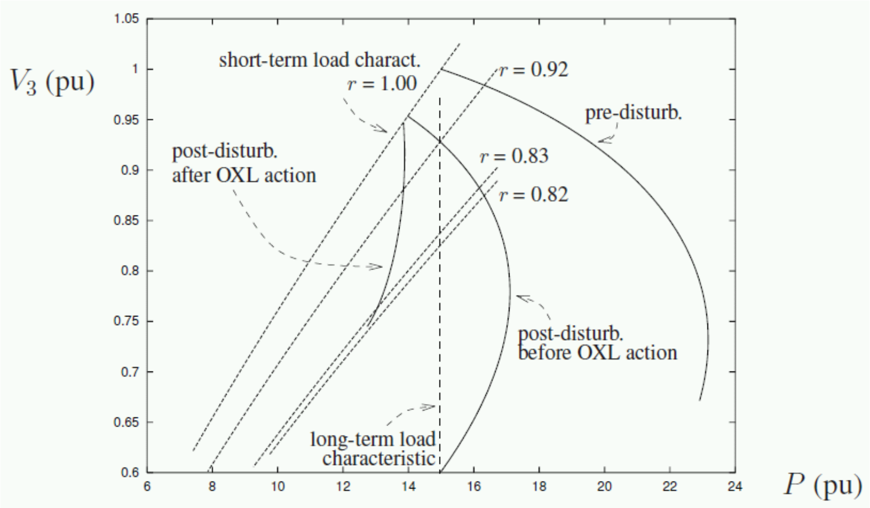




Case 3. Comments

- impact of LTC and OEL similar to Case 2
- but under the effect of the long-term degradation of operating conditions, the (field-current limited) generator loses synchronism, which makes voltages plunge
- emergency actions have to be taken before reaching this "no-return" or "collapse" point

Case 3. Instability mechanism shown by PV curves



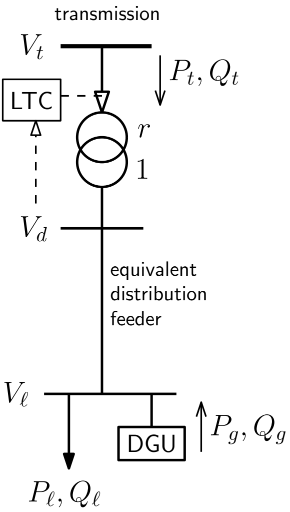
Countermeasures against voltage instability

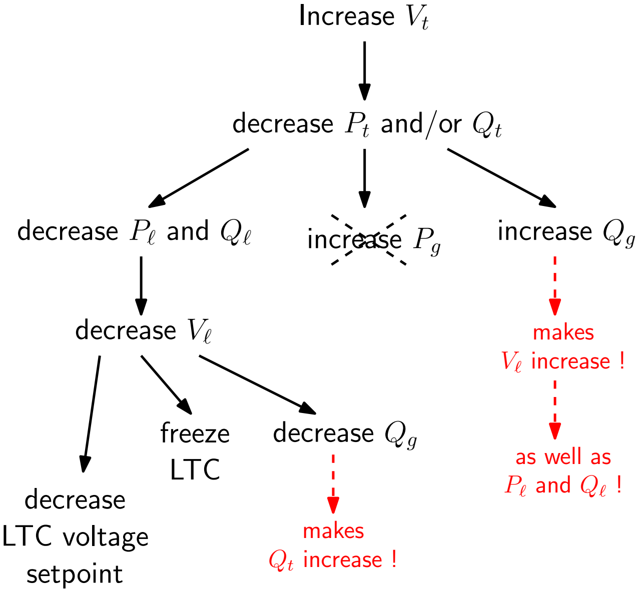
At planning stage

- Series compensation
  - very effective way of reducing series impedance of transmission lines
  - expensive, more complex protection of transmission line
  - possibility of subsynchronous resonance (between network elements and generator shafts in thermal plants)
  - used only in stretched systems with long transmission distances.
- Mechanically switched shunt capacitors
  - cheapest solution
  - switching off shunt inductors equivalent to switching on shunt capacitors
  - preventive control : maintain reactive power reserves on “fast reacting” devices (generators, synchronous condensers, SVCs) to make them ready to face disturbances
  - corrective control : switching triggered by detection of low voltage
- Static Var Compensators (SVCs) - Statcoms
  - fast and smooth variation of shunt compensation
  - more expensive than mechanically switched capacitors
  - justified when speed of action is needed (short-term voltage instability)
  - also used for other instabilities: e.g. transient instability in a long corridor.

During system operation (preventively - correctively)

- Voltage Security Assessment
    - contingency analysis
    - security margins
- Adjustment of generator active power productions
    - keeping "out of merit" generators in service units for security reasons
    - generation rescheduling
    - start-up of fast units (e.g. gas turbines) if located near loads
- Adjustment of generator voltages
    - "boosting" of generator voltages to increase load voltages
    - this also increases the maximum power deliverable to loads
    - variation limited by maximum voltage allowed at generator terminal
    - control of multiple interacting generators must be coordinated.
- Emergency control of load tap changers : see next slide
- Support from dispersed generation at distribution level : see next slide
- Under-voltage load shedding : last-resort countermeasure
    - very effective: shedding need not be large to restore voltages to normal values
    - immediate effect; appropriate to correct large voltage drops
    - unlike under-frequency load shedding, location is important
    - amount and time linked: beyond some time, acting later requires to act more.





Increase V_t

decrease P_t and/or Q_t

decrease P_ℓ and Q_ℓ

~~increase P_g~~

increase Q_g

decrease V_ℓ

makes V_ℓ increase !

decrease LTC voltage setpoint

freeze LTC

decrease Q_g

as well as P_ℓ and Q_ℓ !

makes Q_t increase !

DGU : Dispersed Generation Unit (at distribution level) controlling P_g and Q_g