ELEC0047 - Power system dynamics, control and stability

Long-term voltage stability : load aspects

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Voltage instability results from the inability of the combined transmission and generation system to provide the power requested by loads

Load power restoration

- If loads behaved as constant admittances, no voltage instability would occur (low but steady voltages would be experienced in severe cases)
- voltage instability is largely caused by the trend of loads to restore their pre-disturbance power after a disturbance
- this may take place in several time scales :

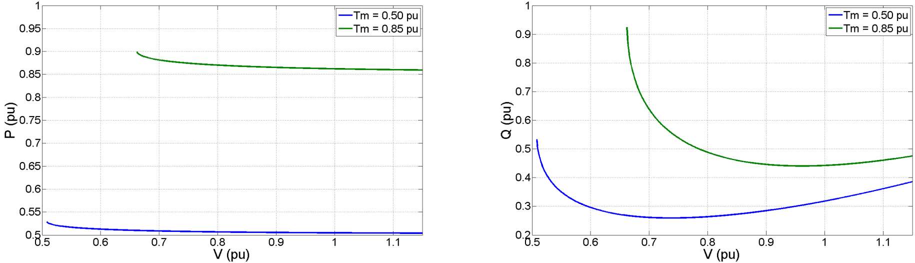
component	time scale	internal variable	equilibrium condition
induction motor	$\simeq$ 1 second	motor speed	mechan. torque $=$ electrom. torque
load tap changer	$\simeq$ few minutes	transformer ratio	controlled voltage within deadband
thermostatically controlled load	$\simeq$ few minutes - tens of min.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

- other devices/processes:

  distribution voltage regulators, consumer reaction to voltage drop

Load power restoration in induction motor

Steady-state characteristics of motor

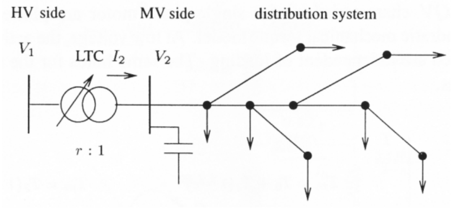


large industrial motor

$$X_s = 0.067,\ X_m = 3.800,\ X_r = 0.17,\ R_s = 0.013, R_r = 0.009 \text{ pu}$$

Load Tap Changers (LTCs)

Also referred to as *on-load tap changers* or *under-load tap changers*.



The LTC adjusts r to keep V_2 into a *deadband* $[V_2^o - \epsilon \;\; V_2^o + \epsilon]$

$r \simeq [0.85 - 0.90 \;\; 1.10 - 1.15]$ $\qquad \Delta r \simeq 0.5$ - 1.5 % $\qquad \Delta r < 2\epsilon$

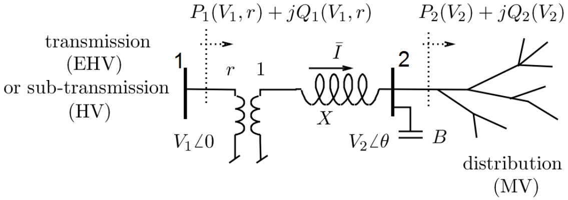
- Widely used to control voltages in networks of lower nominal voltage
  - HV sub-transmission and MV distribution networks
  - where no longer power plants are connected (replaced by more powerful ones connected to transmission network)
  - to compensate for voltage deviations in the EHV transmission network.
- Main way of controlling voltages in MV distribution grids.
  - but dispersed generation connected at MV level will play an increasing role.

The time response of LTCs is typical of *long-term dynamics*.

Delay between two tap changes:

- minimum delay T_m of mechanical origin $\simeq 5$ seconds
- intentional additional delay: from a few seconds up to $1-2$ minutes
  - to let network transients die out before reacting (avoid unnecessary wear)
  - fixed or variable
    - e.g. inverse-time characteristic: the larger the deviation $|V_2 - V_2^o|$, the faster the reaction
  - delay before first tap change ($\simeq 30-60$ seconds) usually larger than delay between subsequent tap changes ($\simeq 10$ seconds)
- if several levels of tap changers in cascade: the higher the voltage level, the faster the reaction (otherwise risk of oscillations between tap changers)

Load power restoration through LTCs



Assume the load is represented by an exponential model:

$$P_2(V_2) = P^o(\frac{V_2}{V_2^o})^\alpha \qquad Q_2(V_2) = Q^o(\frac{V_2}{V_2^o})^\beta$$

For simplicity, the reference voltage V_2^o is taken equal to the LTC set-point.

The power balance equations at bus 2 are:

$$P^o(\frac{V_2}{V_2^o})^\alpha = -\frac{V_1 V_2}{r X}\sin\theta \qquad (1)$$

$$Q^o(\frac{V_2}{V_2^o})^\beta - BV_2^2 = -\frac{V_2^2}{X} + \frac{V_1 V_2}{r X}\cos\theta \qquad (2)$$

- For given values of V_1 and r, Eqs. (1,2) can be solved numerically with respect to θ and V_2 (using Newton method for instance)
- from which the power leaving the transmission network is obtained as:

$$P_1 = -\frac{V_1 V_2}{r X} \sin\theta \quad (= P_2) \qquad\qquad Q_1 = \frac{V_1^2}{r^2 X} - \frac{V_1 V_2}{r X} \cos\theta$$

- repeating this operation for various values of V_1 and r yields the curves shown on the next slide.

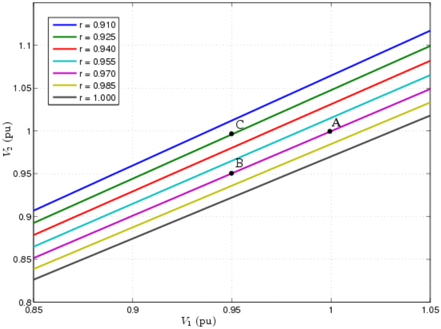
Numerical example

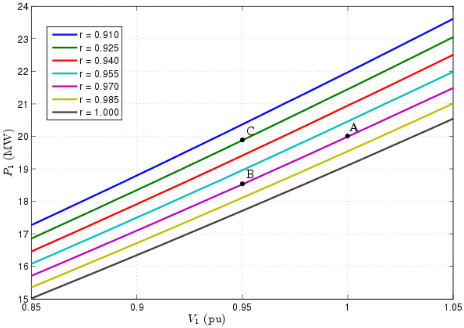
- transformer: 30 MVA, $X = 0.14$ pu, $V_2^o = 1$ pu
- load: $\alpha = 1.5$, $\beta = 2.4$, $P_2 = 20$ MW under $V_2 = 1$ pu,
  $\cos\phi_u = 0.90$ (lagging) under $V_2 = 1$ pu
- with the compensation capacitor: $\cos\phi_c = 0.96$ (lagging) under $V_2 = 1$ pu

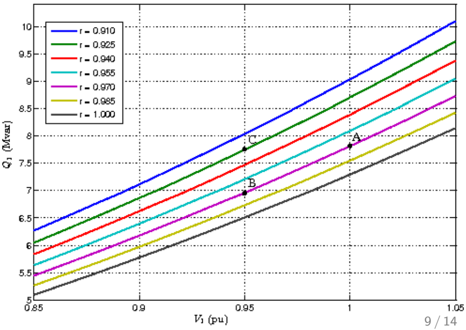
$$\text{On the } S_B = 100 \text{ MVA base:} \qquad X = 0.14(100/30) = 0.467 \text{ pu}$$

$$V_2^o = 1 \text{ pu} \qquad P^o = 0.20 \text{ pu} \qquad Q^o = P^o \tan\phi_u = 0.20 \times 0.4843 = 0.097 \text{ pu}$$

$$B.1^2 = Q^o - P^o \tan\phi_c \;\Rightarrow\; B = 0.097 - 0.20 \times 0.2917 = 0.039 \text{ pu}$$


r = 0.910
r = 0.925
r = 0.940
r = 0.955
r = 0.970
r = 0.985
r = 1.000
C
A
B
V_2 (pu)
V_1 (pu)
0.8
0.85
0.9
0.95
1
1.05
1.1
0.85
0.9
0.95
1
1.05


r = 0.910
r = 0.925
r = 0.940
r = 0.955
r = 0.970
r = 0.985
r = 1.000
C
A
B
P_1 (MW)
V_1 (pu)
15
16
17
18
19
20
21
22
23
24
0.85
0.9
0.95
1
1.05


r = 0.910
r = 0.925
r = 0.940
r = 0.955
r = 0.970
r = 0.985
r = 1.000
C
A
B
Q_1 (Mvar)
V_1 (pu)
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10
0.85
0.9
0.95
1
1.05

Initial operating point: A, where $V_1 = 1$ pu, $r = 0.97$ pu/pu, and $V_2 = V_2^o = 1$ pu

Response to a 0.05 pu drop of voltage V_1:

- in the short term, r does not change; the oper. point changes from A to B
- at point B, $V_2 < V_2^o - \epsilon = 0.99$ pu
- hence, the LTC makes the ratio decrease by three positions, until $V_2 > V_2^o - \epsilon$
- and the operating point changes from B to C.

Neglecting the deadband 2ϵ:

- the V_2 voltage is restored to the setpoint value V_2^o
- hence, the P_2 and Q_2 powers are restored to their pre-disturbance values
- the same holds true for the P_1 and Q_1 powers. This was to be expected since:

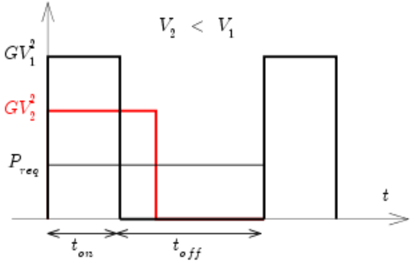
$$
\begin{aligned}
P_1 &= P_2(V_2) \\
Q_1 &= Q_2(V_2) - BV_2^2 + XI_2^2 = Q_2(V_2) - BV_2^2 + X\frac{P_2^2(V_2) + Q_2^2(V_2)}{V_2^2}
\end{aligned}
$$

- hence, the load seen by the transmission system behaves *in the long-term* (i.e. after the tap changer has acted) as a *constant power*.
- This is true as long as the tap changer does not hit a limit.

Power recovery of thermostatic loads

Heating resistors are switched on/off by thermostats so that the mean power consumed over a cycle = power required to keep the temperature = P_{req}

$$\frac{t_{on}}{t_{on}+t_{off}} GV^2 = P_{req} \qquad (3)$$



If V drops, $P = GV^2$ drops $\Rightarrow$ t_{on} increases until (3) is satisfied

For a large number n of identical thermostatically-controlled resistors:

$$P(t) = \sum_{i=1}^{n} f_i(t) GV^2 = n \left(\frac{1}{n} \sum_{i=1}^{n} f_i(t) \right) GV^2 \simeq n \frac{t_{on}}{t_{on}+t_{off}} GV^2$$

where $f_i(t) = 1$ if the i-th resistor is on at time t
$f_i(t) = 0$ if it is off.

$$P(t) \simeq n \frac{t_{on}}{t_{on} + t_{off}} GV^2$$

- following a voltage drop, nGV^2 decreases
  but after some time, $\dfrac{t_{on}}{t_{on} + t_{off}}$ increases until $P(t)$ recovers to nP_{req}
- thus, the load behaves as constant admittance in the short term and as constant power in steady state
- thermostatically controlled loads are also referred to as "constant-energy" loads.

- However, if the voltage drop is too pronounced, all resistors stay connected ($t_{off} = 0$) but P_{req} cannot be obtained. Then, the load behaves as constant admittance.

Generic model of load power restoration

Power consumed by the load at any time t:

$$P(t) = z_P P_o \left(\frac{V}{V_o}\right)^{\alpha_t} \qquad Q(t) = z_Q Q_o \left(\frac{V}{V_o}\right)^{\beta_t} \tag{4}$$

z_P, z_Q: dimensionless state variables associated with load dynamics
α_t, β_t: short-term (or transient) load exponents

In steady-state, the load obeys:

$$P_s = P_o \left(\frac{V}{V_o}\right)^{\alpha_s} \qquad Q_s = Q_o \left(\frac{V}{V_o}\right)^{\beta_s} \tag{5}$$

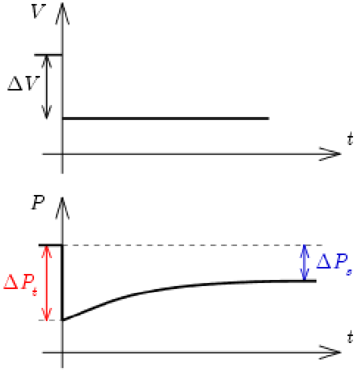
α_s, β_s: steady-state (or long-term) load exponents; usually $\alpha_s < \alpha_t, \beta_s < \beta_t$.

The load dynamics are given by:

$$T\, \dot{z}_P = \left(\frac{V}{V_o}\right)^{\alpha_s} - z_P \left(\frac{V}{V_o}\right)^{\alpha_t} \qquad T\, \dot{z}_Q = \left(\frac{V}{V_o}\right)^{\beta_s} - z_Q \left(\frac{V}{V_o}\right)^{\beta_t} \tag{6}$$

with $z_P^{min} \leq z_P \leq z_P^{max}$ and $z_Q^{min} \leq z_Q \leq z_Q^{max}$. $\quad T \simeq$ several minutes

Response of active power P to a step decrease of voltage V



$$\alpha_t \simeq \frac{\Delta P_t / P_o}{\Delta V / V_o} \qquad \alpha_s \simeq \frac{\Delta P_s / P_o}{\Delta V / V_o}$$

Similar expressions hold true for reactive power