Aalto University
School of Electrical
Engineering

Converter-Fed Electrolyser Systems: State of the Art

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Prof. Marko Hinkkanen

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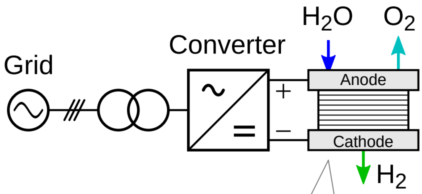
Clean Hydrogen

- Produced through water electrolysis
  - Powered by clean electricity
- Energy carrier and raw material
  - Can be converted to synthetic fuels and chemicals (power-to-X)
  - Biogenic CO_2 needed for sustainable synthetic hydrocarbons
- Potential to decarbonize hard-to-electrify transport and industries
  - Aviation, maritime, steel, fertilizers

10…20 litres of ultrapure water needed to produce 1 kg of hydrogen



- An ideal electrolyser would consume 40 kWh to produce 1 kg of hydrogen
- Typical efficiencies are about 70…80%
- Excess heat is preferably used (e.g. district heating)

Hydrogen Production in Europe

- Current production capacity[1]
  - 12 Mt/year, mostly based on natural gas
  - 0.2% based on water electrolysis (capacity 200…500 MW)
- 2030 clean hydrogen target
  - 10 Mt/year own production (plus 10 Mt/year imports)
  - Deploy 40 GW of electrolyser capacity in 2030
    (in practice about 140 GW needed to produce 10 Mt/year)
- 2050 scenarios
  - Electrolyser capacity 500…1 000 GW

- These targets might be too optimistic[2]

[1] Bolard, Dolci, Gryc *et al.*, *Clean energy technology observatory: Water electrolysis and hydrogen in the European Union*. Publications Office of the European Union, 2023. DOI: 10.2760/133010.

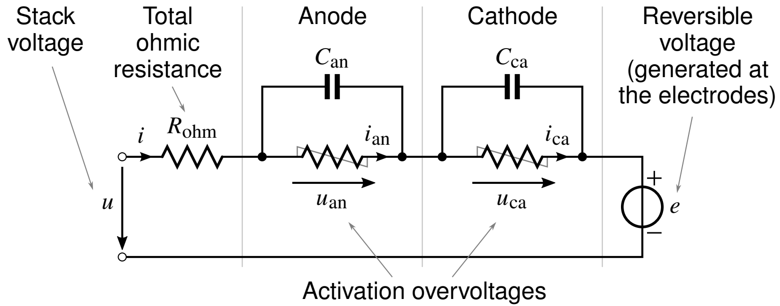
[2] Special report 11/2024, *The EU's industrial policy on renewable hydrogen: Legal framework has been mostly adopted — time for a reality check*. Official Journal C 4650, 2024. [Online]. Available: http://data.europa.eu/eli/C/2024/4650/oj.

Outline

Types of Electrolysers

- Alkaline
  - Mature technology
  - Lower investment costs
- Proton-exchange membrane (PEM)
  - Better dynamics than alkaline
  - Higher power density (less space needed)
  - Currently less efficient but expected to improve
  - Expensive due to noble electrode materials
- Solid-oxide
  - Operate at much higher temperatures
  - Higher efficiencies than alkaline and PEM
  - Can be reversed to act as fuel cells

Dynamic Model for PEM and Alkaline Electrolysers

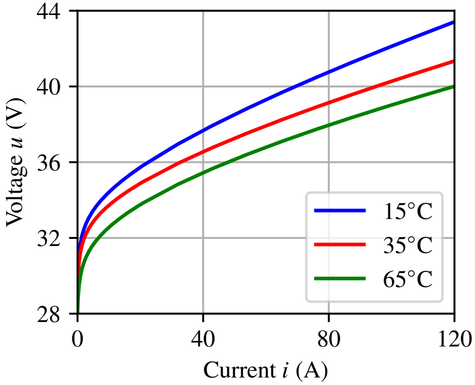


- Reversible voltage e is the minimum (ideal) voltage for the electrolysis process
  - Depends on the temperature and the pressure
- Ohmic and activation losses cause irreversible overvoltages
- Capacitances C_{an} and C_{ca} model the double-layer effect

- Activation overvoltages are nonlinear in the currents

$$u_{\mathrm{an}} = u_{\mathrm{an}}(i_{\mathrm{an}})$$
$$u_{\mathrm{ca}} = u_{\mathrm{ca}}(i_{\mathrm{ca}})$$

- They also decrease with the temperature



Example i–u characteristics of an alkaline electrolyser[3]

[3] Ursúa and Sanchis, 'Static-dynamic modelling of the electrical behaviour of a commercial advanced alkaline water electrolyser,' *Int. J. Hydrogen Energy*, 2012. DOI: 10.1016/j.ijhydene.2012.09.125

- Equivalently, the reciprocal form of the nonlinear characteristics can be used[4]

$$i_{\mathrm{an}} = i_{\mathrm{an}}(u_{\mathrm{an}}) \qquad\qquad i_{\mathrm{ca}} = i_{\mathrm{ca}}(u_{\mathrm{ca}})$$

- State-space representation

$$\begin{aligned}
C_{\mathrm{an}}\frac{\mathrm{d}u_{\mathrm{an}}}{\mathrm{d}t} &= i - i_{\mathrm{an}}(u_{\mathrm{an}}) \\
C_{\mathrm{ca}}\frac{\mathrm{d}u_{\mathrm{ca}}}{\mathrm{d}t} &= i - i_{\mathrm{ca}}(u_{\mathrm{ca}}) \\
u &= R_{\mathrm{ohm}}i + u_{\mathrm{an}} + u_{\mathrm{ca}} + e
\end{aligned}$$

where the current i is the input and the voltage u is the output

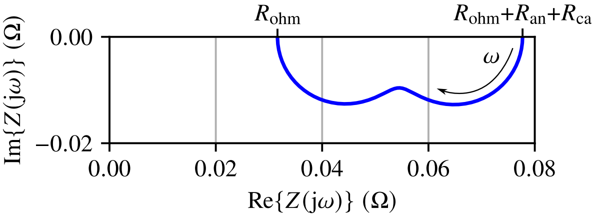
[4] Iribarren, Elizondo, Barrios *et al.*, 'Dynamic modeling of a pressurized alkaline water electrolyzer: A multiphysics approach,' *IEEE Trans. Ind. Appl.*, 2023. DOI: 10.1109/TIA.2023.3247405.

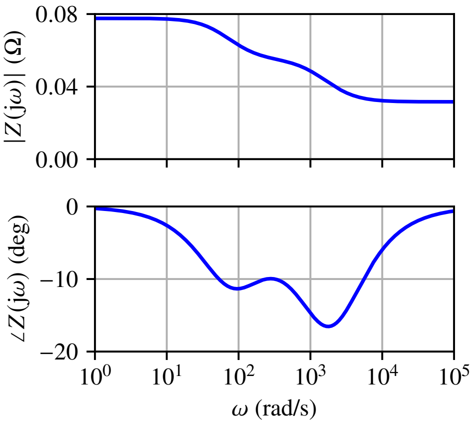
Linearized Model in the Frequency Domain

- Linearization results in the impedance

$$Z(s) = \frac{u(s)}{i(s)} = R_{\text{ohm}} + \frac{R_{\text{an}}}{sR_{\text{an}}C_{\text{an}} + 1} + \frac{R_{\text{ca}}}{sR_{\text{ca}}C_{\text{ca}} + 1}$$

- Same impedance presented using the Nyquist plot (below) and the frequency response (right)



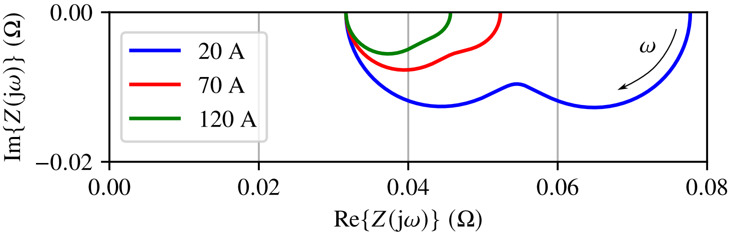


Parameters $R_{\text{ohm}} = 0.032\ \Omega$, $R_{\text{an}} = 0.023\ \Omega$, $C_{\text{an}} = 0.638$ F, $R_{\text{ca}} = 0.023\ \Omega$, and $C_{\text{ca}} = 0.031$ F are used

- Incremental resistances depend on the operating-point current

$$R_{\mathrm{an}} = \frac{\partial u_{\mathrm{an}}}{\partial i_{\mathrm{an}}} \qquad R_{\mathrm{ca}} = \frac{\partial u_{\mathrm{ca}}}{\partial i_{\mathrm{ca}}}$$

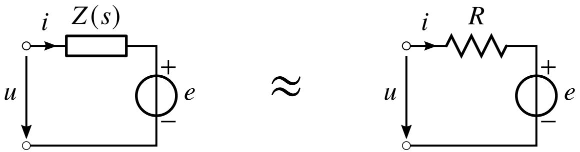
- Figure below shows an example of the impedances at three different currents[3]



Outline

Industrial-Scale Converter-Fed Electrolyser Systems

- Industrial-scale electrolysers are multi-MW low-voltage devices[5,6]
- Stack voltage is typically from a few hundred volts up to 1 kV
- Connected typically to a medium-voltage grid using a 50-Hz transformer
- Power quality should meet the grid and electrolyser requirements
- From the converter perspective, an electrolyser can be modeled as a resistive voltage source (where $R = R_{\mathrm{ohm}} + R_{\mathrm{an}} + R_{\mathrm{ca}}$ at low frequencies)

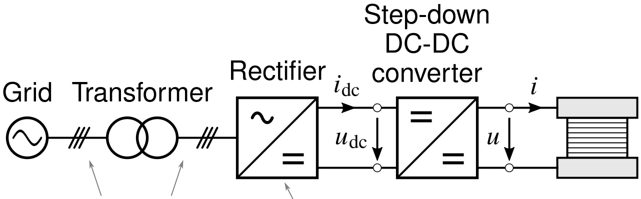


[5] Abdelhakim, Viitanen and Canales, 'State-of-the-art power supplies for electrolyzers: Hydrogen production,' *ABB Review*, 2022.

[6] Schumann, Runser, Herzig *et al.*, 'Water electrolysis power supply: Status & future trends,' in *ETG Symposium*, 2023, pp. 122–128.

Typical Converter Topologies

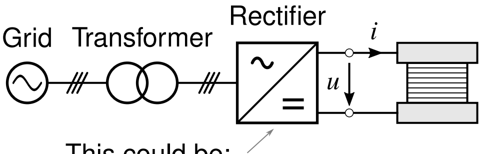
Dual-stage converter topology



Example: 20 kV / 400 V

This could be:
- Diode rectifier (passive)
- Voltage-source rectifier (active)

Single-stage converter topology

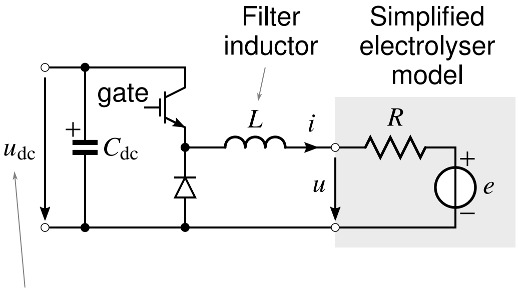


This could be:
- Thyristor rectifier (semi-active, step-down)
- Voltage-source rectifier (active, step-up)
- Current-source rectifier (active, step-down)

Outline

Step-Down DC-DC Converter

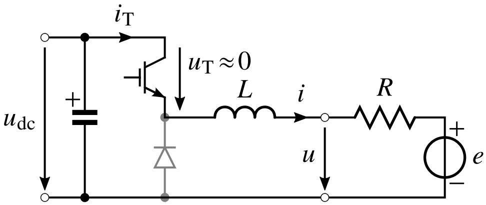
- To avoid high losses, the transistor is switched periodically on and off by means of pulse-width modulation (PWM)
- Insulated-gate bipolar transistors (IGBTs) are typically used
- Typical switching frequencies $f_{\mathrm{sw}} = 1 \dots 10$ kHz
- At high frequencies, the filter inductance L dominates over the electrolyser impedance



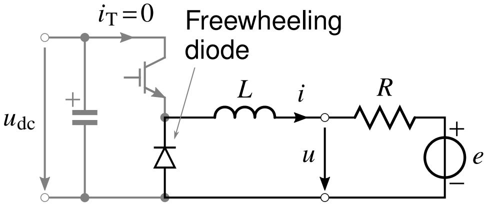
DC-bus voltage u_{dc} is almost constant due to signicant capacitance C_{dc}

Switching Waveforms

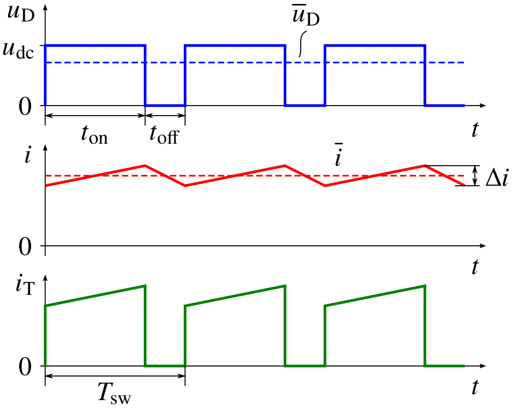
- Low power loss $u_T i_T$ in the transistor
  - On-state: $u_T \approx 0$
  - Off-state: $i_T = 0$
  - Switching losses are proportional to the switching frequency
- Freewheeling diode is needed due to the inductive filter
  - Current i must flow also when the transistor is switched off
- As short time periods are considered in the following, we can assume
  - u_{dc} = constant
  - e = constant
  - $R = 0$

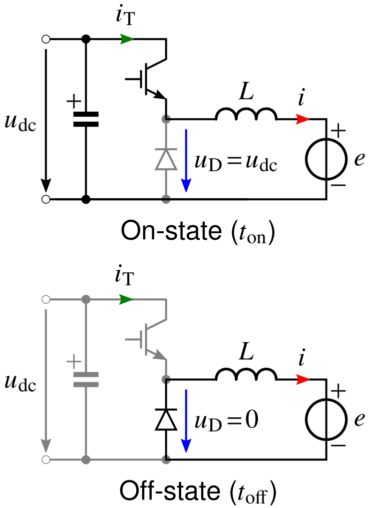


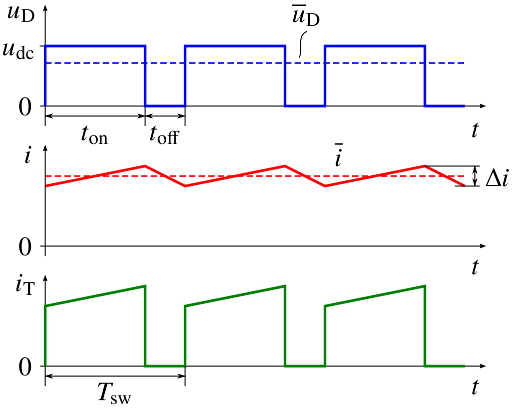
On-state



Off-state


u_D
$\bar{u}_D$
u_{dc}
0
t_{on}
t_{off}
t
i
$\bar{i}$
Δi
0
t
i_T
0
T_{sw}
t


i_T
u_{dc}
+
L
i
+
$u_D = u_{dc}$
e
−
On-state (t_{on})
i_T
u_{dc}
+
L
i
+
$u_D = 0$
e
−
Off-state (t_{off})



- Duty ratio

$$d = \frac{t_{on}}{T_{sw}} \qquad 0 \leq d \leq 1$$

- t_{on} is the on-time
- T_{sw} is the switching period
- Average of the voltage u_D over the period T_{sw}

$$\overline{u}_D = \frac{1}{T_{sw}} \int_0^{T_{sw}} u \, dt = d u_{dc}$$

- Voltage equation

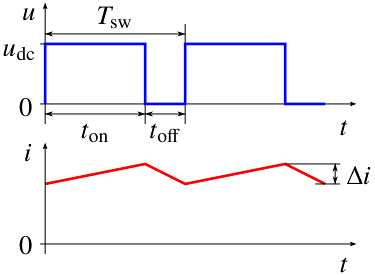
$$L\frac{\mathrm{d}i}{\mathrm{d}t} = u - e$$

- On-state: $u_\mathrm{D} = u_\mathrm{dc}$

$$\Delta i = \frac{1}{L}\int_0^{t_\mathrm{on}} (u_\mathrm{dc} - e)\mathrm{d}t = \frac{(u_\mathrm{dc} - e)t_\mathrm{on}}{L}$$

- Off-state: $u_\mathrm{D} = 0$

$$-\Delta i = \frac{1}{L}\int_0^{t_\mathrm{off}} (-e)\mathrm{d}t = -\frac{e t_\mathrm{off}}{L}$$



- Duty ratio in steady state

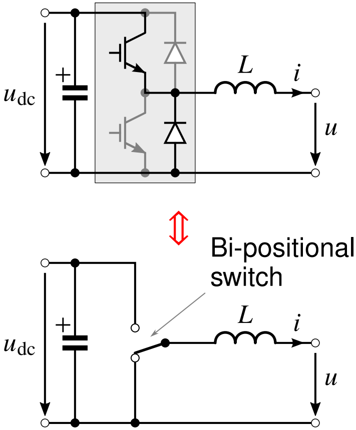
$$d = \frac{t_\mathrm{on}}{T_\mathrm{sw}} = \frac{\overline{u}_\mathrm{D}}{u_\mathrm{dc}} \quad (\overline{u}_\mathrm{D} = \overline{e} \text{ if } R = 0)$$

- Current ripple in steady state

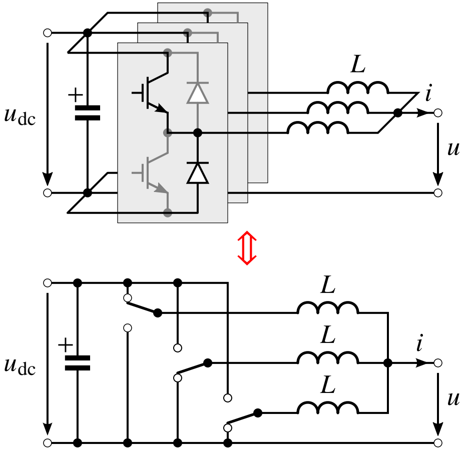
$$\Delta i = \frac{d(1-d)u_\mathrm{dc}}{f_\mathrm{sw} L}$$

Interleaved Converter for High-Power Applications

DC-DC converter



Multiphase interleaved DC-DC converter

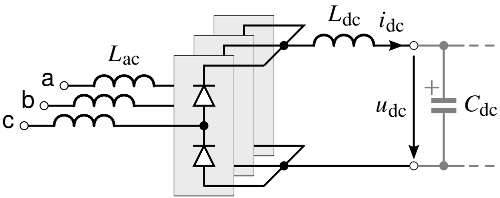


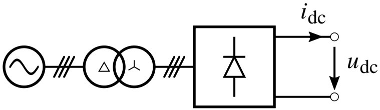
Transistors and diodes drawn in gray are not used in the case of electrolysers, because the current $i \geq 0$. The waveforms of interleaved converters are essentially the same as those of the regular converter, but the load current ripple is reduced (effective switching frequency is increased).

Outline

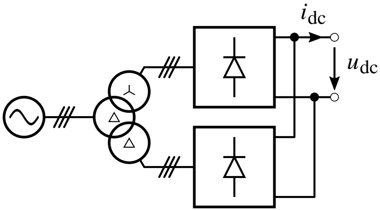
Diode Rectifier

- Simple, reliable, efficient
- Not controllable
- High current harmonics on the grid side





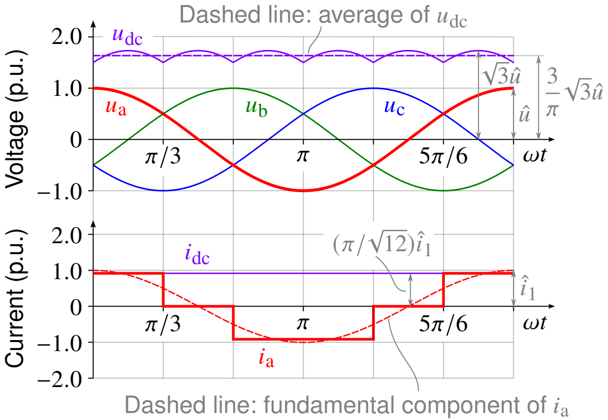
6-pulse diode rectifier



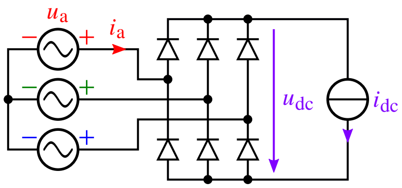
12-pulse diode rectifier
(reduces grid-current harmonics
but needs a special transformer)

The inductor can be placed either on the AC- or DC-side (or both), i.e., either L_{ac} or L_{dc} can be zero. The following analysis assumes $L_{ac} = 0$.

Preliminary Example: Constant DC-Bus Current

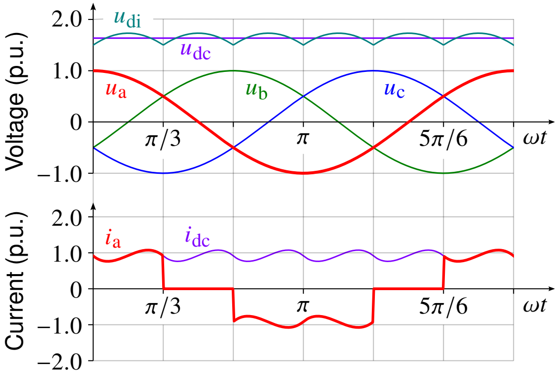


$$u_{dc} = \max(u_a, u_b, u_c) - \min(u_a, u_b, u_c)$$

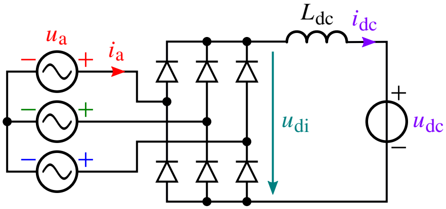


i_{dc} = constant $\Leftrightarrow$ $L_{dc} \to \infty$

Constant DC-Bus Voltage, $L_{\mathrm{dc}} = 0.1$ p.u.

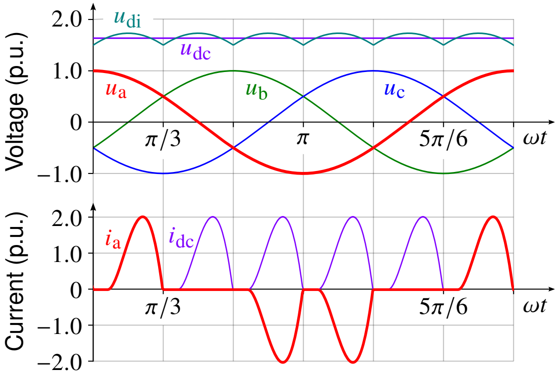


$$u_{\mathrm{di}} = \max(u_{\mathrm{a}}, u_{\mathrm{b}}, u_{\mathrm{c}}) - \min(u_{\mathrm{a}}, u_{\mathrm{b}}, u_{\mathrm{c}})$$

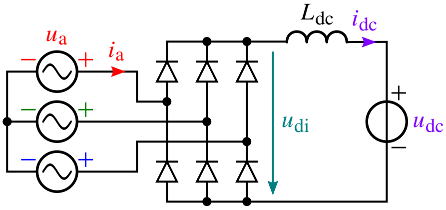


u_{dc} = constant $\quad\Leftrightarrow\quad C_{\mathrm{dc}} \to \infty$

Constant DC-Bus Voltage, $L_{\mathrm{dc}} = 0.01$ p.u.



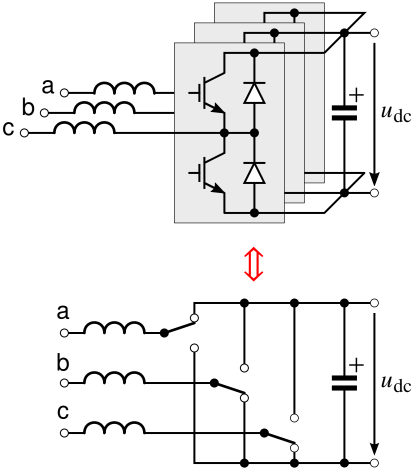
$$u_{\mathrm{di}} = \max(u_{\mathrm{a}}, u_{\mathrm{b}}, u_{\mathrm{c}}) - \min(u_{\mathrm{a}}, u_{\mathrm{b}}, u_{\mathrm{c}})$$



u_{dc} = constant $\Leftrightarrow$ $C_{\mathrm{dc}} \to \infty$

Voltage-Source Rectifier

- Controllable alternative to diode rectifiers
- Typical switching frequencies 1 . . . 10 kHz
- Grid currents are almost sinusoidal
- DC-bus voltage is regulated but cannot be lowered from that of the diode rectifier
- Step-down DC-DC converter is typically needed (to avoid high current stress)
- Higher losses and more expensive compared to diode rectifiers

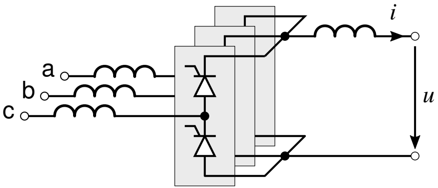


Instead of an L filter, a more compact LCL filter is typically used. Notice that the bridge is the same as the one used in the three-phase interleaved DC-DC converter (and in many other applications, such as electric machine drives).

Outline

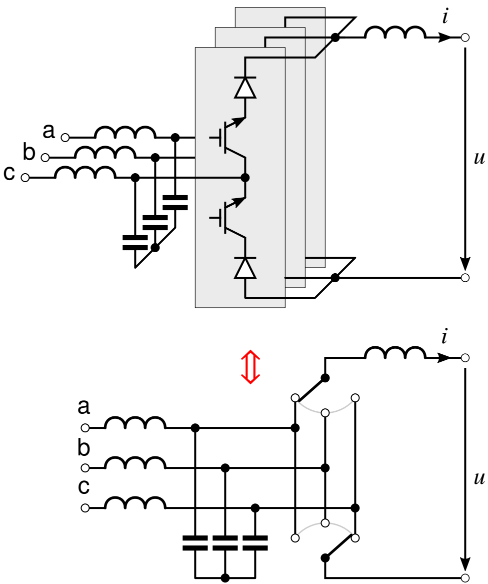
Thyristor Rectifier

- Thyristors are like diodes whose turn-on instant can be delayed
- This feature allows to adjust (decrease) the DC voltage
- Simple, reliable, and efficient
- Very high harmonic contents on both the grid and electrolyser sides
- Can also be used in 12-pulse configuration to reduce harmonics



Current-Source Rectifier[7]

- Controllable step-down rectifier
- Output voltage is less than (or equal to) that of the diode rectifier
- Step-down DC-DC converter not needed
- Grid currents are almost sinusoidal
- This technology is not as mature as the voltage-source rectifiers



[7] Solanki, Fröhleke, Böcker *et al.*, 'High-current variable-voltage rectifiers: State of the art topologies,' *IET Power Electron.*, 2014. DOI: 10.1049/iet-pel.2014.0533.

Future Outlook

- Higher power density and efficiency
- Lower weight and costs, reduced complexity, and modularity
- New topologies, control methods, and semiconductor materials (like SiC)
- Hydrogen production from renewable energy (managing inherent fluctuations)
- Better compatibility with both the grid and electrolysers
- Fault-ride-through: Mitigating the effects of
  - Multi-MW electrolyser system faults on the grid
  - Grid faults on the electrolyser system