ELEC0014 - Introduction to electric power and energy systems

Voltage control

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Two major differences between frequency and voltage controls:

- frequency = "signal" available throughout whole system, whatever its size. Nothing similar for voltage.

  Example:

  - change of active power setpoint of a generator
    $\Rightarrow$ frequency variation sensed by all speed governors
    $\Rightarrow$ reaction of all power plants under frequency control
  - change of voltage setpoint of a generator
    $\Rightarrow$ voltages at buses in some neighbourhood are modified
    $\Rightarrow$ among the other generators under voltage control, only those in some neighbourhood have their reactive power modified

- frequency hold very close to its nominal value
  - voltage control is comparatively less accurate
  - deviation of ± 5 % with respect to nominal value is very acceptable
  - in any case, voltage drops along the network impedances is inevitable.

However, voltages must be kept within acceptable limits:

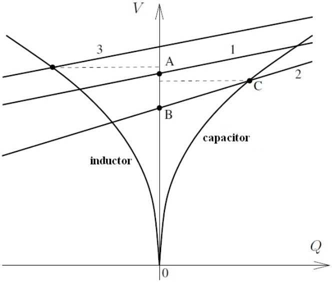
- not too high:
  - degradation of insulating materials
  - damage to sensitive (electronic) equipment
  - etc.
- not too low:
  - higher Joule losses in network
  - disturbed operation of some components: e.g.
    - commutation failures of power electronics
    - tripping of some loads (e.g. motors) by undervoltage protections
    - stalling of induction motors

Two main ways of acting on voltages:

1. inject (resp. extract) reactive power into (resp. from) the network
2. adjust the ratios of transformers equipped with load tap changers

Voltage correction by shunt capacitors or inductors

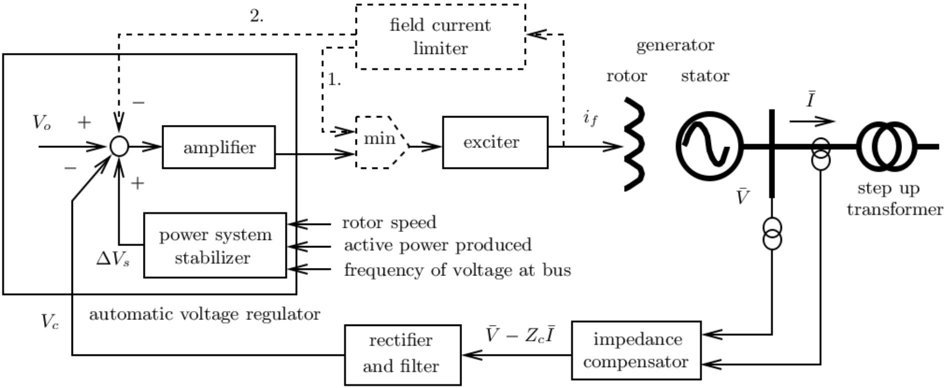
The most economical way of correcting voltage deviations at a bus



- control:
  - manual: by operator from dispatch center
  - automatic: by a local controller measuring voltage, comparing to threshold value, and reacting after some delay
- this is an adjustment "in steps", not a fine tuned control
- repeated and/or fast switching not possible with the mechanical breakers
  $\rightarrow$ use power electronics components

Excitation systems of synchronous machines: overview

Components of control chain



Automatic Voltage Regulator (AVR)

Exciter

- injects in the field winding a DC current under a DC voltage
- can quickly vary v_f and i_f in response to disturbances

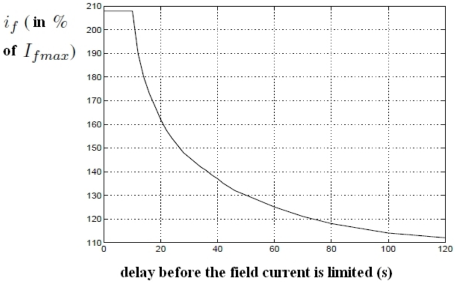
- rotating (auxiliary) machine on the same shaft as generator : power $v_f i_f$ provided by turbine
  - in the past: Direct Current generator
  - nowadays: Alternating Current generator + rectifier
- "static" system: transformer + rectifier

Impedance compensator

- voltage drop in step-up transformer partly compensated
- voltage controlled at a fictitious point closer to the transmission network
  - typically $Z_c \simeq 50 - 90$ % of the transformer series impedance
  - in what follows, it is assumed that $Z_c = 0$.

Field current limiter (or Over-Excitation Limiter - OEL

- In response to a large disturbance (typically a short-circuit), it is important to let the excitation system produce a high current i_f in order to support voltage
- in such circumstances, i_f may quickly rise up to a "ceiling" value $\simeq 2I_{fmax}$
  I_{fmax} : permanent admissible value
- such high value cannot be tolerated for more than a few seconds
- but milder field current overloads can be tolerated for longer $(\int i^2 dt)$
- *inverse time* characteristic:



Two techniques to limit the field current:

1. control the exciter with :

   min (AVR signal, OEL signal)

   - main voltage control loop opened when limiter is active
2. inject in the main AVR summing junction a correction signal
   - zero as long as the limiter does not act
   - such that the field current is smoothly brought back to its limit
   - can be seen as an automatic reduction of the voltage setpoint V_o.

The voltage regulator regains control as soon as operating conditions permit.

Stator current limiter

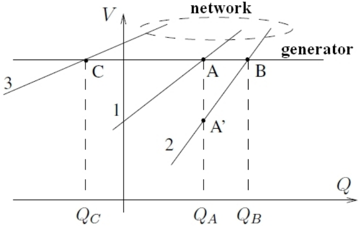
- less widespread than rotor current limiter
- larger thermal inertia of stator $\Rightarrow$ slower action, by power plant operator is enough
- two possibilities: decrease voltage setpoint V_o or generated active power P
- some generators are equipped with an automatic stator current limiter, acting on the exciter as the field current limiter does.

Response to a disturbance of a voltage-controlled synchronous machine

Simplifying assumptions:

- round-rotor machine with synchronous reactance X
- saturation and stator resistance neglected
- constant active power production P (since we focus on V and Q)
- infinitely accurate voltage control: terminal voltage V constant in steady state.

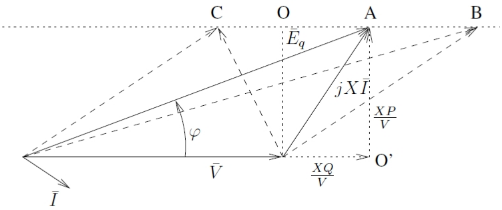
What happens in the network



$1 \rightarrow 2$: the generator produces more reactive power to keep its voltage constant

$1 \rightarrow 3$: the generator produces less reactive power to keep its voltage constant

What happens in the voltage-controlled machine



$\bar{V}$ is constant

When Q varies, under constant P, the extremity of $\bar{E}_q$ moves on a parallel to $\bar{V}$.

When the emf phasor $\bar{E}_q$ ends up:

- at point O: zero reactive power
- to the right of point O: the generator operates in *over-excitation mode*
- to the left of point O: the generator operates in *under-excitation mode*

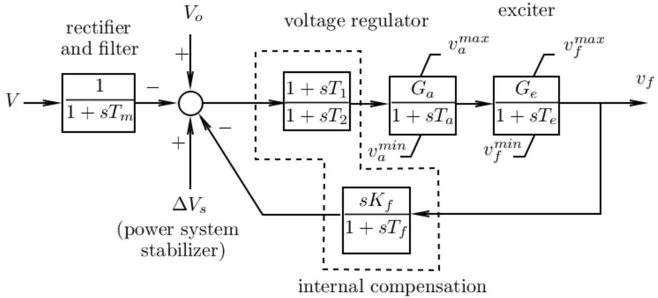
$1 \rightarrow 2$: A $\rightarrow$ B : Q, E_q and i_f increase

$1 \rightarrow 3$: A $\rightarrow$ C : Q, E_q and i_f decrease

QV curves of a synchronous machine

Machine under voltage control

Simplified generic model of an excitation system : **first type**



In steady state :

- $v_f = G_a G_e (V_o - V)$
- there must be a permanent error : $v_f \neq 0 \;\Rightarrow\; V \neq V_o$

In steady-state :

$$E_q = \frac{\omega_N L_{af}}{\sqrt{2}} i_f = \frac{\omega_N L_{af}}{\sqrt{2}\, R_f} v_f = \frac{\omega_N L_{af}}{\sqrt{2}\, R_f} G_a G_e (V_o - V) \tag{1}$$

Open-loop static gain : $G = G_a G_e \ \simeq\ 20 - 200$ pu/pu
(smaller values usually observed in older systems)

The phasor diagram gives :

$$E_q^2 = (V + X\frac{Q}{V})^2 + (X\frac{P}{V})^2 \tag{2}$$

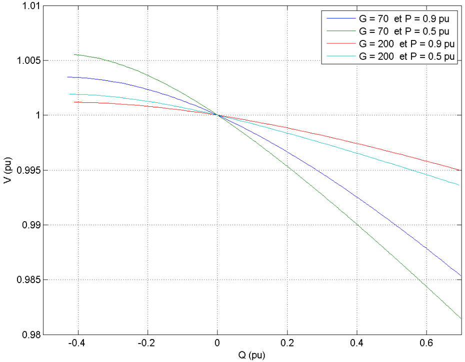
The steady-state behaviour is obtained by substituting (1) for E_q in (2).

Example of QV characteristic

Machine with $X = 2.2$ pu

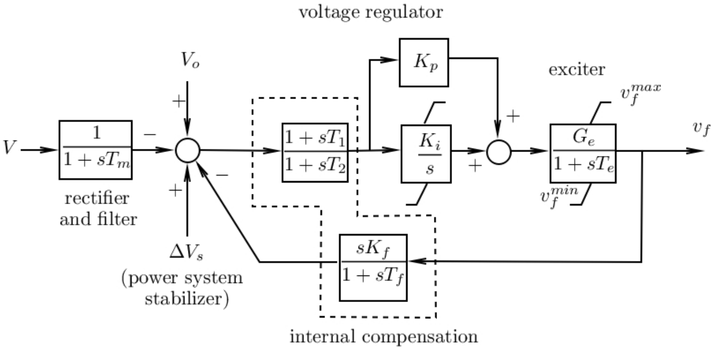
P and Q in pu on the machine (voltage and power) base

For each (G, P) combination, V_o was adjusted to have $Q = 0$ when $V = 1$ pu



- The machine experiences a *slight* voltage drop as Q increases
  - slope of the curve larger if G is smaller
  - slope slightly influenced by the value of P
- steady-state error stems from proportional control

Simplified generic model of an excitation system : **second type**
PI control with $K_p, K_i > 0$

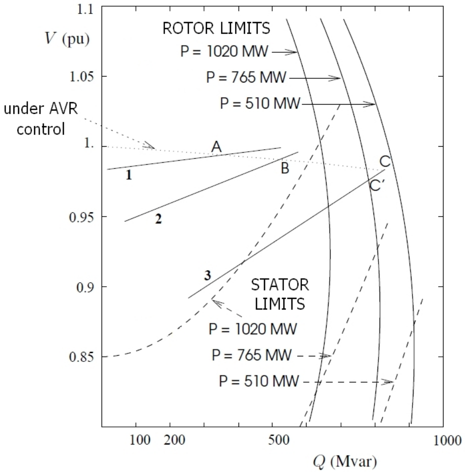


- In steady state : $V = V_o$
- no permanent regulation error
  (assumption made in previous section accurate for this excitation system)
- the QV curve is simply an horizontal line

Machine under rotor or stator current limit

Example :

nominal apparent power: 1200 MVA
turbine nominal power: 1020 MW



Under stator current limit: $S = V\, I_N = \sqrt{P^2 + Q^2} \quad \Rightarrow \quad Q = \sqrt{(V\, I_N)^2 - P^2}$

Extreme scenario: machine under limit $\Rightarrow$ V drops a lot $\Rightarrow$ generator tripped by undervoltage protection $\Rightarrow$ productions P and Q lost !!

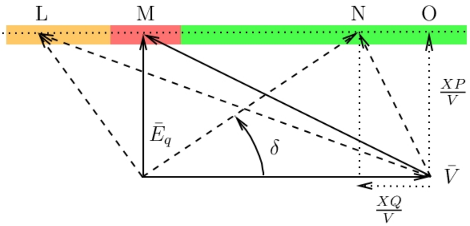
Underexcitation limiter

As the machine absorbs more and more reactive power:

- the extremity of the $\bar{E}_q$ phasor moves to the left (N $\rightarrow$ M $\rightarrow$ L)
- E_q first decreases, then increases
- δ increases

At point M :

- $\delta = 90^o$
- excitation is minimum
- $E_q = E_q^{min} = \frac{XP}{V}$
- $X\frac{Q}{V} = -V \;\Leftrightarrow\; Q = -\frac{V^2}{X}$



orange zone: unstable operation under constant excitation (constant E_q),
stable operation under the control of the AVR;
operation would become unstable if AVR had a failure !

red zone: if an excitation system failure makes E_q drop (even a little) below E_q^{min},
the machine looses synchronism (torque T_e too small, due to low i_f);
it is then tripped by the "loss of field" protection.

The underexcitation limiter :

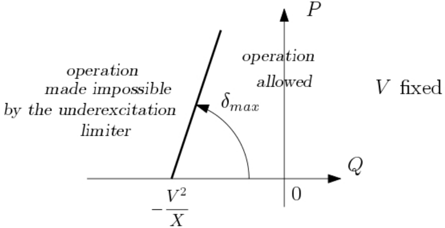
- prevents operation to the left of, and in some neighbourhood of point M
- keeps a security margin with respect to M.

Capability curve corresponding to $\delta = \delta_{max}$ (for instance 75^o) ?

$$\text{phasor diagram projected on } \bar{V} : \quad E_q \cos\delta_{max} = V + X\frac{Q}{V}$$

$$\text{phasor diagram projected on } \perp \bar{V} : \quad E_q \sin\delta_{max} = X\frac{P}{V}$$

$$\tan\,\delta_{max} = \frac{X\frac{P}{V}}{V + X\frac{Q}{V}} = \frac{P}{\frac{V^2}{X} + Q} \quad \Leftrightarrow \quad P = \tan\delta_{max}\left(Q + \frac{V^2}{X}\right)$$

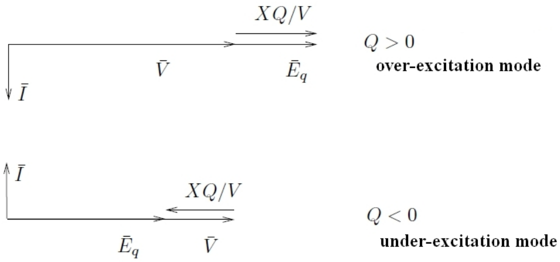


Acts on excitation system using the same techniques as for the OEL.

Synchronous condenser

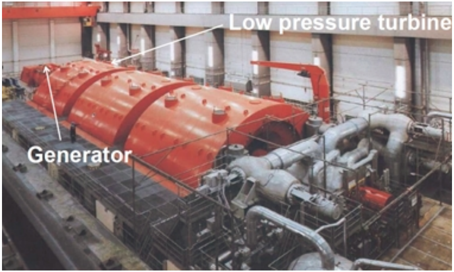
Synchronous machine equipped with an automatic voltage regulator, used to control the voltage at one bus of the network

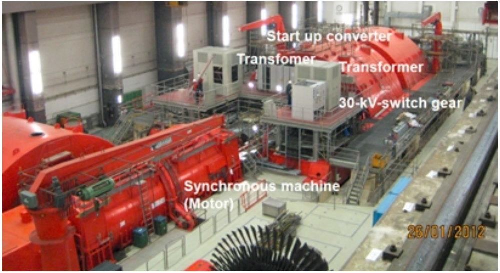
- produces or absorbs reactive power, as required by voltage control
- not driven by a turbine $\Rightarrow$ does not produce active power
- consumes a small active power corresponding to Joule losses at the stator and mechanical friction of rotor
- still in use nowadays, but static var compensator[1] is often preferred.



[1] see next section

Example of synchronous condenser





Shut down nuclear plant Biblis A, Germany: the generator has been converted into a synchronous condenser (2012)

Capacity : - 400 / + 900 Mvar

Source: Amprion & RWE Power

Static Var Compensator (SVC)

Device using power electronics to inject a fast-varying reactive power into the network[2].

Usages:

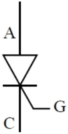
1. load compensation:
   - balance large loads presenting significant phase imbalance
   - stabilize voltage (amplitude) near fast varying loads
     - e.g. arc furnaces, rollers, etc. . .
     - mitigate *voltage flicker*: voltage fluctuations with a frequency $2 - 10$ Hz causing visible discomfort in lamps and disturbing some electronic devices
2. network applications:
   - maintain the voltage at a network bus nearly constant
   - contribute to stability improvement.

First generation of devices named *FACTS (Flexible AC Transmission Systems)*

[2] in French: compensateur statique de puissance réactive

The thyristor

Electronic component used as a switch



A : anode
C : cathode
G : gate

- current can flow if the anode voltage is higher than the cathode voltage ($v_A - v_C > 0$) *and* an impulse is applied to the gate[3] (thyristor is "fired")
- current can flow from anode to cathode only (as in a diode): the thyristor blocks if the current attempts to change direction.

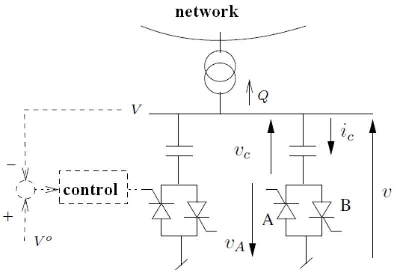
The gate impulses are produced by an *electronic control system*, independent of the power part but synchronized with the latter.

[3] in French: gachette

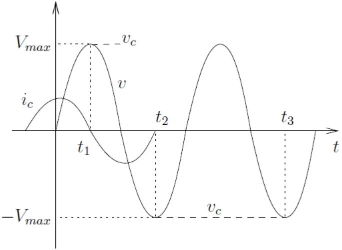
First compensator type: Thyristor Switched Capacitor (TSC)

Principle:

- switch on/off a number of capacitors banks connected in parallel
- use thyristors as bidirectional switches.



- shunt compensation is varied in discrete steps
- no reaction as long as voltage remains in a deadband
- each capacitor can be switched at multiples of a half-period (10 ms at 50 Hz)



$t = 0$: capacitor in service

- thyristor B is conducting
- the current i_c leads by 90^o the voltage v_c across the capacitor

$t = t_1$: assume that we want to keep the capacitor in service

- thyristor B blocks
- capacitor remains charged at the peak voltage V_{max}
- voltage across thyristor A: $v_c - v = V_{max} - v > 0$
- impulse applied to gate of A as soon as possible (to avoid transients !)
- unavoidable delays $\Rightarrow$ small inductor (not shown) in series with capacitor

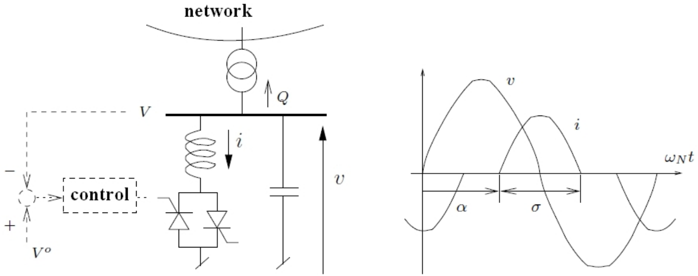
$t = t_2$: assume that we want to take the capacitor out of service

- no impulse applied to the gate of B
- capacitor remains charged with $v_c = -V_{max} \Rightarrow$ wait until time t_3 to put it back into service.

Second compensator type: "Thyristor Controlled Reactor" (TCR)

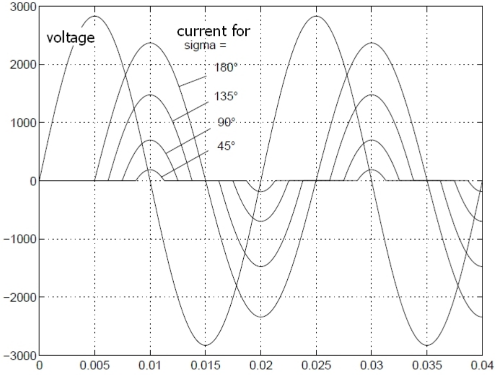
Principle:

- fire with intentional delay thyristors placed in series with an inductance
- use thyristors as bidirectional switches.



$\alpha =$ *firing delay angle*[4] $\sigma =$ *conduction angle*.

[4] angle de retard à l'allumage



Magnitude of fundamental (@ 50/60 Hz) of current:

$$I_{fund} = \frac{V}{\omega_N L} \frac{\sigma - \sin \sigma}{\pi} \qquad (\sigma \text{ in radian})$$

$$\sigma = \pi \quad \Rightarrow \quad I_{fund} = \frac{V}{\omega_N L} \quad \Rightarrow \quad \text{seen inductance is equal to } L$$

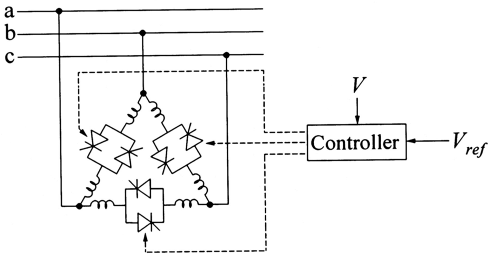
$$\sigma = 0 \quad \Rightarrow \quad I_{fund} = 0 \quad \Rightarrow \quad \text{seen inductance is infinite}$$

To produce reactive power: shunt capacitor placed in parallel

Filtering of harmonics

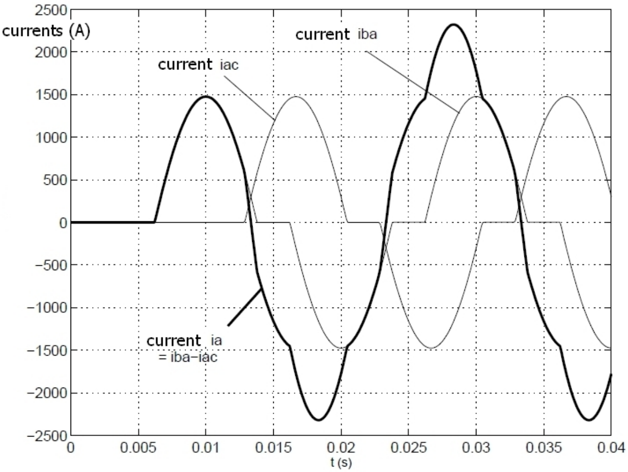
An exercise of Chapter 2 has shown that:

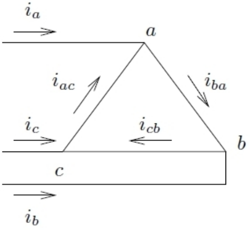
- in a current of this shape, there are no even harmonics
- mounting in triangle eliminates harmonics of rank 3, 6, 9, etc.



6-pulse TCR

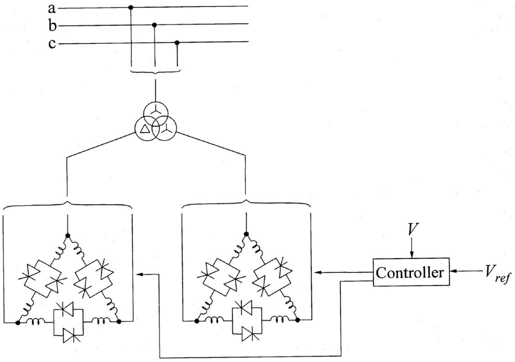
First remaining harmonics : rank 5 and 7. Eliminated by filters.


currents (A)
2500
2000
1500
1000
500
0
−500
−1000
−1500
−2000
−2500
current iac
current iba
current ia
= iba−iac
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
t (s)


i_a
a
i_{ac}
i_{ba}
i_c
i_{cb}
b
c
i_b

Filtering of harmonics

More elaborate scheme to also eliminate the harmonics of rank 5 and 7



12-pulse TCR

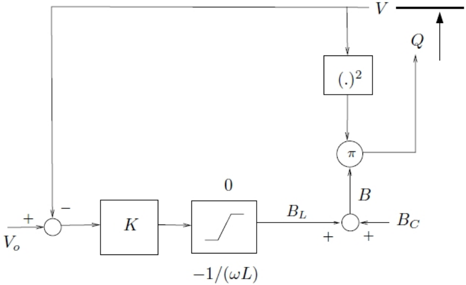
Phase shift of 30 degrees between the voltages of the two secondary windings

The remaining harmonics are eliminated by means of simpler filters.

Bloc diagram and nominal power

Bloc diagram of a TCR
in steady state
and in per unit

U_{nom} : nominal voltage
phase-to-phase



Nominal power :

$$Q_{nom} = 3 \max \left(|B_C - \frac{1}{\omega L}| , \ B_C \right) . (\frac{U_{nom}}{\sqrt{3}})^2 = \max \left(|B_C - \frac{1}{\omega L}| , \ B_C \right) . \ U_{nom}^2$$

If the TCR is designed to produce more reactive power than consume:

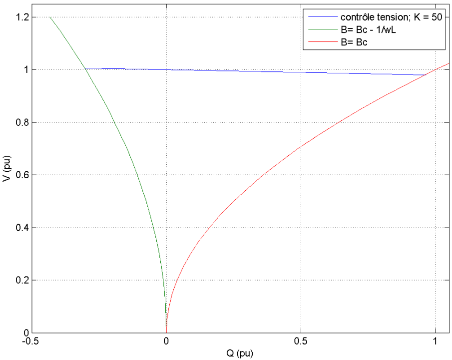
$$B_C > |B_C - \frac{1}{\omega L}| \quad \text{and} \quad Q_{nom} = B_C \ U_{nom}^2 \qquad (3)$$

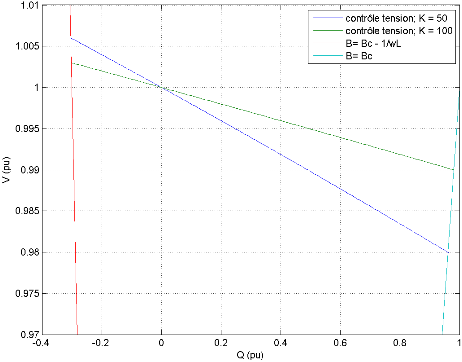
In the base $(U_{nom}/\sqrt{3}, Q_{nom})$:

- K is in the range $25 - 100$ pu/pu
- if Q_{nom} is given by (3) : $B_C = 1$ pu

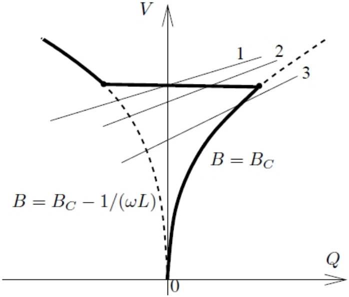
QV characteristics and voltage regulation

Example





- Q in pu on the compensator base $Q_{nom} = B_C\, U_{nom}^2$
- $B_C = 1$ pu $\qquad B_C - \frac{1}{\omega L} = -0.3$ pu
- voltage setpoint V_o adjusted to have $Q = 0$ under $V = 1$ pu



Adjustment of compensator operating point:

- Q is kept close to zero, to leave a reactive power reserve on the TCR, so that it is ready to counteract a disturbance in the network
- Q adjusted by switching on/off capacitors in parallel with the TCR
  - mechanically: with breakers
  - electronically : via a TSC

Static Var System : combination (TCR + TSC) or (TCR + mech. switched caps)

. . . compared to synchronous condensers:

- higher speed of response
- does not contribute to short-circuit current
- easier maintenance (no moving part)
- but no internal e.m.f. $\Rightarrow$ lower voltage support during short-circuits.

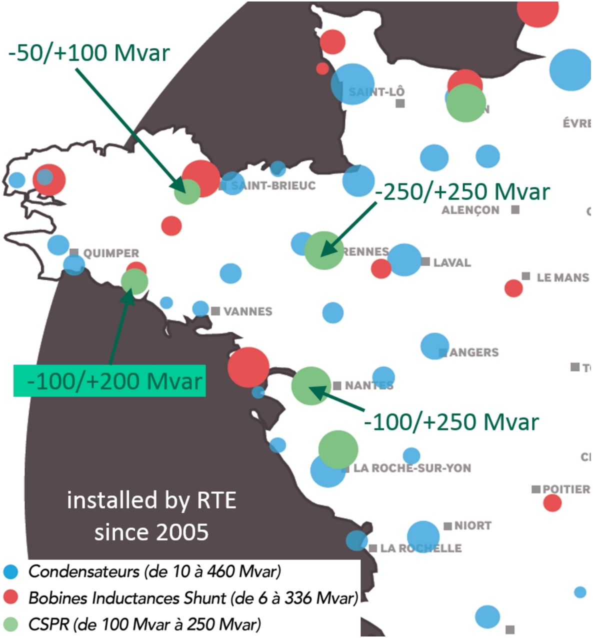
. . . with respect to mechanically switched capacitors/inductors:

- SVC remains significantly more expensive
- justified when there is a need for fast response and/or accurate voltage control (stability improvement)
- otherwise, mechanically switched capacitors/inductors are sufficient.

Reactive power compensation in Western French transmission grid

CSPR = Compensateur Statique de Puissance Réactive (= SVC)

- has a “standby” mode (to minimize losses): thyristors switched off when network voltage remains in a deadband
- reacts mainly to incidents impacting grid voltages (“dynamic reactive power reserve”)
- reaction time: 0.10 – 0.15 s

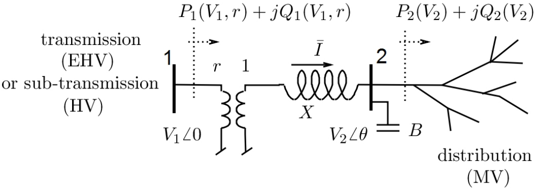


Voltage control by load tap changers

Principle

- 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 and serve the end consumers under correct voltage
- main way of controlling voltages in MV distribution grids.

  Other ways available at distribution level:
  - switch on/off shunt capacitors (but this is mainly for power factor correction)
  - ajust the active and/or reactive production of distributed generation units
    - not much used yet, but
    - likely to be required in the future, with the expected deployment of renewable energy sources



$r \simeq$ 85-90 to 110-115 %

$\Delta r \simeq 0.5 - 1.5$ %

$\Delta r < 2\epsilon$

Automatic load tap changer: adjusts r to keep V_2 into the *deadband*:

$$[V_2^o - \epsilon \;\; V_2^o + \epsilon]$$

Voltage setpoint V_2^o :

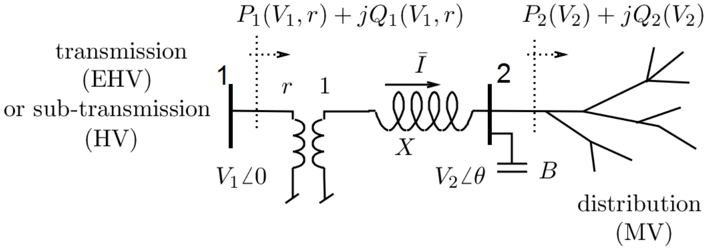
- standard MV distribution systems "importing" active power:
  - V_2^o higher than nominal voltage to counteract the voltage drop in MV grid
  - in some cases, the tap changer controls a "downstream" voltage $|\bar{V}_2 - Z_c\bar{I}|$
    $\bar{I}$: see figure $\qquad$ Z_c : compensation impedance
- MV distribution systems hosting distributed generation sources and "exporting" active power:
  - V_2^o lower than nominal voltage to avoid overvoltages at MV buses

Load tap changers are rather slow devices.

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)

Behaviour of a distribution network controlled by a load tap changer



Assume the load is represented by the *exponential model*:

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

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

The power balance equations at bus 2 are:

$$P^o\left(\frac{V_2}{V_2^o}\right)^\alpha = -\frac{V_1 V_2}{r\,X}\sin\theta \qquad (4)$$

$$Q^o\left(\frac{V_2}{V_2^o}\right)^\beta - BV_2^2 = -\frac{V_2^2}{X} + \frac{V_1 V_2}{r\,X}\cos\theta \qquad (5)$$

- For given values of V_1 and r, Eqs. (4,5) 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.

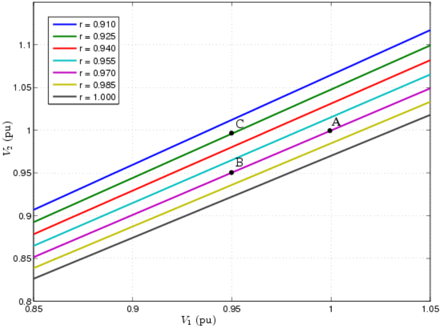
Numerical example

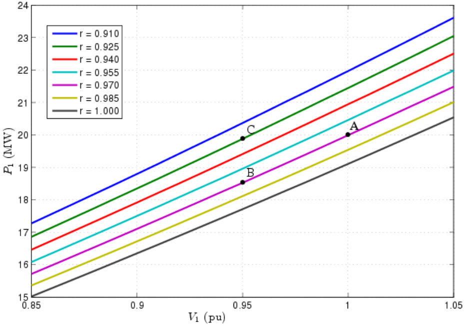
- transformer: 30 MVA, $X = 0.14$ pu, $V_2^o = 1$ pu
- load: $\alpha = 1.5$, $\beta = 2.4$, $P_2 = 20$ MW under $V_2 = 1$ pu,
  $\cos\phi_u = 0.90$ (lagging) under $V_2 = 1$ pu
- with the compensation capacitor: $\cos\phi_c = 0.96$ (lagging) under $V_2 = 1$ pu

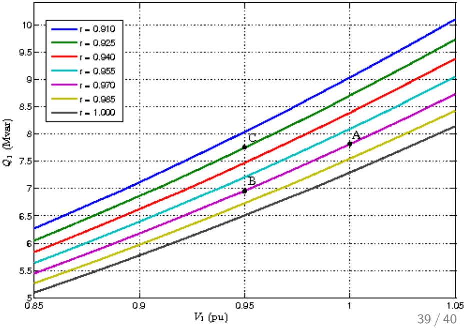
On the $S_B = 100$ MVA base: $X = 0.14(100/30) = 0.467$ pu

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

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


r = 0.910
r = 0.925
r = 0.940
r = 0.955
r = 0.970
r = 0.985
r = 1.000
A
B
C
V_2 (pu)
V_1 (pu)


r = 0.910
r = 0.925
r = 0.940
r = 0.955
r = 0.970
r = 0.985
r = 1.000
A
B
C
P_1 (MW)
V_1 (pu)


r = 0.910
r = 0.925
r = 0.940
r = 0.955
r = 0.970
r = 0.985
r = 1.000
A
B
C
Q_1 (Mvar)
V_1 (pu)

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.