LIÈGE université
Sciences Appliquées

High Voltage DC Transmission

ELEC0447 - Analysis of electric power and energy systems

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Overview

1. Overview of HVDC applications

2. Components of an LCC HVDC link

3. Thyristor valves

4. Operation of the LCC line

5. Control

6. HVDC in the power flow analysis

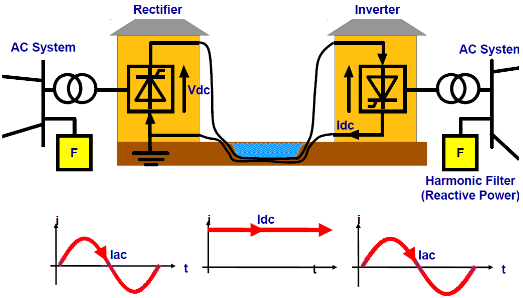
Overview of HVDC applications

Overview of HVDC applications

Introduction of former course "ELEC0445 - HVDC grids".

Principle of HVDC links

- HVDC links embedded in AC systems
- Rely on converters:
  - rectifier: from AC to DC
  - inverter: from DC to AC



Historical perspective I

- At the beginning (end of 19th century): two struggling parties
  - first generators producing Direct Current (DC) - Gramme, Edison
  - first generators producing Alternating Current (AC) - Ferranti, Tesla
- Have a look at the video “War of the currents” at YouTube.
- The AC system won:
  - possibility to increase and lower the voltage thanks to the transformer $\Rightarrow$ transmission of higher powers possible
  - creation of a rotating field easy with three-phase AC windings
  - Difficulty to raise the DC voltage $\Rightarrow$ impossibility to transmit large powers with DC
  - limitation of the power of early converters: a few kW only

Historical perspective II

  - difficulty of interrupting a DC current.
- Revival of DC technology in the ‘50s
- Advances in power electronics: converters can carry larger currents through higher voltages $\Rightarrow$ higher power ratings $\Rightarrow$ transmission applications possible
- **1882**: Marcel Deprez (France) and Oskar Von Miller (Germany, AEG) design the first transmission link between a DC source and a DC load: 15 kW – 2 kV – 56.3 km.
- See also René Thury’s work
- **mid ‘30s**: mercury-arc valve rectifiers made available. They open the way to HVDC transmission link projects

Historical perspective III

- **1945**: first commercial project of HVDC transmission in Germany. Not commissioned and moved to USSR (Moscow-Kashira) in 1950: 60 MW – 200 kV – 115 km, with buried cables.
- **1954**: first commercial HVDC submarine installation: from Gotland island to Sweden: 20 MW – 100 kV – 98 km.
- Up to the mid ‘60s, due to its higher cost, HVDC was favoured only where AC met operational difficulties, e.g. sea crossing.
- **late ‘60s**: advent of high power **thyristor**-based valve converters

Historical perspective IV

- **1975**: 1st long-distance HVDC transmission using thyristor valve converters: Cahora Bassa in Mozambique: 1920 MW – 533 kV – 1420 km, with overhead line

- thyristor ratings have grown up to $V = 9\,\mathrm{kV}$ and $I = 4\,\mathrm{kA}$ (per thyristor)

Historical perspective V

- **late ‘90s**: high power **transistor**-based components become available: IGBT, MOSFET
- development of **Voltage Source Converters**. Among other advantages, they allow controlling both the active and the reactive powers at the AC terminals of an HVDC link.

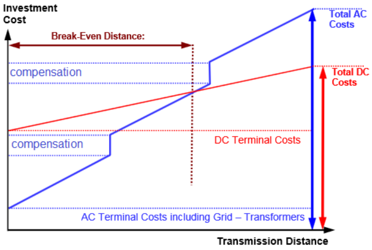
First application: Power transmission over long distances

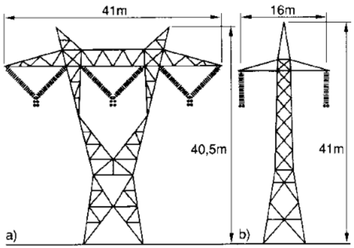
Long AC lines require reactive power compensation / voltage support and for distances larger than 600 km-800 km, HVDC is more economical

Examples:

- Pacific DC inter-tie along West coast of USA: 1360 km – 3100 MW – $\pm$500 kV
- Cahora-Bassa line in Mozambique: 1420 km – 1920 MW – $\pm$533 kV
- Hydro-Québec DC line: 1018 km – 2000 MW – $\pm$450 kV

Smaller investment costs

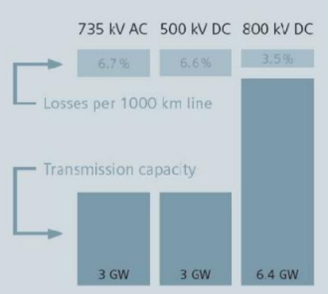




- initial investment is higher for DC (due to converters) but
- with increasing distance, reactive power compensation is required for an AC line
- break-even distance 600 km-800 km

- comparison of towers: same transmission capacity of 3 GW, a) 735 kV AC b) $\pm$500 kV DC
- smaller Right-of-Way for DC corridor
- reduced footprint

Lower losses, higher thermal capacity

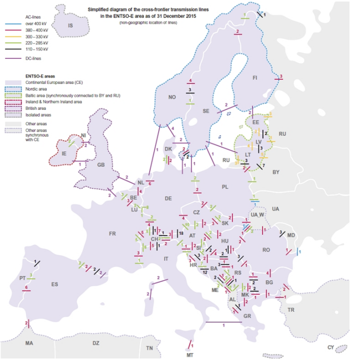


At a similar voltage level (RMS phase-to-phase vs. DC pole-to-ground):

- a DC line can transmit more than twice the power of an AC line
- with about half the losses of an AC line.

Second application: submarine power transmission

- AC cables have large capacitance. Maximal acceptable length: 50 km-70 km.
  - For larger distances, HVDC is the only (reasonable) solution
- Examples from Europe:
  - NorNed link between Norway and The Netherlands (2008): 580 km – 700 MW – $\pm$450 kV (LCC type)
  - Nemo link between Belgium and UK (2019): 140 km – 1000 MW – $\pm$400 kV (VSC type)
  - Connections of off-shore wind parks in North Sea to the continental European grid



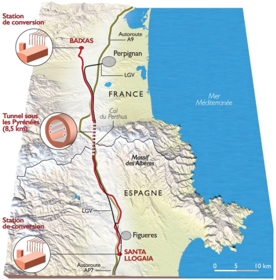
Source ENTSOe (www.entsoe.eu)

Third application: DC link in AC grid, for power flow control

- power flows in AC lines cannot be controlled directly
  - determined by line impedances, obeying Ohm and Kirchhoff laws
  - partially controllable by phase shifting transformers
- power flows in HVDC links can be controlled directly (through the controllers of converters). This can be used:
  - to limit *loop flows* and overloading of AC lines
  - to make the link participate in energy tradings.
- Examples:
  - ALEGrO (Aachen Liège Electric Grid Overlay) project of HVDC link between Belgium and Germany (2020): 100 km (49 km in Belgium) – 1000 MW – buried cable
  - France - Spain DC interconnection: 65 km – buried XLPE cable – $\pm$ 320 kV DC – 2000 MW.

France - Spain DC interconnection

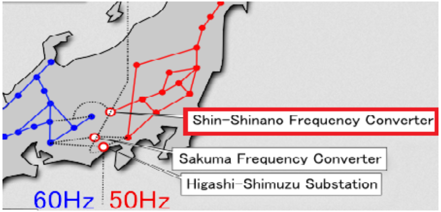
- Can reverse power flow in 150 milliseconds (!)
- Investment cost: 700 $\mathrm{M€}$



Fourth application: interconnection of asynchronous AC systems

Two AC networks with different nominal frequencies. Back-to-back connection (rectifier and inverter in same substation)

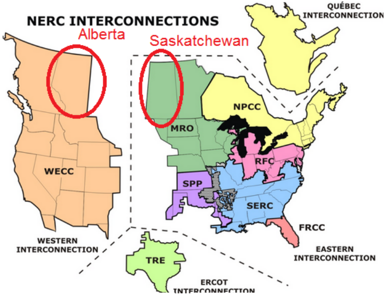
- Melo HVDC link between Uruguay (50 Hz) and Brazil (60 Hz): 500 MW – $\pm 79\,\mathrm{kV}$
- Shin Shinano HVDC link between Western (60 Hz) and Eastern (50 Hz) power grids of Japan: 600 MW – $\pm 125\,\mathrm{kV}$



Two AC networks with identical nominal frequency but different frequencies (not interconnected for size reasons)

- Highgate back-to-back HVDC link between Québec and Vermont: 200 MW – $\pm 57\,\mathrm{kV}$

- McNeil HVDC link between Alberta and Saskatchewan: 150 MW – $\pm 42\,\mathrm{kV}$



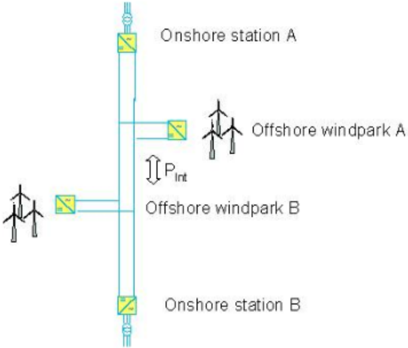
Fifth application: Multiterminal DC grids I

Radial DC link with AC/DC converter(s) connected at intermediate points.

- A few systems are in operation today with proven technology.
  - example: the Sardinia-Corsica-Italy link (SACOI) 3 terminals. The 2-terminal Italy-Sardinia link was initially built, and the Corsica terminal installed at a later stage
- more elaborate control scheme than for a two-terminal link.

Fifth application: Multiterminal DC grids II

- Another application: collect power from off-shore wind parks located along a DC link between two on-shore terminals.

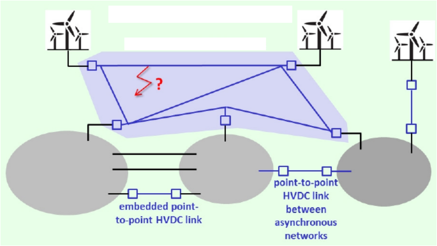


Meshed DC grids

- Still at research level
- Typical targeted application: (i) collect power from off-shore wind parks, and (ii) allow power exchanges between on-shore grids.

Main technological challenges:

- identification of faults in DC grid (to isolate only the faulted branch)
- DC circuit breaker to interrupt the DC fault current.



Two technologies

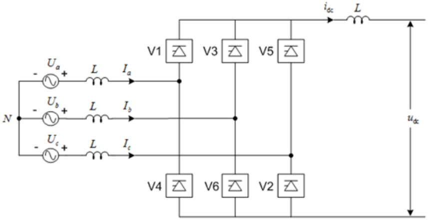
Line Commuted Converters (LCC)

- large power ratings
- large harmonics filters
- requires a strong enough AC grid
- active power is controlled
- always consumes reactive power
- cannot be used as off-shore terminal to collect wind power
- cheaper (but VSC is a fast evolving technology)
- less commutation losses than VSC
- but possible commutation failure

Voltage Source Converters (VSC)

- lower power ratings (but fast growing technology)
- less harmonic filters needed
- can operate with a weak AC grid
- active **and reactive** powers can be controlled
- can be used as off-shore terminal to collect wind power
- black start capability

LCC technology

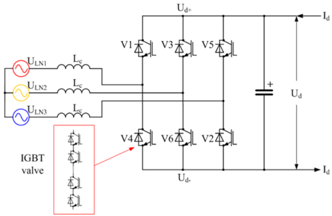


- based on thyristors, used as switches closed with delay
- thyristor commutation synchronized with grid voltage (hence the term “line commutated”)
- also referred to as “Current Source Converter” or “classic HVDC”
- DC current cannot be reversed (due to thyristors). Hence, power is reversed by reversing the DC voltage polarity.

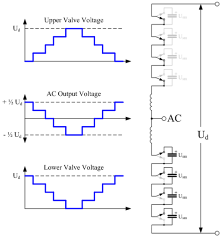
VSC technology

Based on Insulated Gate Bipolar Transistors (IGBT), used as interrupteurs *self-commutating* switches.

Two topologies:



Pulse Width Modulation (PWM)



Modular Multilevel Converter (MMC)

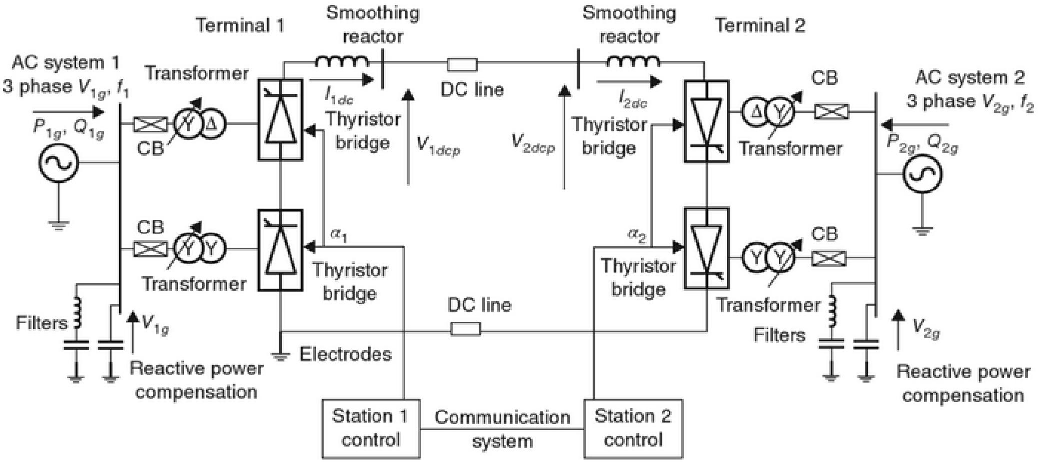
Power is reversed by reversing the current.

Components of an LCC HVDC link

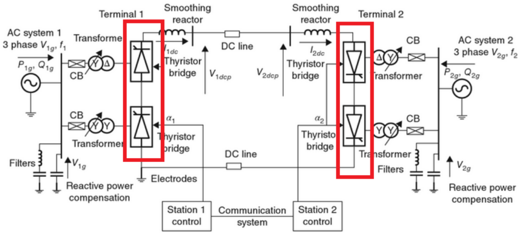
Components of an LCC HVDC link

Extract of chapter 1 of former course "ELEC0445 - HVDC grids".

A typical LCC HVDC system

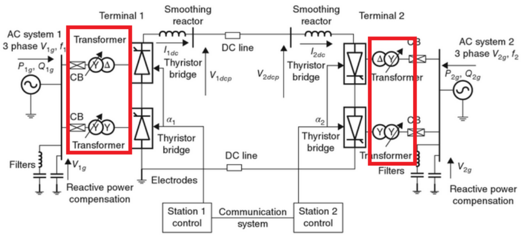


Converters



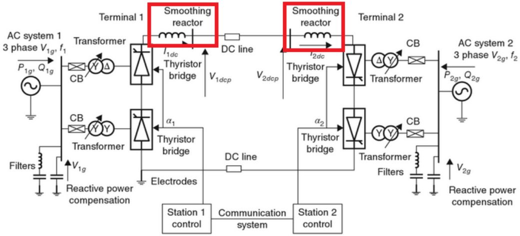
- one converter at each terminal: the sending power end acts as a rectifier, the receiving power end as an inverter
  - each converter includes one or several thyristor **bridges**
  - each bridge is made up of **6** thyristor valves
  - each thyristor valve contains **hundreds of individual thyristors**

Converter transformers



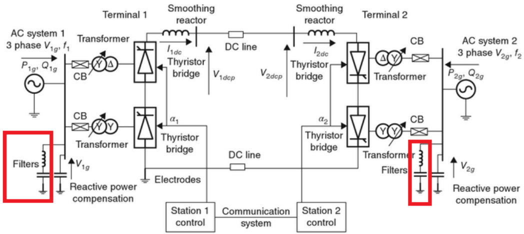
- most generally equipped with load tap changers. The transformer ratios are adjusted to optimize the HVDC link operation
- designed to operate with high harmonic currents
  - generally more expensive than typical transmission transformers of the same rating

Smoothing reactors on the DC side



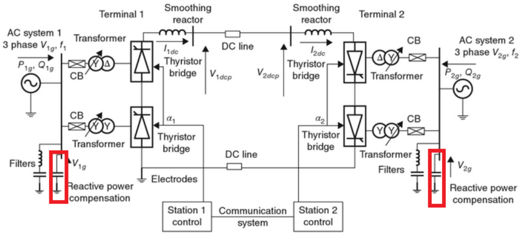
- aimed at limiting the DC current variations
  - designed considering response to DC faults and commutation failures
  - typical values of inductance: 0.1 H to 0.5 H
  - air-core, natural air cooling type

Harmonic filters



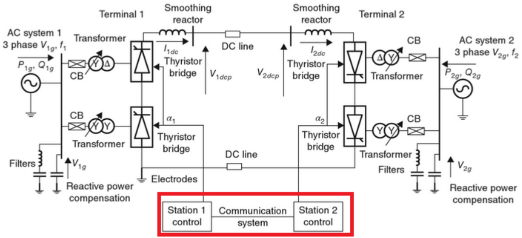
- aimed at filtering the harmonics generated by the AC/DC conversion
  - most important harmonics to eliminate: 11th, 13th, 23rd and 25th (for converters with two bridges)
  - some HVDC systems are also equipped with filters on the DC side

Reactive power compensation



- the converters consume reactive power (around 60% of power rating)
- that reactive power varies with the active power level
- a large part of the reactive compensation comes from the filter banks
- the remaining part is supplied by switchable capacitor banks

Control and communication systems



- each terminal has a control system with multiple hierarchical layers: control of resp. the DC current, the DC voltage, the thyristors, etc.
- a dedicated communication link is needed between both terminals to optimize system operation

Thyristor valves

Thyristor valves

A summary of chapter 2 of former course "ELEC0445 - HVDC grids".

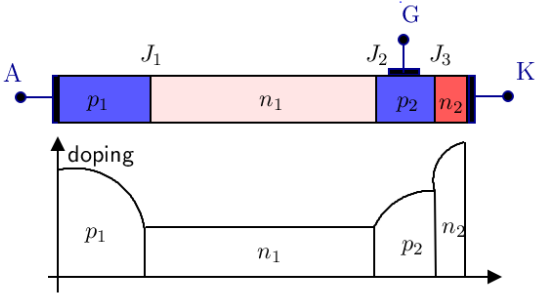
The thyristor I

- Essential component of HVDC valves in the LCC technology
- operates as a controllable diode
- can have high power ratings: up to $8.5\,\mathrm{kV}$, $4500\,\mathrm{A}$ capability
- is robust and efficient.

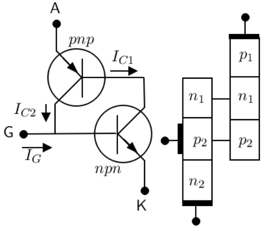
The thyristor II

Four-layer, three-terminal device.

Three *pn* junctions J_1, J_2, J_3



- equivalent to two bipolar transistors
- assume $V_{AK} > 0$ and inject I_G
- both transistors remain in saturation even if I_G is suppressed



Usage of a thyristor I

A thyristor can be used as a controllable bistable switch

- the control is performed by injecting a current at the gate input
- the thyristor is *ON* and conducts when it is forward biased and the gate receives a current pulse
- the thyristor keeps on conducting as long as it is forward biased
- the thyristor is turned *OFF* when the anode current falls below the holding current threshold IH or when it is reverse biased
- the thyristor remains in blocking mode until it is triggered by a new gate pulse current

Usage of a thyristor II

The process of turning OFF is called commutation

- when commutating, the thyristor cannot immediately withstand a forward voltage; it should remain reverse biased for a minimum time, otherwise *commutation failure* can take place.

Modes of operation of the thyristor

Three modes of operation depending on:

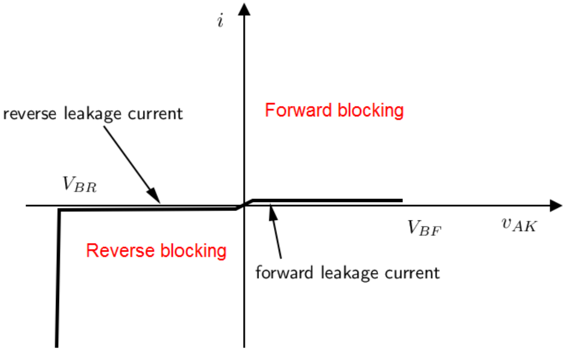
- the sign of the anode - cathode voltage v_{AK}
- whether a current I_G is injected at the gate terminal

1. A *reverse voltage* $v_{AK} < 0$ is applied

- Junction J_2 is in *forward* bias mode
- junctions J_1 and J_3 are in *reverse* bias mode
- the thyristor acts as a diode in reverse bias mode; it is in *off-state*
- breakdown occurs when v_{AK} is more negative than the *reverse breakdown voltage* V_{BR}. Most often this is associated with junction J_1
- in HVDC applications, the breakdown mode must be avoided since it can lead to material destruction.
- hence, thyristors with high $|V_{BR}|$ values must be used, and measures taken to limit the avalanche current.

2. A *forward voltage* $v_{AK} > 0$ is applied

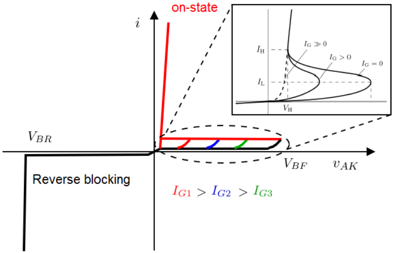
- Junctions J_1 and J_3 are *forward* in bias mode
- junction J_2 is in *reverse* bias mode
- the thyristor behaves as a diode in reverse bias mode; it is in *off-state*
- breakdown occurs when v_{AK} is larger than the forward breakdown voltage of junction J_2.



3. A *forward voltage* $v_{AK} > 0$ is applied and *a current* I_g *is injected*

- the current injection results in an avalanche process
- "as if" layer p_2 would become of n-type. Hence, the thyristor behaves as a *pn* diode in forward bias mode: it switches to *on-state*
- the thyristor resistance is dramatically reduced (from $1\,\mathrm{M\Omega}$ to $0.1\,\Omega$)
- the larger I_G, the smaller the value of v_{AK} needed to initiate the avalanche.

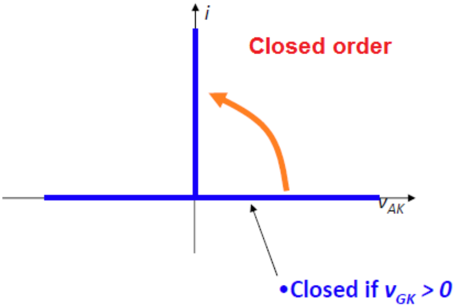
Operation of the thyristor in on-state

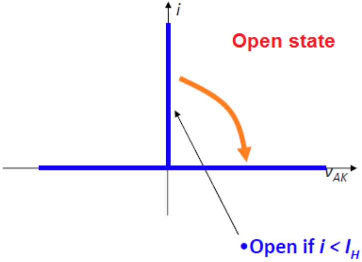


- Once the anode current *i* reaches I_L, the *latching curent*, the thyristor switches to on-state
- once the thyristor is in on-state, the gate current can be removed
- the gate current is usually a short pulse lasting 10-50 μs
- if *i* falls below I_H, the *holding curent*, the thyristor switches to off-state.

Commutation is not instantaneous -> dynamics -> and care must be taken with applied currents and voltages -> snubber circuits

The ideal characteristic





- Closed order given by gate current
- in open state, V_{BR} and V_{BF} are assumed infinite
- when the thyristor conducts, a zero internal resistance is assumed
- when the thyristor conducts, a zero terminal voltage is assumed.

Thyristor valves

Thyristor modules (i.e. thyristor + snubber circuit + voltage balancing circuits) are associated in series to form a thyristor valve.

- Objective: reach the HVDC link
- voltage rating:
  - thyristor: up to 5 kV to 9 kV
  - HVDC link: 500 kV to 800 kV

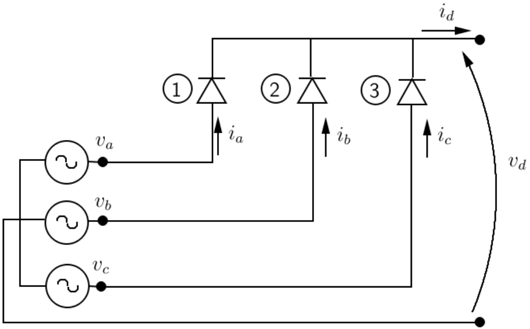
On the right: A 2000 A, 250 kV *high voltage direct current (HVDC) thyristor valve at Manitoba Hydro's Henday converter station. Photo taken April 2001. Source: Wikipedia.*

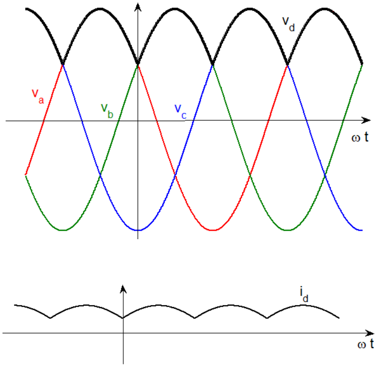
Operation of the LCC line

Operation of the LCC line

A summary of chapter 3 of former course "ELEC0445 - High Voltage Direct Current grids".

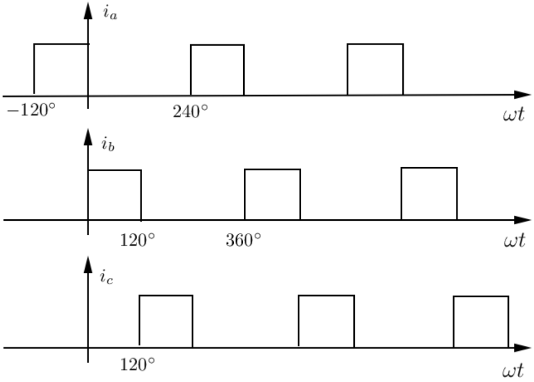
Diode based rectifier





Without filtering, we already have a relatively good rectification.

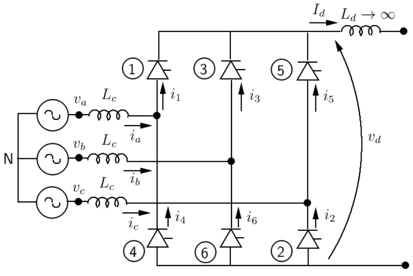
To get a more constant current, we use smoothing reactors in series. The bigger L_d, the more constant the current. Hence we suppose I_d is constant, and the currents in the 3 phases on the AC side look like:

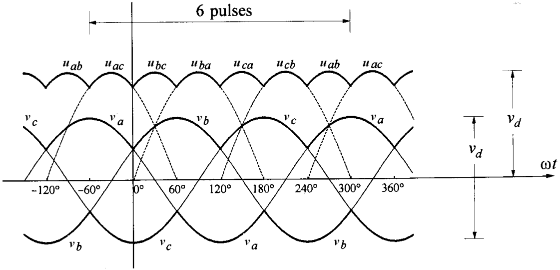


Note that in practice, as there are inductors in the system, currents cannot vary abruptly, and there is a *commutation overlap* (two of the three diodes conducting simultaneously), hence an angle μ and a voltage reduction. We'll neglect this in the sequel (to keep it simple), but this is important in practice.

The thyristor-based 6-pulse rectifier with *no ignition delay*

In this case Thyristor = Diode (natural conduction)





Average direct voltage

The average direct voltage is $V_{d0} = \frac{3\sqrt{2}}{\pi} U \approx 1.35U$.

Exercise: verify this formula, what is exactly U in this case?

Solution I

Let $x = \omega t$.

The average direct voltage value is given by

$$V_{d0} = \frac{1}{2\pi} \int_0^{2\pi} v_d(x)dx$$

Since $v_d(t)$ repeats 6 times over a period of 2π, we can equivalently write

$$V_{d0} = \frac{6}{2\pi} \int_{\pi/3}^{2\pi/3} v_d(x)dx$$

arbitrarily selecting the interval $[\pi/3, 2\pi/3]$ of length $\pi/3$ where $v_d(x) = \sqrt{2}Usin(x)$

Solution II

Hence

$$V_{d0} = \frac{6}{2\pi} \int_{\pi/3}^{2\pi/3} \sqrt{2} U \sin(x) dx = -\frac{3\sqrt{2}}{\pi} U \left(cos\frac{2\pi}{3} - cos\frac{\pi}{3} \right) = \frac{3\sqrt{2}}{\pi} U$$

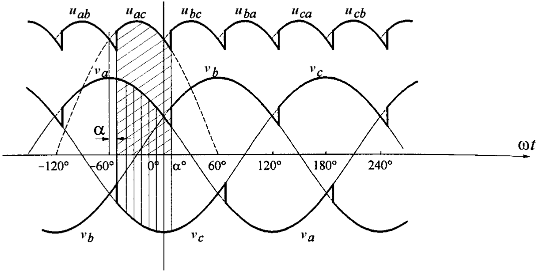
U is the rms line-to-line voltage.

Average direct voltage with an ignition delay α

The average direct voltage is

$$V_d = V_{d0} \cos \alpha$$

Exercise: verify this formula.



The ignition can be delayed up to $\alpha = 180°$

- for instance: switching from valve 1 to valve 3 is possible as long as $v_a < v_b$.
- After that, valve 3 is in reverse blocking mode.

Solution I

The average DC voltage is the average of the instantaneous voltage over one period. We integrate the instantaneous voltage over a $\frac{\pi}{3}$ interval, taking into account the firing angle α. The instantaneous output voltage is a segment of the line-to-line voltage, which can be modeled as $v_d(\omega t) = \sqrt{2}U\sin(\omega t)$. The conduction interval spans from $\omega t = \frac{\pi}{3} + \alpha$ to $\omega t = \frac{2\pi}{3} + \alpha$.

The formula for the average value is:

$$V_d = \frac{1}{\text{period}} \int_{\text{interval}} v_d(\omega t) d(\omega t)$$

Solution II

Substituting the values:

$$V_d = \frac{1}{\pi/3} \int_{\pi/3+\alpha}^{2\pi/3+\alpha} \sqrt{2}U \sin(\omega t) d(\omega t)$$

We solve the definite integral:

$$V_d = \frac{3\sqrt{2}U}{\pi} \left[- \cos(\omega t)\right]_{\pi/3+\alpha}^{2\pi/3+\alpha}$$

$$V_d = -\frac{3\sqrt{2}U}{\pi} \left(\cos(2\pi/3 + \alpha) - \cos(\pi/3 + \alpha)\right)$$

Solution III

Using the trigonometric identity $\cos(A+B) = \cos A \cos B - \sin A \sin B$:

$$\cos(2\pi/3 + \alpha) = \cos\left(\frac{2\pi}{3}\right)\cos(\alpha) - \sin\left(\frac{2\pi}{3}\right)\sin(\alpha) = -\frac{1}{2}\cos(\alpha) - \frac{\sqrt{3}}{2}\sin(\alpha)$$

$$\cos(\pi/3 + \alpha) = \cos\left(\frac{\pi}{3}\right)\cos(\alpha) - \sin\left(\frac{\pi}{3}\right)\sin(\alpha) = \frac{1}{2}\cos(\alpha) - \frac{\sqrt{3}}{2}\sin(\alpha)$$

We substitute these results back into the equation for V_d:

$$V_d = -\frac{3\sqrt{2}U}{\pi}\left[\left(-\frac{1}{2}\cos(\alpha) - \frac{\sqrt{3}}{2}\sin(\alpha)\right) - \left(\frac{1}{2}\cos(\alpha) - \frac{\sqrt{3}}{2}\sin(\alpha)\right)\right]$$

Solution IV

$$V_d = -\frac{3\sqrt{2}U}{\pi}\left[-\frac{1}{2}\cos(\alpha) - \frac{\sqrt{3}}{2}\sin(\alpha) - \frac{1}{2}\cos(\alpha) + \frac{\sqrt{3}}{2}\sin(\alpha)\right]$$

$$V_d = -\frac{3\sqrt{2}U}{\pi}\left[-\cos(\alpha)\right]$$

This gives us the final formula for the average output voltage:

$$V_d = \frac{3\sqrt{2}U}{\pi}\cos(\alpha)$$

Average direct voltage and power factor

Since $V_d = V_{d0} \cos \alpha$, V_d may take values from V_{d0} down to $-V_{d0}$

- positive values of V_d ($0 < \alpha < 90^\circ$):
  - **Rectifier operation**. Power flows from AC to DC since $V_d I_d > 0$.
- negative values of V_d ($90 < \alpha < 180^\circ$):
  - **Inverter operation**. Power flows from DC to AC since $V_d I_d < 0$.

Power factor

Without accounting for commutation delays, it can be shown that

$$\cos \phi = \cos \alpha$$

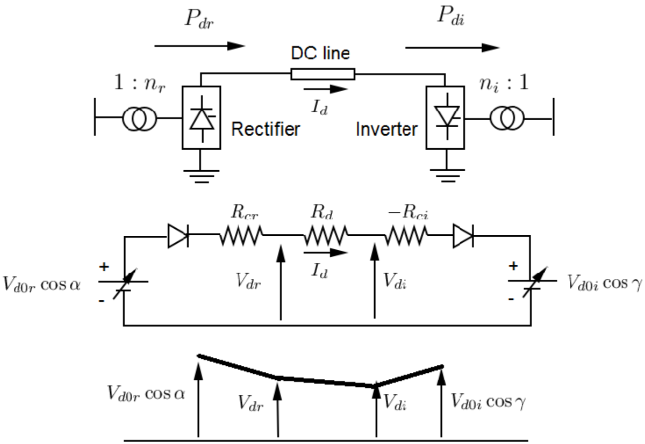
(See [1], page 49, conservesion of power, AC to DC.)

Control

Introduction

- HVDC links allow rapid control of transmitted power by playing on the firing angles.
- The control system is very complex, with many layers.
- We cover here the very basic principles.
- See Chapter 4 in [1].

The HVDC link, its equivalent circuit and its voltage profile I



Thus,

$$I_d = \frac{V_{d0r} \cos\alpha - V_{d0i} \cos\gamma}{R_{cr} + R_d - R_{ci}}$$

and

$$P_{dr} = V_{dr} I_d,$$

$$P_{di} = V_{di} I_d = P_{dr} - R_d I_d^2$$

The HVDC link, its equivalent circuit and its voltage profile II

Since $R_{cr} + R_d - R_{ci}$ is typically small, sudden voltage variations can lead to large current variation if firing angles are kept constant. Hence it is important to regulate DC voltages close to their nominal value:

- high enough to minimize the losses
- small enough to avoid damages (thyristors)

Available controls

We thus have

$$V_{dr} = V_{d0r} \cos\alpha - R_{cr} I_d$$

$$V_{di} = V_{d0i} \cos\gamma - R_{ci} I_d$$

$$V_{dr} = V_{di} + R_d I_d$$

and as established previously

$$V_{d0r} = \frac{3\sqrt{2}}{\pi} n_r U_r$$

$$V_{d0i} = \frac{3\sqrt{2}}{\pi} n_i U_i$$

Available controls are used in complementary manner:

- (fast) the internal DC voltage $V_{d0r} \cos\alpha$ (resp. $V_{d0i} \cos\gamma$) by adjusting the ignition angle α (resp. the extinction angle γ).
- (slow) the AC voltages of the converters through the transformer ratios n_r and n_i.

Remarks

Attention must be paid to:

- avoiding too low a current I_d (unstable commutation)
- avoiding too high a current I_d (overload of valves)
- having a stable HVDC link operation in spite of variations of AC voltages.

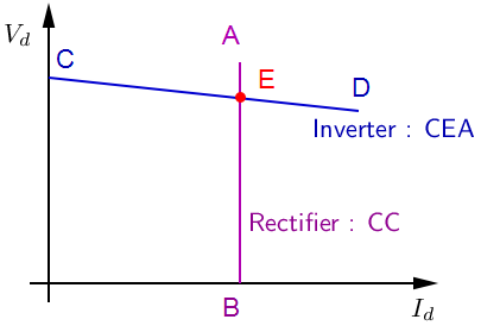
The power P_{dr} (or P_{di}) can be controlled instead of the current I_d.

Control principle

Overall principle:

- the regulations of resp. V_d and I_d are performed by the terminals separately
- this does not require fast exchange of information between both terminals
  - only when the respective roles of the rectifier and the inverter change
- Under normal operation:
  - the rectifier maintains a Constant Current (CC) I_d mode (increase power transfer by decreasing α, which imporves the power factor, and minimizes reactive power consumption)
  - the inverter maintains Constant Extinction Angle (CEA) γ mode, above the minumum value required to avoid commutation failure, for economical reasons.

Ideal steady-state $V - I$ characteristics:



- Rectifier characteristic: $I_d =$ constant
- Inverter characteristic: from previous equations

$$V_{dr} = V_{d0i} \cos\gamma + (R_d - R_{ci})I_d$$

generally, R_{ci} is slightly larger than R_d and the characteristic has a small negative slope

- Operating state: point **E** at the intersection of the two characteristics

Exercise

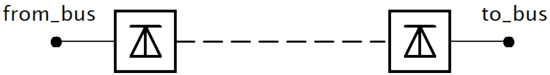
Consider a HVDC link of $1000\,\mathrm{MW}$, $\pm\,450\,\mathrm{kV}$, with $R_{cr} = \frac{3}{8}\Omega$, $R_{ci} = \frac{3}{8}\Omega$, $R_d = \frac{1}{4}\Omega$. Neglect the transformers (assume $n = 1$ at the rectifier and inverter sides).

- What is the maximal value $I_d^{\max}$ of I_d?
- If $I_d = 0.5 I_d^{\max}$, what are possible values of α and γ?
- What is the voltage drop along the DC section?

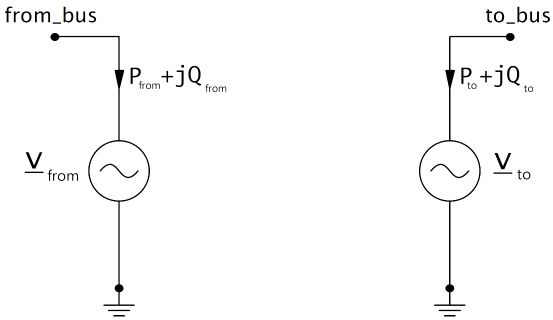
HVDC in the power flow analysis

A simple implementation for point to point HVDC I

From PandaPower [2] documentation, a DC line



is modelled as two generators in the loadflow:



A simple implementation for point to point HVDC II

- The active power at the from side is defined by the parameters in the dcline table.
- The active power at the to side is equal to the active power on the from side minus the losses of the DC line.
- The voltage control with reactive power works just as described for the generator model. Maximum and Minimum reactive power limits are considered in the OPF, and in the PF if it is run with enforce_q_lims=True.

References I

- K. Padiyar, *HVDC power transmission systems: technology and system interactions*. New Age International, 1990.
- L. Thurner, A. Scheidler, F. Schäfer, J.-H. Menke, J. Dollichon, F. Meier, S. Meinecke, and M. Braun, “pandapower—an open-source python tool for convenient modeling, analysis, and optimization of electric power systems,” *IEEE Transactions on Power Systems*, vol. 33, no. 6, pp. 6510–6521, 2018.
- N. Mohan, *Electric power systems: a first course*. John Wiley & Sons, 2012.
- T. Van Cutsem *et al.*, “High voltage direct current (HVDC) ELEC0445.” Course notes.