Aalto University
School of Electrical
Engineering

Lecture 6: DC-DC Conversion

ELEC-E8405 Electric Drives (5 ECTS)

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Autumn 2020

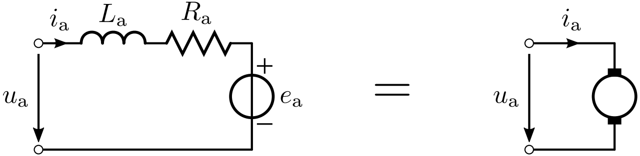
Learning Outcomes

After this lecture and exercises you will be able to:

- Explain basic operating principles of switched DC-DC conversion
- Draw the equivalent circuit of a 4-quadrant DC-DC converter
- Implement a simple pulse-width modulator in the Simulink software

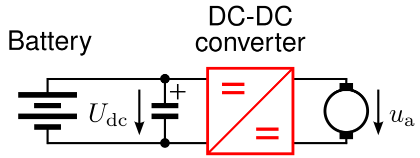
Outline

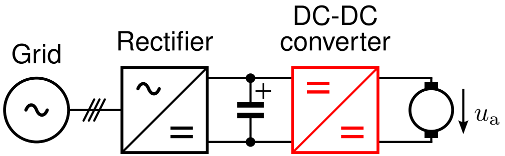
Symbol Used for the DC Motor



Introduction

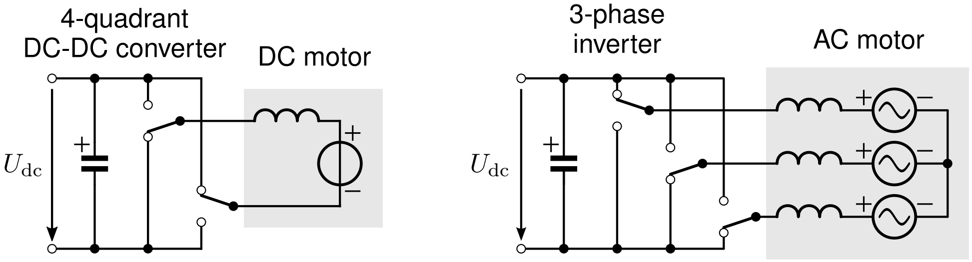
- DC source voltage U_{dc} is typically a battery or a diode bridge
- Armature voltage u_{a} has to be adjusted in order to be able to control the speed and torque
- Topologies and control of DC-DC converters are very similar to those of three-phase inverters





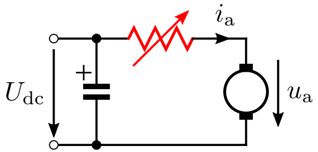
Thyristor bridges could be used to feed the DC motors, but they are not considered in this course.

DC-DC Converters Are Similar to 3-Phase Inverters

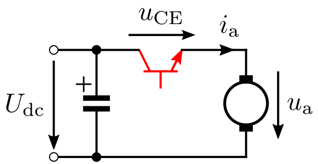


Why Not Linear Voltage Regulation?

- In principle, u_{a} could be adjusted using a rheostat or a transistor in the linear region
- What would be the efficiency if $U_{\mathrm{dc}} = 100$ V and $u_{\mathrm{a}} = 50$ V? What would be the losses in the transistor if $i_{\mathrm{a}} = 10$ A?
- Why linear voltage regulation does not work in practice (except in very low-power drives)?



Rheostat

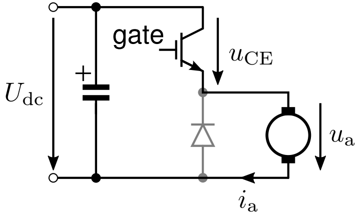


Transistor in the linear region

Outline

Switched-Mode DC-DC Conversion

- To avoid high losses, the transistor is switched periodically on and off
- Typical power semiconductors:
  IGBT, MOSFET, thyristor, GTO
- We will assume ideal switches
- Typical switching frequencies $f_{\mathrm{sw}} = 1 \dots 50$ kHz
- Figure shows a buck converter
  (step-down converter)

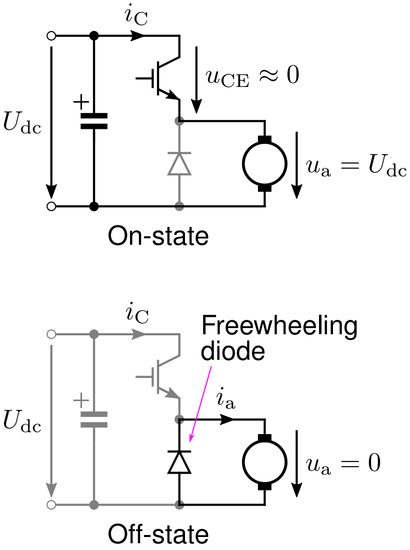


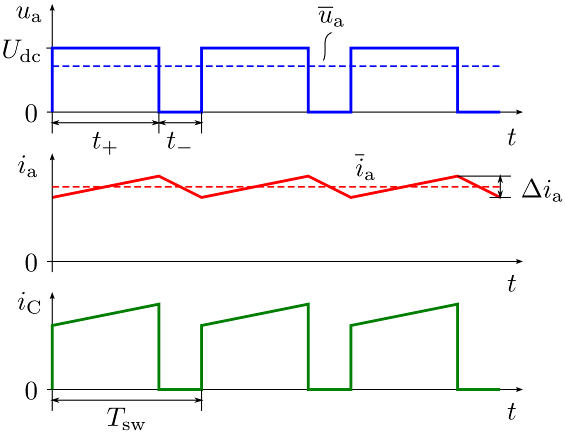
Buck Converter

- Low power loss $u_{\mathrm{CE}} i_{\mathrm{C}}$ in the transistor

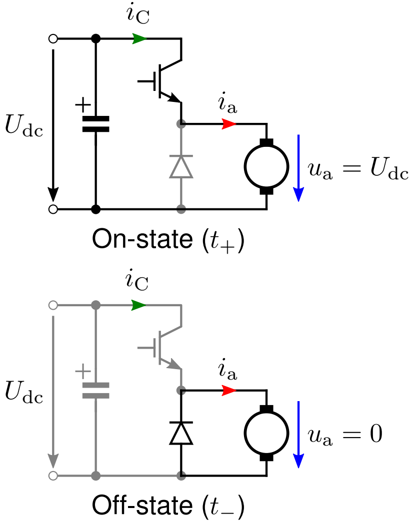
  On-state: $u_{\mathrm{CE}} \approx 0$

  Off-state: $i_{\mathrm{C}} = 0$
- Motor is an inductive load
  - Current i_{a} must flow even when the transistor is switched off
  - Freewheeling diode is needed
- Next we will consider short time periods
  - $e_{\mathrm{a}} =$ constant and $R_{\mathrm{a}} = 0$ can be assumed

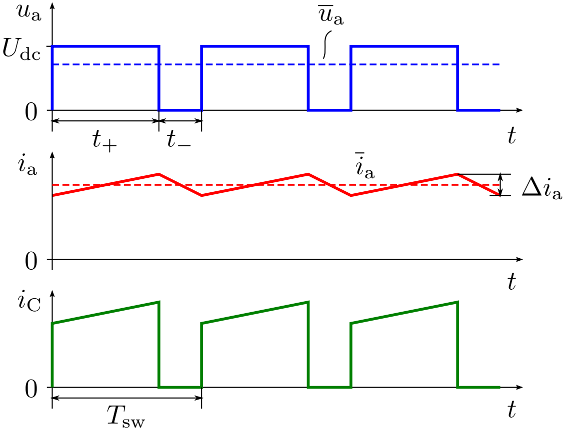




u_a
U_{dc}
$\overline{u}_a$
0
t_+
t_-
t
i_a
$\bar{i}_a$
Δi_a
0
t
i_C
0
T_{sw}
t



i_C
U_{dc}
i_a
$u_a = U_{dc}$
On-state (t_+)
i_C
U_{dc}
i_a
$u_a = 0$
Off-state (t_-)



- Duty cycle

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

- t_+ is the on-time
- T_{sw} is the switching period
- Average of the voltage u_a

$$\overline{u}_a = \frac{1}{T_{sw}} \int_0^{T_{sw}} u_a \, \mathrm{d}t$$
$$= dU_{dc}$$

over the period T_{sw}

Current Ripple

- Voltage equation

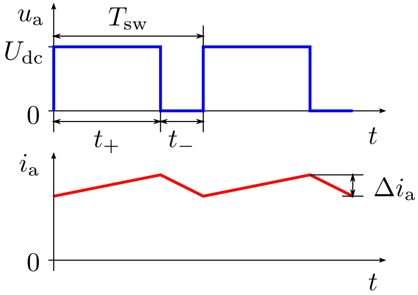
$$L_\mathrm{a}\frac{\mathrm{d}i_\mathrm{a}}{\mathrm{d}t} = u_\mathrm{a} - e_\mathrm{a}$$

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

$$\Delta i_\mathrm{a} = \frac{1}{L_\mathrm{a}}\int_0^{t_+}(U_\mathrm{dc} - e_\mathrm{a})\mathrm{d}t = \frac{(U_\mathrm{dc} - e_\mathrm{a})t_+}{L_\mathrm{a}}$$

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

$$-\Delta i_\mathrm{a} = \frac{1}{L_\mathrm{a}}\int_0^{t_-}(-e_\mathrm{a})\mathrm{d}t = -\frac{e_\mathrm{a}t_-}{L_\mathrm{a}}$$



- Duty ratio in steady state

$$D = \frac{t_+}{T_\mathrm{sw}} = \frac{U_\mathrm{a}}{U_\mathrm{dc}} = \frac{E_\mathrm{a}}{U_\mathrm{dc}}$$

- Current ripple in steady state

$$\Delta i_\mathrm{a} = \frac{D(1-D)U_\mathrm{dc}}{f_\mathrm{sw}L_\mathrm{a}}$$

Maximum Current Ripple

- Maximum ripple for $D = 1/2$ (at about half base speed)

$$\Delta i_{\mathrm{a,max}} = \frac{U_{\mathrm{dc}}}{4 f_{\mathrm{sw}} L_{\mathrm{a}}}$$

- Example parameter values for a 1-kW DC motor

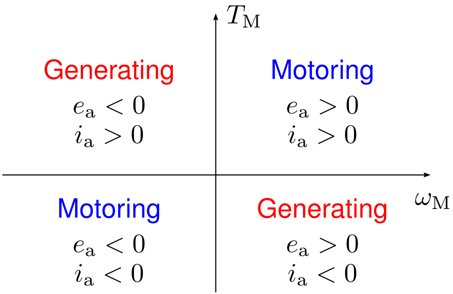
$$L_{\mathrm{a}} = 50 \text{ mH} \quad U_{\mathrm{dc}} = 100 \text{ V} \quad f_{\mathrm{sw}} = 5 \text{ kHz} \quad \Rightarrow \quad \Delta i_{\mathrm{a,max}} = 0.1 \text{ A}$$

- If the rated current is 10 A, the current ripple is only 1%
  (5 kHz is not a high switching frequency at 1-kW power level)
- Current ripple Δi_{a} and torque ripple $\Delta T_{\mathrm{M}} = k_{\mathrm{f}} \Delta i_{\mathrm{a}}$ are typically insignificant

Outline

Four Quadrants

- Back-emf $e_{\mathrm{a}} = k_{\mathrm{f}} \omega_{\mathrm{M}}$
- Torque $T_{\mathrm{M}} = k_{\mathrm{f}} i_{\mathrm{a}}$
- Mechanical power
  $p_{\mathrm{M}} = \omega_{\mathrm{M}} T_{\mathrm{M}} = e_{\mathrm{a}} i_{\mathrm{a}}$
- Converter should allow both its output voltage $u_{\mathrm{a}} \approx e_{\mathrm{a}}$ and current i_{a} to reverse in 4-quadrant operation



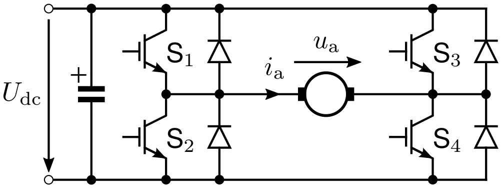
4-Quadrant DC-DC-Converter

S_1 and S_4 switched ON: $u_\mathrm{a} = U_\mathrm{dc}$

S_2 and S_3 switched ON: $u_\mathrm{a} = -U_\mathrm{dc}$

S_1 and S_3 switched ON: $u_\mathrm{a} = 0$

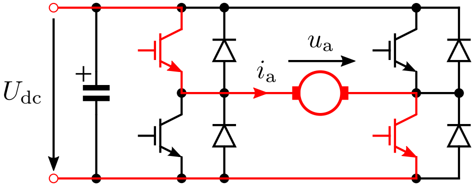
S_2 and S_4 switched ON: $u_\mathrm{a} = 0$



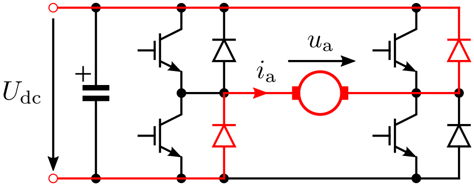
This circuit topology is also known as a 1-phase inverter, full bridge, and H-bridge.

Operation Modes

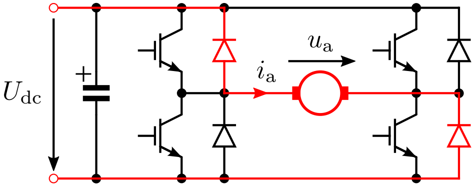
Only Nonzero Voltage Switching States Are Shown



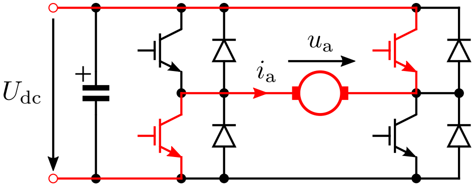
$u_a = U_{dc}, \quad i_a > 0$



$u_a = -U_{dc}, \quad i_a > 0$



$u_a = U_{dc}, \quad i_a < 0$

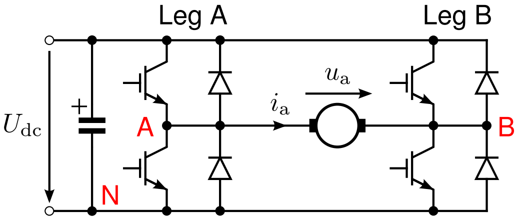


$u_a = -U_{dc}, \quad i_a < 0$

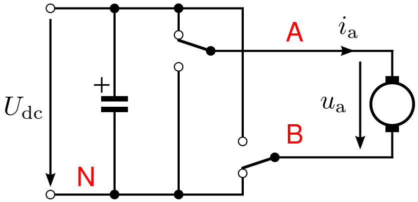
Notation of Potentials and Voltages

- Legs can be modelled as bi-positional switches
- Negative DC-bus potential N
- u_{AN} is the voltage between potentials A and N
- u_{BN} is the voltage between potentials B and N
- Converter output voltage

$$u_{\mathrm{a}} = u_{\mathrm{AN}} - u_{\mathrm{BN}}$$



Circuit diagram



Equivalent circuit

Switching States of the Bi-Positional Switches

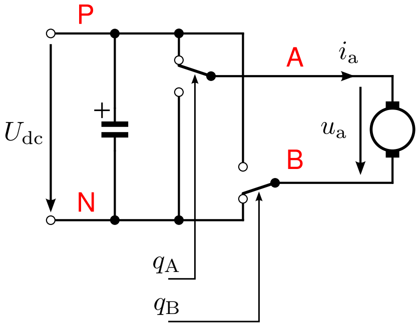
- Switching state q
  - $q = 0$ if the switch is connected to N
  - $q = 1$ if the switch is connected to P
- Pole voltages

$$u_{\mathrm{AN}} = q_{\mathrm{A}} U_{\mathrm{dc}} \qquad u_{\mathrm{BN}} = q_{\mathrm{B}} U_{\mathrm{dc}}$$

- Converter output voltage

$$u_{\mathrm{a}} = (q_{\mathrm{A}} - q_{\mathrm{B}}) U_{\mathrm{dc}}$$

- Figure: $q_{\mathrm{A}} = 1$ and $q_{\mathrm{B}} = 0$, giving $u_{\mathrm{a}} = U_{\mathrm{dc}}$



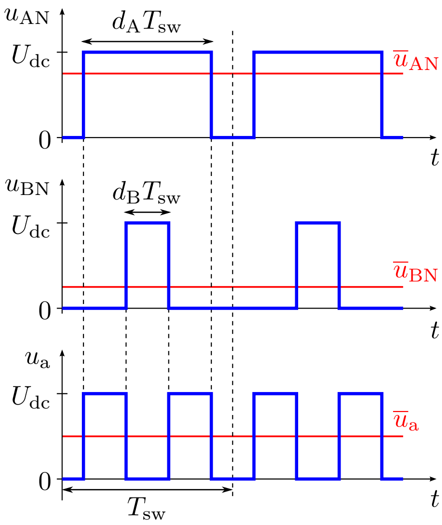
Switching-Cycle Averaged Quantities

- Average pole voltage over T_{sw}

$$\overline{u}_{\mathrm{AN}} = \frac{1}{T_{\mathrm{sw}}} \int_0^{T_{\mathrm{sw}}} u_{\mathrm{AN}} \mathrm{d}t = d_{\mathrm{A}} U_{\mathrm{dc}}$$

- Average voltage $\overline{u}_{\mathrm{BN}}$ is obtained similarly
- Average output voltage

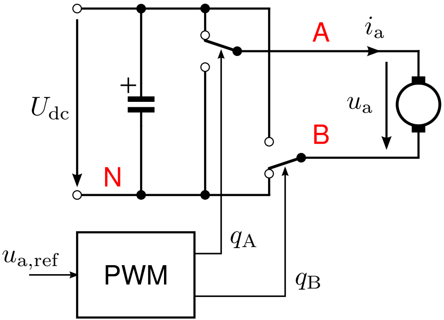
$$\overline{u}_{\mathrm{a}} = (d_{\mathrm{A}} - d_{\mathrm{B}}) U_{\mathrm{dc}}$$



Outline

Pulse-Width Modulation

- PWM generates the control signals q_A and q_B for the power switches
- Goal: switching-cycle averaged voltage $\overline{u}_\mathrm{a}$ equals the reference voltage $u_\mathrm{a,ref}$
- Various PWM methods exist: they all give $\overline{u}_\mathrm{a} = u_\mathrm{a,ref}$ but produce different pulse patterns
- Unipolar PWM will be considered in the following

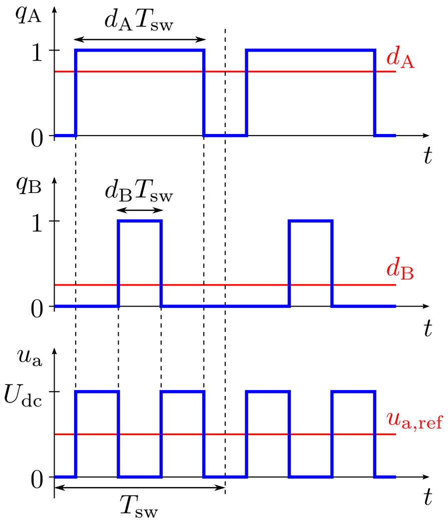


Duty Cycles

- Conditions $\overline{u}_{\mathrm{a}} = u_{\mathrm{a,ref}}$ and $d_{\mathrm{A}} + d_{\mathrm{B}} = 1$ lead to the duty cycles

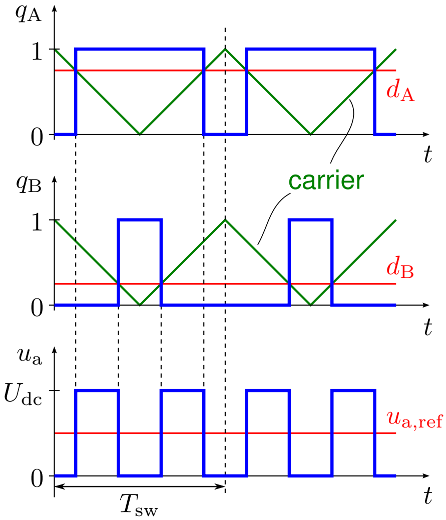
$$d_{\mathrm{A}} = \frac{1}{2}\left(1 + \frac{u_{\mathrm{a,ref}}}{U_{\mathrm{dc}}}\right)$$
$$d_{\mathrm{B}} = \frac{1}{2}\left(1 - \frac{u_{\mathrm{a,ref}}}{U_{\mathrm{dc}}}\right)$$

- Example in the figure: $u_{\mathrm{a,ref}} = 0.5U_{\mathrm{dc}}$
- What are the duty cycles d_{A} and d_{B}?
- How to generate the control signals q_{A} and q_{B}?



Carrier Comparison

- Carrier comparison is often used for generating the control signals
  - Triangular carrier with the period T_{sw}
  - Magnitude varies between 0 and 1
- If d is higher than the carrier, then $q = 1$ (otherwise $q = 0$)
- Same carrier for both d_{A} and d_{B}
- Next slide: step change in the voltage reference ($-0.5U_{\mathrm{dc}} \rightarrow 0.75U_{\mathrm{dc}}$)

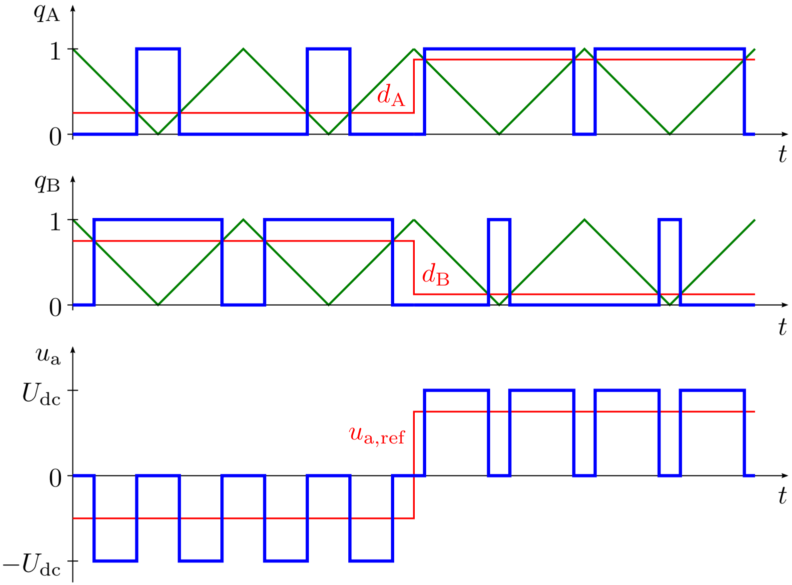


There are various ways to scale the carrier waveform and the reference quantities. Using the carrier varying between 0 and 1 together with the duty cycle references is convenient in digital implementation.

$$d_{\mathrm{A}} = \frac{1}{2}\left(1 + \frac{u_{\mathrm{a,ref}}}{U_{\mathrm{dc}}}\right)$$

$$d_{\mathrm{B}} = \frac{1}{2}\left(1 - \frac{u_{\mathrm{a,ref}}}{U_{\mathrm{dc}}}\right)$$

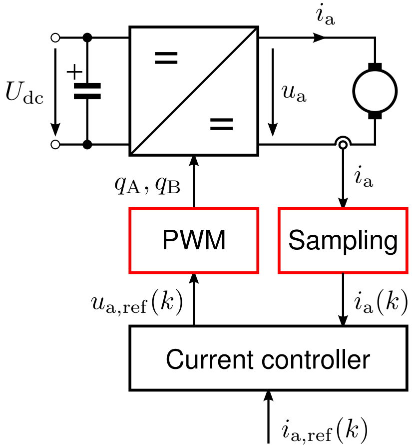
$$\overline{u}_{\mathrm{a}} = (d_{\mathrm{A}} - d_{\mathrm{B}})U_{\mathrm{dc}}$$



Outline

Digital Controller

- Current is measured for the feedback of the current controller
- Digital controllers are used nowadays
- Sampling of the current is typically synchronized with the PWM
- Synchronised sampling effectively removes the current ripple from the samples

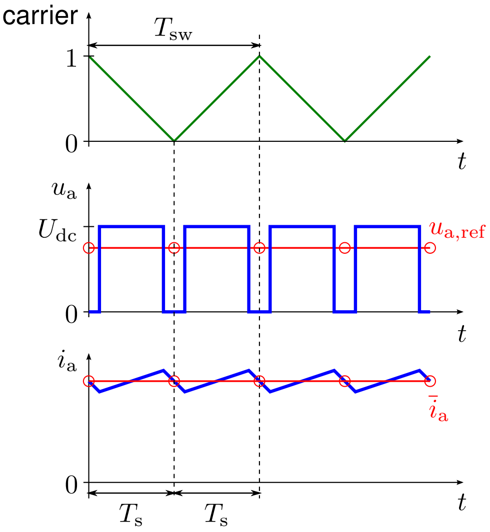


Synchronous Sampling

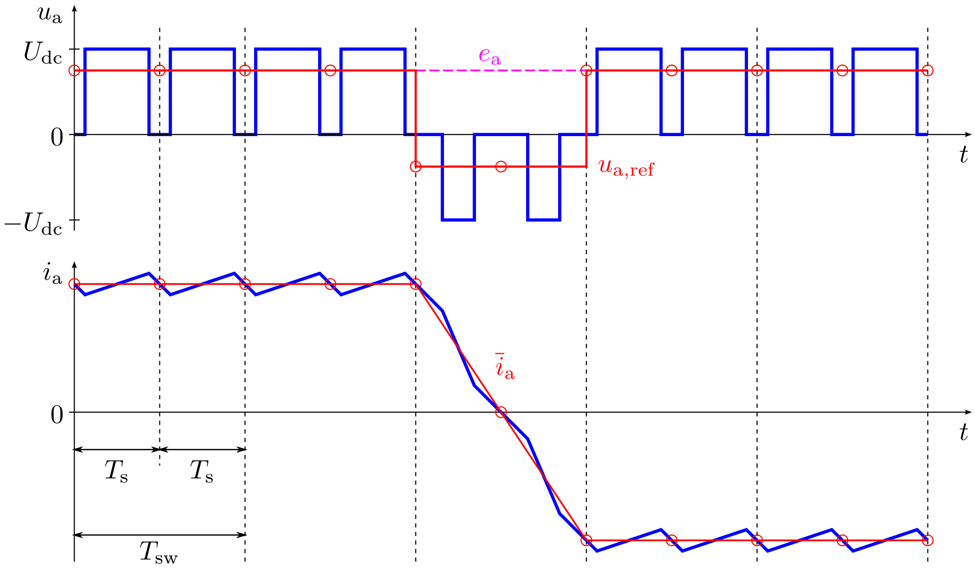
- Voltage reference $u_{\mathrm{a,ref}}$ can be updated in the beginning and in the middle of the carrier (marked with the circles)
- Current samples (circles) can be taken at these same time instants
- Next slide: Current response is governed by

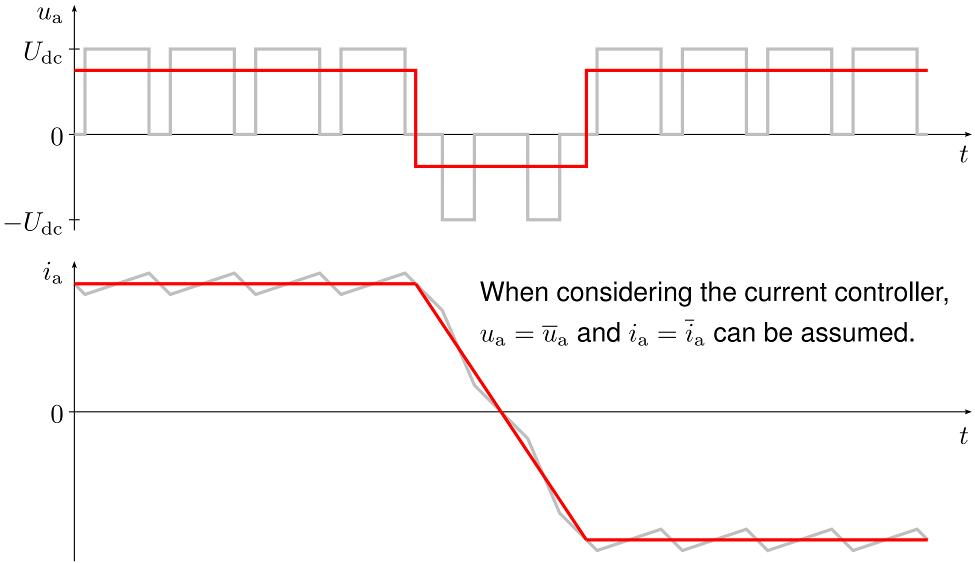
$$L_{\mathrm{a}} \frac{\mathrm{d}i_{\mathrm{a}}}{\mathrm{d}t} = u_{\mathrm{a}} - e_{\mathrm{a}}$$

where $R_{\mathrm{a}} = 0$ is assumed



Different variants of sampling synchronized with the PWM exist, while only one is presented here. Furthermore, it can be noticed that actually four current samples per carrier period could be taken without the current ripple in the case of the unipolar PWM.


u_a
U_{dc}
e_a
0
t
$u_{a,ref}$
$-U_{dc}$
i_a
$\bar{i}_a$
0
t
T_s
T_s
T_{sw}



When considering the current controller, $u_a = \overline{u}_a$ and $i_a = \overline{i}_a$ can be assumed.