Chapter 6.
Interactions of LCC-HVDC links with AC grids

Thierry Van Cutsem
(in replacement of Patricia Rousseaux)

t.vancutsem@ulg.ac.be www.montefiore.ulg.ac.be/~vct

March 2020
Introduction

- An HVDC link withdraws (resp. injects) a large active power from (resp. into) the AC grid to which it is connected
- LCC-HVDC links consume high reactive powers at both their terminals
- this may result in AC voltage problems
  - compensation is required
  - the simplest solution is through shunt capacitors
  - part of that compensation is provided by the harmonic filters.
- There is a maximum power that can be exchanged between an HVDC converter and the AC grid to which it is connected
  - recall: see next slide.
- The inverter side is *usually* more problematic than the rectifier
  - rectifiers are *usually* located in high production regions where generators make the AC system stronger
  - while inverters are *usually* located in areas with deficit of generation.
Recall from course ELEC0014
Study of a simple system: modelling

- Steady-state operation at fundamental frequency
- $I_d$ being kept constant by the rectifier in CC mode, the converter is treated as a current source of constant magnitude $I_{co}$:

\[
\bar{I}_{co} = I_{co} e^{j\phi_{co}} \quad \text{with} \quad I_{co} = n_r B_r \frac{\sqrt{6}}{\pi} I_d \quad \text{or} \quad I_{co} = n_i B_i \frac{\sqrt{6}}{\pi} I_d \quad (1)
\]

- the connected AC system is simply represented by its Thévenin equivalent at the Point of Common Coupling (PCC):

\[
\bar{V}_s = V_s e^{j\theta_s} \quad Z_s = R_s + jX_s \quad \text{where} \quad V_s \text{ is constant}
\]

- the reactive compensation is provided by a shunt capacitor with susceptance $B_c$
- the phase reference is taken at the PCC:

\[
\bar{V}_{PCC} = V_{PCC} e^{j0}
\]

\[1\]Hence, the term “Current Source Converters” also used for LCC converters
Chapter 6. Interactions of LCC-HVDC links with AC grids

Study of a simple system: modelling

Rectifier

\[-90^\circ < \phi_{co} < 0^\circ\]

\[P_{co} > 0, \quad Q_{co} > 0\]

Inverter

\[-180^\circ < \phi_{co} < -90^\circ\]

\[P_{co} < 0, \quad Q_{co} > 0\]
Further assumptions

- We focus on the inverter
- we consider the “short-term” response where the power electronics and their controllers have acted, but not the slower:
  - load tap changer: $n_i$ is constant
  - capacitor bank switching: $B_c$ is constant
- no control action is taken in the AC system: $V_s$ and $Z_s$ are constant
- the inverter operates in CEA mode: $\gamma = \gamma_0$
- we are going to perform a parametric study in which the DC current $I_d$ (controlled by the rectifier) is progressively increased.

- for simplicity, and without loss of generality, it is assumed that:
  - the link is monopolar and
  - $n_i = 1$ and $B_i = 1$. 
Equations on the DC side

\[ V_{di} = \frac{3\sqrt{6}}{\pi} V_{PCC} \cos \gamma - R_c I_d \]  
(2)

\[ I_d = \frac{\sqrt{6}}{2X_t} V_{PCC} (\cos \gamma_0 - \cos \beta) \]

\[ \cos \phi_{co} = -\frac{1}{2} (\cos \beta + \cos \gamma_0) \]

Eliminating \( \cos \beta \) from the last two equations yields:

\[ I_d = \frac{\sqrt{6}}{X_t} V_{PCC} (\cos \gamma_0 + \cos \phi_{co}) \]  
(3)
Equations on the AC side

\[ Z_s = R_s + j X_s \]

\[ Y_s = \frac{R_s}{\sqrt{R_s^2 + X_s^2}} - j \frac{X_s}{\sqrt{R_s^2 + X_s^2}} = G_s + j B_s \]

\[ I_{co} = Y_s (V_s - V_{PCC}) - j B_c V_{PCC} \]

where:

\[ I_{co} = \frac{\sqrt{6}}{\pi} l_d \cos \phi_{co} = G_s V_s \cos \theta_s - B_s V_s \sin \theta_s - G_s V_{PCC} \]  \hspace{1cm} (4)

\[ I_{co} = \frac{\sqrt{6}}{\pi} l_d \sin \phi_{co} = B_s V_s \cos \theta_s + G_s V_s \sin \theta_s - B_s V_{PCC} - B_c V_{PCC} \]  \hspace{1cm} (5)
Solution scheme

For given values of $I_d$, $V_s$ and $\gamma_0$, solve (2, 3, 4, 5) with respect to $V_{PCC}$, $\theta_s$, $\phi_{co}$ and $V_{di}$ using a nonlinear algebraic equations solver.

Numerical example

<table>
<thead>
<tr>
<th>DC system power rating</th>
<th>500 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC system line-to-line nominal voltage</td>
<td>$U_s = 420$ kV</td>
</tr>
<tr>
<td>DC voltage at inverter</td>
<td>$V_{di} = 496$ kV</td>
</tr>
<tr>
<td>Converter transformer rating</td>
<td>$S_t = 500$ MVA</td>
</tr>
<tr>
<td>Transformer reactance</td>
<td>$X_t = 0.1$ pu</td>
</tr>
<tr>
<td>Transformer tap ratio</td>
<td>$n_i = 1$</td>
</tr>
<tr>
<td>Extinction angle</td>
<td>$\gamma_0 = 18^\circ$</td>
</tr>
<tr>
<td>Impedance of AC system</td>
<td>$Z_s = 7.96 + j79.6$ $\Omega$</td>
</tr>
<tr>
<td>Reactive power compensation</td>
<td>$B_c = 0.0014$ S</td>
</tr>
<tr>
<td>(250 Mvar under nominal voltage $U_s$)</td>
<td></td>
</tr>
</tbody>
</table>
“Reference” operating point

For:

\[ I_d = 1000 \, \text{A} \quad V_s = 240.4 \, \text{kV} \quad \gamma_0 = 18^\circ \]

the DC variables take the values:

\[ V_{di} = 495.1 \, \text{kV} \quad \beta = 33.9^\circ \]

and the AC variables:

\[ I_{co} = 779.7 \, \text{A} \quad \phi_{co} = -152.9^\circ \quad \theta_s = -13.3^\circ \quad V_{PCC} = 237.7 \, \text{kV} \]

Hence the phase-to-phase voltage is:

\[ U_{PCC} = \sqrt{3} V_{PCC} = 411.7 \, \text{kV} \]

and the powers are:

\[ P_{co} = -V_{di} I_d = -495.1 \, \text{MW} \quad Q_{co} = -P_{co} \tan \phi_{co} = 253 \, \text{Mvar} \]

The DC current \( I_d \) is going to be varied from 0 to 2000 A.

Note: the reactive power compensation \( B_c \) has been adjusted to the reference operating point, and remains constant at other values of \( I_d \).
Study of a simple system: numerical results

Variations of phase angles and voltages

As $I_d$ increases:
- the phase angle $\phi_{co}$ increases; hence, the reactive power $Q_{co}$ increases
- $V_{PCC}$ decreases $\Rightarrow$ $V_{di}$ decreases.

At low loading, the AC voltage is too high.
- this is due to $B_c$ remaining constant
- in practice, the shunt compensation is adjusted with the operating point.
Active and reactive powers

\[ Q_{\text{net}} = Q_{\text{co}} - 3B_c V_{\text{PCC}}^2 \]

- As \( I_d \) increases, \( V_{di} \) decreases \( \Rightarrow |P_{co}| = V_{di} I_d \) increases at slower rate than \( I_d \)
- as expected (see slide \# 3), there exists a maximum power \( P_{\text{max}} \) that can be transmitted from the converter to the AC grid
- any attempt to increase the DC current above the value corresponding to this maximum will result in unstable operation!
- That maximum transmissible power varies with the AC system strength.
A larger extinction angle may be desired for higher protection against commutation failure.

A larger value of $\gamma_0$ results in a reduced maximum power $P_{\text{max}}$, reached for a smaller value of $I_d$. 
A higher reactive power compensation leads to:

- a higher voltage $V_{PCC}$\(^2\) and, hence, a higher DC voltage $V_{di}$
- a higher maximum transmissible power $P_{max}$.

\(^2\text{unacceptably high at low loading}\)
Control variant:

- inverter in Constant Voltage (CV) mode with $V_{di} = V_{di0} = 496$ kV
- unless $\gamma$ falls below $\gamma_{\text{min}} = 15^\circ$, in which case the inverter switches to Constant Extinction Angle (CEA) mode, with $\gamma = \gamma_{\text{min}}$.

DC voltage and extinction angle

The system switches from CV to CEA for $I_d \simeq 1100$ A
- while $V_{di}$ is kept constant, the power $|P_{co}| = V_{di}I_d$ varies in proportion to $I_d$
Firing advance angle and AC voltage

- Better AC voltage evolution while the inverter operates in CV mode
- when the inverter switches to CEA mode, we are brought back to the previous configuration; at high loading the curves are the same.
Indicators of AC/DC system interaction

- The characteristics of the AC system have a significant impact on the operation of the HVDC system.
- An AC system with high equivalent impedance may result in:
  - voltage fluctuations and, in the worst case, voltage instability
  - power transfer limitations (see previous slides).
- A “weak” AC system may cause other operating issues:
  - small-signal control instability
  - commutation failures
    - depression in AC voltage is the primary cause
    - recovery becomes particularly difficult
  - harmonic resonances
    - the AC system admittance has characteristic resonant peaks
    - with weak AC systems the first resonant peak is shifted to lower frequencies
    - and it may coincide with the low harmonics produced by the converters
    - if AC harmonics are magnified, they can cause control problems with HVDC firing circuit
  - temporary overvoltages: e.g. if the HVDC converter is blocked and the shunt compensation remains connected
- The “strength” of the AC system must be assessed in comparison with the rated power of the HVDC link.
Strength of an AC system

A simple measure of the AC system strength is the *short-circuit capacity* (or *fault level*; refer to course ELEC0014):

\[
S_{cc} = 3V_N I_{cc} = \sqrt{3} U_N I_{cc}
\]

where \( V_N \) is the phase-to-neutral nominal AC voltage (kV)
\( U_N \) is the phase-to-phase nominal AC voltage (kV)
\( I_{cc} \) is current in each phase of a zero-impedance three-phase short-circuit.

Adapting that notion to the Thévenin equivalent introduced in slide \# 4:

\[
V_N = V_s \quad \text{and} \quad I_{cc} = \frac{V_s}{|Z_s|}
\]

and hence:

\[
S_{cc} = 3 \frac{V_s^2}{|Z_s|} = \frac{U_s^2}{|Z_s|}
\]
**Short-Circuit Ratio (SCR)**

Refer the short-circuit capacity $S_{cc}$ (in MVA) to the rated power $P_{DC}$ of the HVDC link (in MW):

$$SCR = \frac{S_{cc}}{P_{DC}}$$

Usual SCR classification:

- $SCR \geq 3$: *strong AC system*: no operating problem
- $2 \leq SCR < 3$: *weak AC system*: operating difficulties can be expected. Some special controls are required
- $SCR < 2$: *very weak AC system*: serious operating difficulties can be expected. Very few HVDC systems operate with such low SCR.
Study of a simple system : effect of SCR

We continue with the simple system of slides # 4 - 16, using the variant detailed in slide # 15 (CV - CEA modes).

The SCR ratio was:

\[
SCR = \frac{U_s^2}{P_{DC}|Z_s|} = \frac{420^2}{500 \sqrt{7.96^2 + 79.6^2}} = 4.4
\]

The AC system impedance \( Z_s \) is now modified to vary the SCR:
- \( X_s \) is decreased/increased
- the ratio \( X_s/R_s \) is kept constant.
Case with $\text{SCR} = 2$ ($Z_s = 17.55 + j175.5 \ \Omega$)

Active/reactive powers and AC voltage

---

**dotted lines refer to the case with $\text{SCR} = 4.4$ ($Z_s = 7.96 + j79.6$)**

- The maximum transmissible power is dramatically reduced
- so much that that it drops below the rated power $P_{dc} = 500$ MW
- very steep change of AC voltage with DC current
- high AC voltage at low loading (risk of over-voltage in case of power interruption, e.g. due to commutation failure)
For a rated power $P_{DC} = 500$ MW and considering a 10% security margin, the theoretical $SCR$ should be at least 3.
Solutions to enhance operation with a weak AC system

- Special control modes, such as current control at the inverter.
- Connection of a synchronous condenser at/near the PCC
  - varies its reactive power injection to control the voltage
  - decreases the equivalent system impedance (increases $S_{cc}$)
    - its impedance comes in parallel with $Z_s$, yielding a smaller Thévenin impedance
  - but its response time may be too slow.
- Connection of a Static Var Compensator (SVC) at/near the PCC
  - varies its reactive power injection to control the voltage
  - with a faster response time than a synchronous condenser.
- Use of capacitor commutated converters.
Capacitor Commutated Converter (CCC)

A capacitor is inserted on the AC side, in series with the converter transformer.

- An LCC bridge uses **natural commutation**: commutation between valves is directly dictated by the AC voltages (commutation voltage $u_{ba}$ for commutation from valve 1 to valve 3).
- A CCC bridge uses **forced commutation**: a circuit (the capacitor) is used to provide the commutating voltage.
Consider the commutation from valve 1 to valve 3:

- while valve 1 is conducting, the capacitor in phase a is charging
- its voltage increases and eventually becomes larger than $V_d$
- the current in the valve is decreasing and goes to zero
- the commutation to valve 3 (if properly fired) takes place
During valve conduction, the capacitor voltage is directly proportional to the DC current $I_d$

$$v_C = \frac{I_d t_c}{C_s}$$

with $t_c$ the time elapsed since the last commutation

- the capacitor voltage increases with $I_d$
- consequently, the DC voltage increases with $I_d$

steady-state characteristics

more stable operation than LCC converter in CEA mode
- A proper choice of the capacitor value allows controlling the commutation instants.
- It is possible to control the AC phase current, lagging or even leading the voltage.
- The capacitor provides reactive power, which compensates the classical converter reactive power consumption.
- By providing a more stable commutating voltage, the probability of commutation failure is reduced.
- Limitations: higher costs, higher harmonics, higher stress on the valves.
- Very few systems have been implemented...