



**Aalto University**  
**School of Electrical**  
**Engineering**

# **Converter-Fed Electrolyser Systems: State of the Art**

## **Unite! Research School, Grenoble, France**

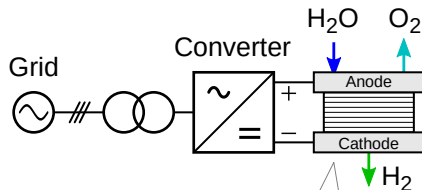
Prof. Marko Hinkkanen

15 October 2024

# 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<sub>2</sub> needed for sustainable synthetic hydrocarbons
- ▶ Potential to decarbonize hard-to-electrify transport and industries
  - ▶ Aviation, maritime, steel, fertilisers

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<sup>1</sup>
  - ▶ 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<sup>2</sup>

---

<sup>1</sup> 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.

<sup>2</sup> 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

## **Electrolysers**

Overview of Converter Topologies

Dual-Stage Converter: Step-Down DC-DC Converter

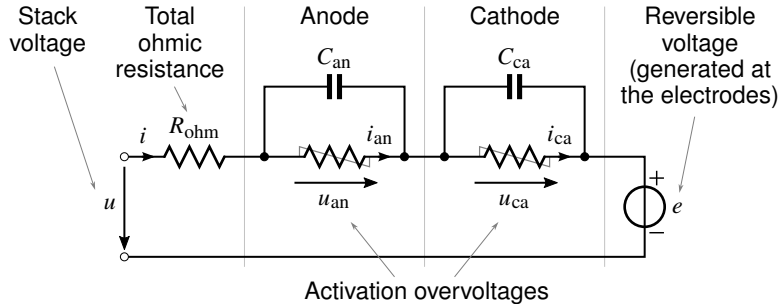
Dual-Stage Converter: Rectifier

Single-Stage Converter Topologies

# 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



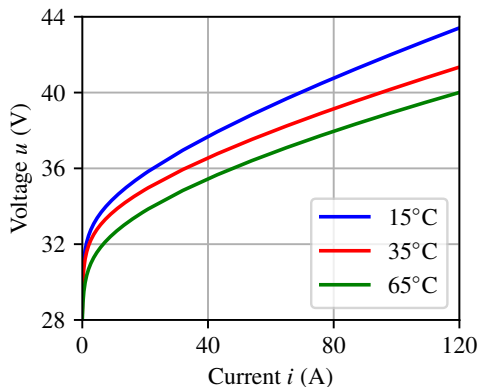
- ▶ Reversible voltage  $e$  is the minimum (ideal) voltage for the electrolysis process
  - ▶ Depends on the temperature and the pressure
- ▶ Ohmic and activation losses cause irreversible overvoltages
- ▶ Capacitances  $C_{an}$  and  $C_{ca}$  model the double-layer effect

- Activation overvoltages are nonlinear in the currents

$$u_{\text{an}} = u_{\text{an}}(i_{\text{an}})$$

$$u_{\text{ca}} = u_{\text{ca}}(i_{\text{ca}})$$

- They also decrease with the temperature



Example  $i$ – $u$  characteristics of an alkaline electrolyser<sup>3</sup>

<sup>3</sup>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<sup>4</sup>

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

- State-space representation

$$C_{\text{an}} \frac{du_{\text{an}}}{dt} = i - i_{\text{an}}(u_{\text{an}})$$

$$C_{\text{ca}} \frac{du_{\text{ca}}}{dt} = i - i_{\text{ca}}(u_{\text{ca}})$$

$$u = R_{\text{ohm}} i + u_{\text{an}} + u_{\text{ca}} + e$$

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

---

<sup>4</sup>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.

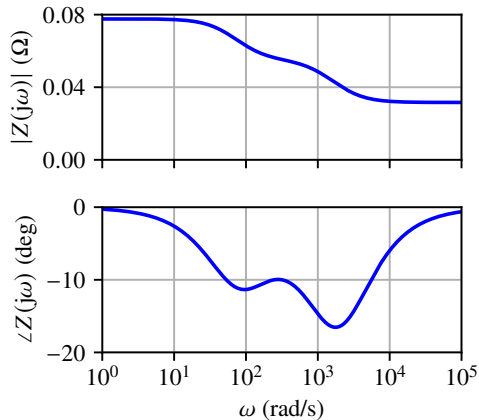
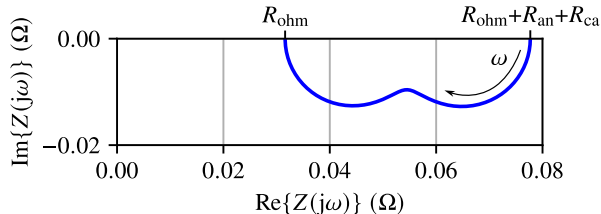


# Linearized Model in the Frequency Domain

- 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)

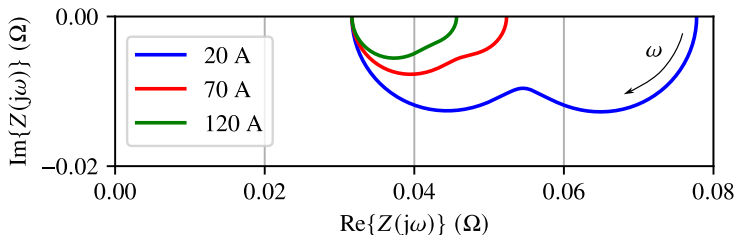


Parameters  $R_{\text{ohm}} = 0.032 \Omega$ ,  $R_{\text{an}} = 0.023 \Omega$ ,  $C_{\text{an}} = 0.638 \text{ F}$ ,  $R_{\text{ca}} = 0.023 \Omega$ , and  $C_{\text{ca}} = 0.031 \text{ F}$  are used

- Incremental resistances depend on the operating-point current

$$R_{\text{an}} = \frac{\partial u_{\text{an}}}{\partial i_{\text{an}}} \quad R_{\text{ca}} = \frac{\partial u_{\text{ca}}}{\partial i_{\text{ca}}}$$

- Figure below shows an example of the impedances at three different currents<sup>3</sup>



# Outline

Electrolysers

## **Overview of Converter Topologies**

Dual-Stage Converter: Step-Down DC-DC Converter

Dual-Stage Converter: Rectifier

Single-Stage Converter Topologies

# Industrial-Scale Converter-Fed Electrolyser Systems

- ▶ Industrial-scale electrolyzers are **multi-MW low-voltage devices**<sup>5,6</sup>
- ▶ 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  $R = R_{\text{ohm}} + R_{\text{an}} + R_{\text{ca}}$  at low frequencies)

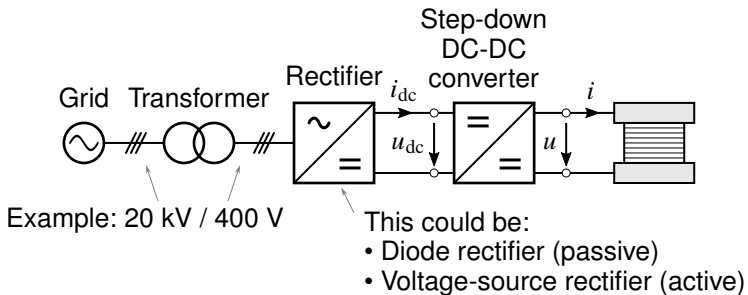


<sup>5</sup>Abdelhakim, Viitanen and Canales, 'State-of-the-art power supplies for electrolyzers: Hydrogen production,' *ABB Review*, 2022.

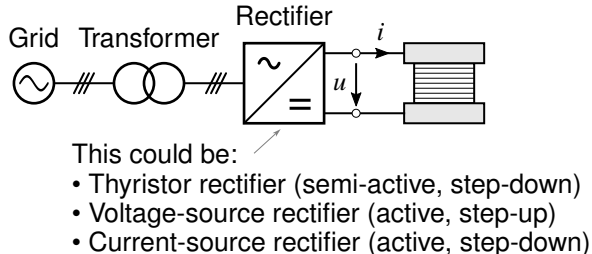
<sup>6</sup>Schumann, Runser, Herzog *et al.*, 'Water electrolysis power supply: Status & future trends,' in *ETG Symposium*, 2023, pp. 122–128.

# Typical Converter Topologies

## Dual-stage converter topology



## Single-stage converter topology



# Outline

Electrolysers

Overview of Converter Topologies

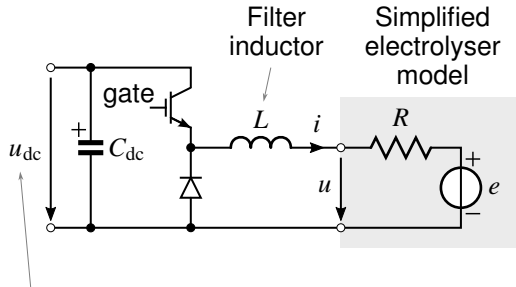
**Dual-Stage Converter: Step-Down DC-DC Converter**

Dual-Stage Converter: Rectifier

Single-Stage Converter Topologies

# Step-Down DC-DC Converter

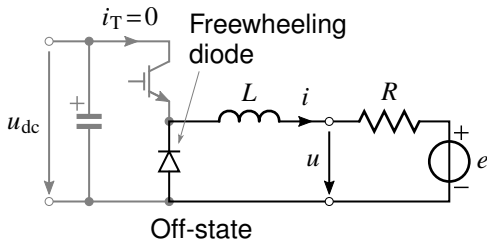
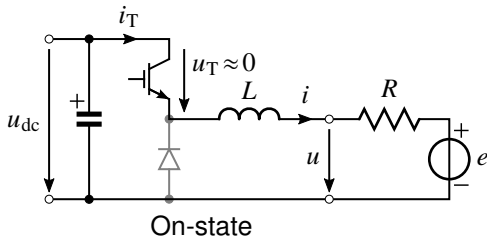
- ▶ To avoid high losses, the transistor is **switched periodically on and off** by means of pulse-width modulation (PWM)
- ▶ Insulated-gate bipolar transistors (IGBTs) are typically used
- ▶ Typical switching frequencies  $f_{sw} = 1 \dots 10 \text{ kHz}$
- ▶ At high frequencies, the filter inductance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



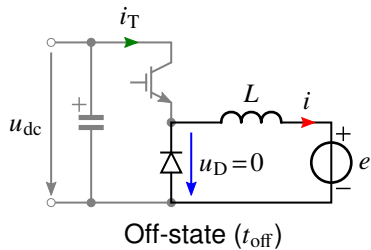
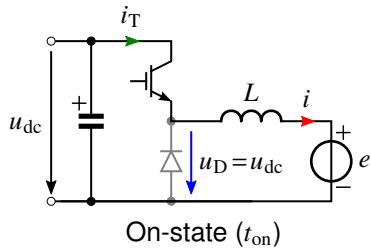
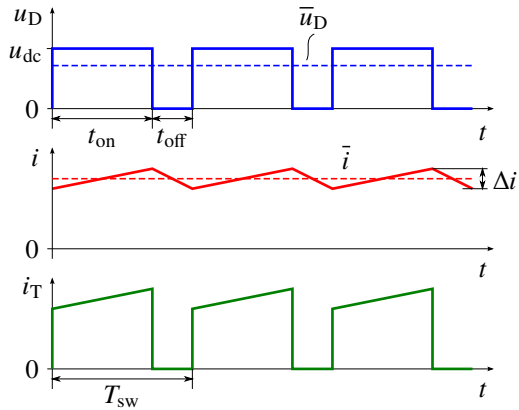
DC-bus voltage  $u_{dc}$  is almost constant due to significant capacitance  $C_{dc}$

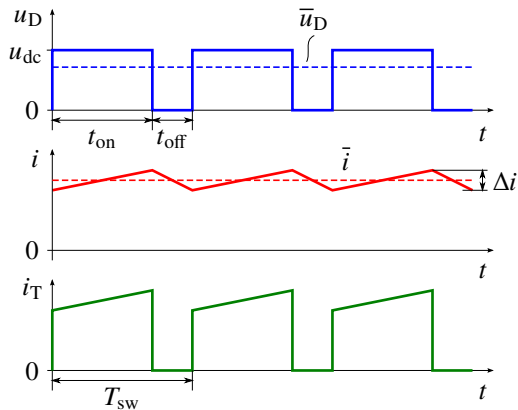
# Switching Waveforms

- ▶ 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
  - ▶  $u_{dc} = \text{constant}$
  - ▶  $e = \text{constant}$
  - ▶  $R = 0$









## ► Duty ratio

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

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

$$\begin{aligned} \bar{u}_D &= \frac{1}{T_{sw}} \int_0^{T_{sw}} u \, dt \\ &= d u_{dc} \end{aligned}$$

- Voltage equation

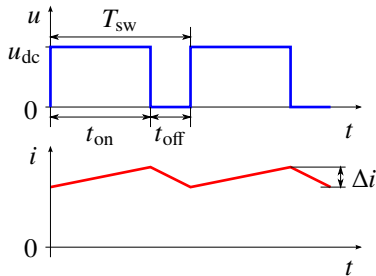
$$L \frac{di}{dt} = u - e$$

- On-state:  $u_D = u_{dc}$

$$\begin{aligned} \Delta i &= \frac{1}{L} \int_0^{t_{on}} (u_{dc} - e) dt \\ &= \frac{(u_{dc} - e)t_{on}}{L} \end{aligned}$$

- Off-state:  $u_D = 0$

$$-\Delta i = \frac{1}{L} \int_0^{t_{off}} (-e) dt = -\frac{et_{off}}{L}$$



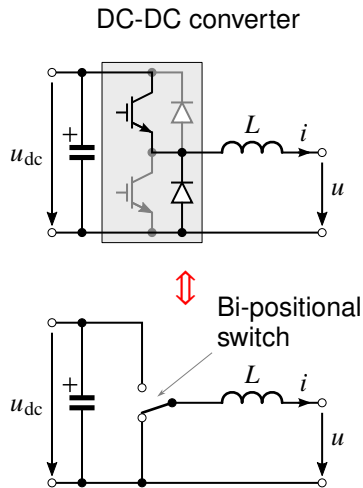
- Duty ratio in steady state

$$d = \frac{t_{on}}{T_{sw}} = \frac{\bar{u}_D}{u_{dc}} \quad (\bar{u}_D = \bar{e} \text{ if } R = 0)$$

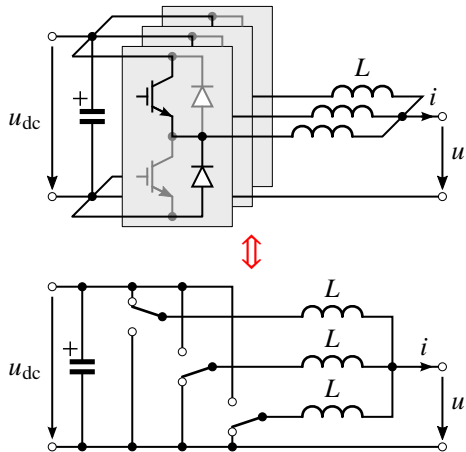
- Current ripple in steady state

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

# Interleaved Converter for High-Power Applications



Multiphase interleaved DC-DC converter



Transistors and diodes drawn in gray are not used in the case of electrolyzers, 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

Electrolysers

Overview of Converter Topologies

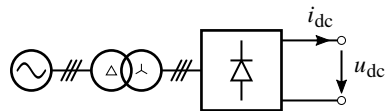
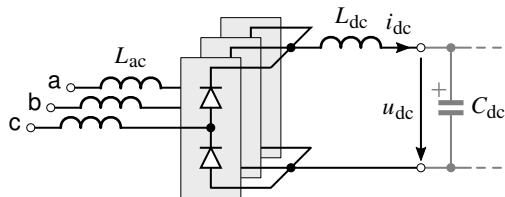
Dual-Stage Converter: Step-Down DC-DC Converter

**Dual-Stage Converter: Rectifier**

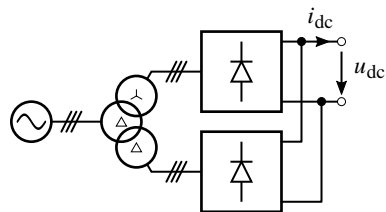
Single-Stage Converter Topologies

# Diode Rectifier

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



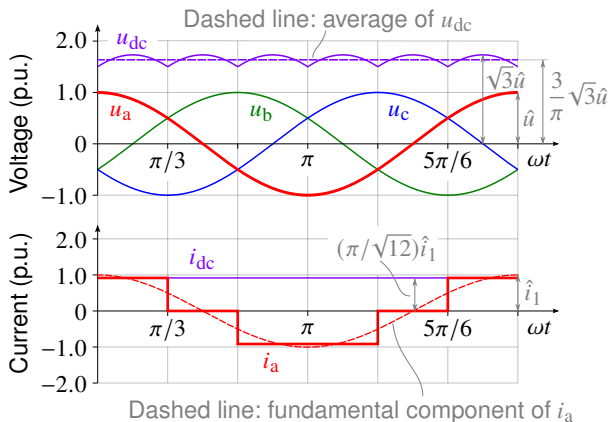
6-pulse diode rectifier



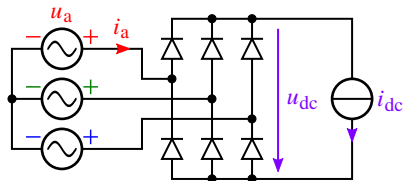
12-pulse diode rectifier  
(reduces grid-current harmonics  
but needs a special transformer)

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

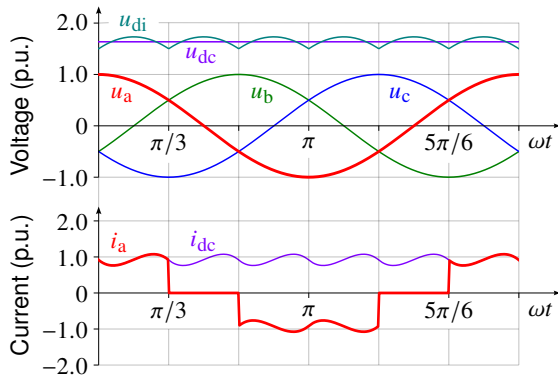


$$u_{dc} = \max(u_a, u_b, u_c) - \min(u_a, u_b, u_c)$$

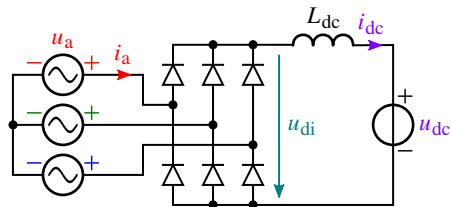


$$i_{dc} = \text{constant} \Leftrightarrow L_{dc} \rightarrow \infty$$

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



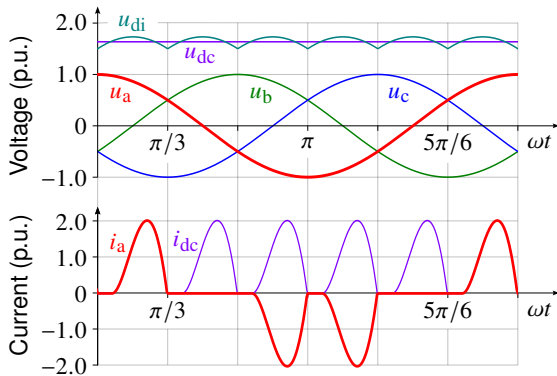
$$u_{di} = \max(u_a, u_b, u_c) - \min(u_a, u_b, u_c)$$



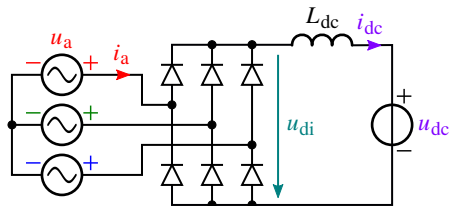
$$u_{dc} = \text{constant} \Leftrightarrow C_{dc} \rightarrow \infty$$



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



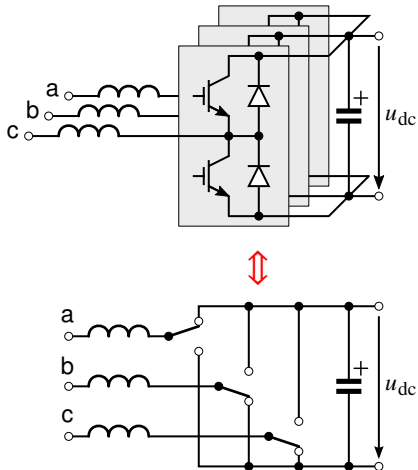
$$u_{di} = \max(u_a, u_b, u_c) - \min(u_a, u_b, u_c)$$



$$u_{dc} = \text{constant} \Leftrightarrow C_{dc} \rightarrow \infty$$

# 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

Electrolysers

Overview of Converter Topologies

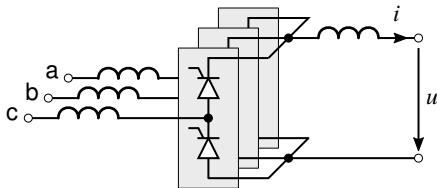
Dual-Stage Converter: Step-Down DC-DC Converter

Dual-Stage Converter: Rectifier

**Single-Stage Converter Topologies**

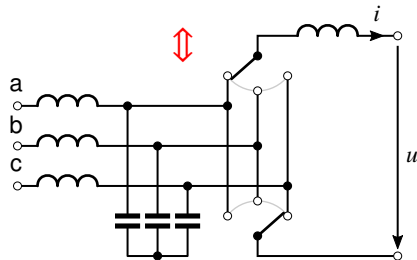
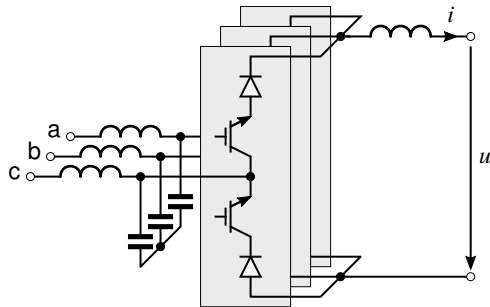
# Thyristor Rectifier

- ▶ 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<sup>7</sup>

- ▶ 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



<sup>7</sup>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 electrolyzers
- ▶ Fault-ride-through: Mitigating the effects of
  - ▶ Multi-MW electrolyzer system faults on the grid
  - ▶ Grid faults on the electrolyzer system