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Fundamentals of power electronics for electric drives

Actuators - IRO6

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Task of power electronics

- Supply of electrotechnical devices (e.g. drives) with optimal voltage / frequency for optimum efficiency

4 different cases

- **Rectifiers**: AC voltage system at input, DC voltage system at output
- **Inverters**: DC voltage system at input, AC voltage system at output
- **Converters**: AC voltage system at the input and output (different input and output voltages/frequencies)
- **Regulators or DC converters**: DC voltage system at input and output (different input and output voltages)

And for electric drives?

- **DC servo motors** require variable DC voltage
  - DC converter for DC supply
  - Rectifier for AC supply
- **Synchronous servo motors** require 3-phase variable AC voltage
  - 3-phase inverter for DC supply
  - 3-phase rectifier + 3-phase inverter for AC supply

Use of power electronics

Power electronic devices control or regulate the flow of energy between producers and consumers:

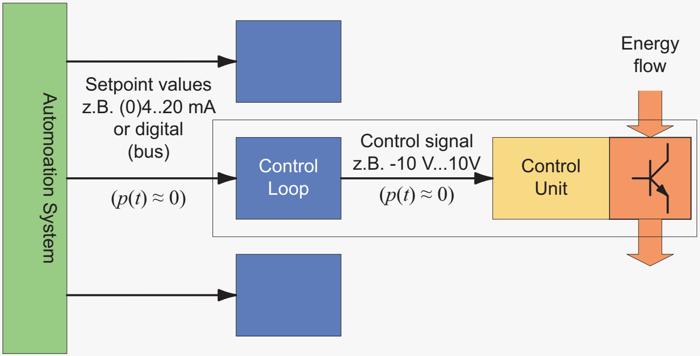
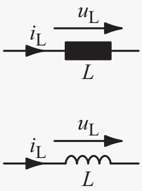


Figure Basic structure of power electronic devices

Passive components: coil as energy storage

Energy is stored in a (magnetic) coil:



$$u_L(t) = L\frac{\mathrm{d}i_L}{\mathrm{d}t}$$

$$\begin{aligned} W_{mag} &= \int_{-\infty}^{t} p(\tau)\,\mathrm{d}\tau = \int_{-\infty}^{t} u_L(\tau) i_L(\tau)\,\mathrm{d}\tau = \int_{-\infty}^{t} L\frac{\mathrm{d}i_L}{\mathrm{d}\tau} i_L(\tau)\,\mathrm{d}\tau \\ &= L\int_{i_L(-\infty)}^{i_L(t)} i_L(\tau)\,\mathrm{d}i_L = \frac{1}{2}L(i_L^2(t) - \underbrace{i_L^2(-\infty)}_{=0}) = \frac{1}{2}L i_L^2(t) \end{aligned}$$

Figure Voltage, current and energy of a coil

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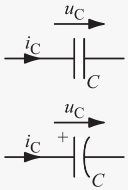
Passive components: capacitor as energy storage



$$i_C(t) = C\frac{\mathrm{d}u_C}{\mathrm{d}t}$$

$$\begin{aligned} W_{\mathrm{el}} &= \int_{-\infty}^{t} p(\tau)\,\mathrm{d}\tau = \int_{-\infty}^{t} i_C(\tau)u_C(\tau)\,\mathrm{d}\tau = \int_{-\infty}^{t} C\frac{\mathrm{d}u_C}{\mathrm{d}\tau}u_C(\tau)\,\mathrm{d}\tau \\ &= C\int_{u_C(-\infty)}^{u_C(t)} u_C(\tau)\,\mathrm{d}u_C = \frac{1}{2}C(u_C^2(t) - \underbrace{u_C^2(-\infty)}_{=0}) = \frac{1}{2}Cu_C^2(t) \end{aligned}$$

Figure Current, voltage and energy of a capacitor

Summary 1

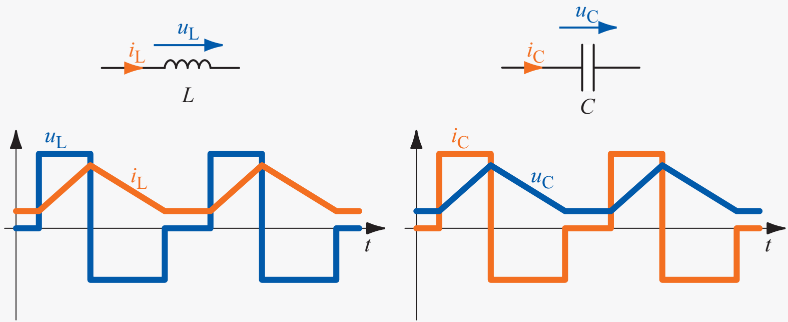


Figure Current and voltage curves with pulsed operation

Summary 2

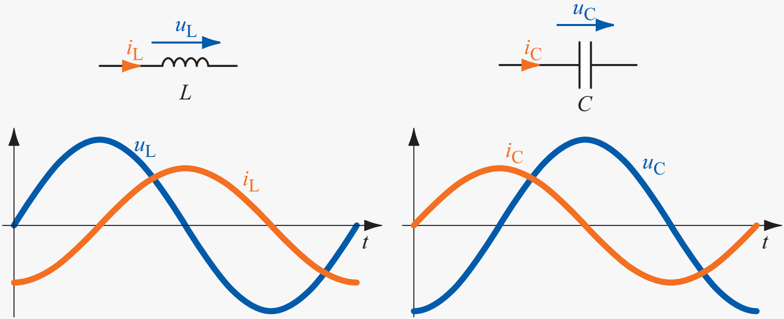


Figure Current and voltage curves with sinusoidal operation

Active Components

- Non-controllable valves:
  - Diodes
- Controllable valves:
  - Valves that can be switched on: thyristors
  - Valves that can be switched on and off: transistors, IGBTs, MOSFETs

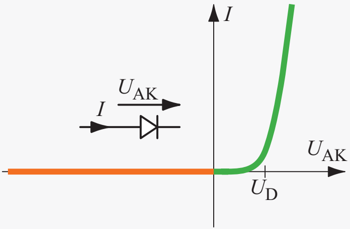
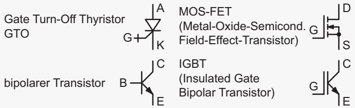


Figure Diode characteristic

Application: rectifier, fly-back diode

Active components: can be switched on and off



A: Anode
B: Basis
C: Collector
D: Drain
E: Emitter
G: Gate
S: Source

Similarities

- Conduct electricity in only one direction
- Can be switched on and off via auxiliary voltage
  ON: $U_{GS} > 0$ (MOSFETs) / $U_{GE} > 0$ (IGBTs)
  OFF: $U_{GS} \approx 0$ (MOSFETs) / $U_{GE} \approx 0$ (IGBTs)
- State-of-the-art Si components
- SiC and GaN in industrialization

- GTO
  - similar to normal thyristor
  - can be switched off
  - switching frequencies 200...400 Hz
  - only in legacy systems
- Bip. transistor
  - due to high switching losses only for very low power
- MOSFET
  - small forward resistance
  - medium power range
  - power supplies for electronic devices, ...
- IGBT
  - greater dielectric strength
  - high voltage systems
  - outputs up to 2 MW

Idealized Theory

- Considered semiconductor elements:
  - only valves that can be switched on and off (IGBT/MOSFET) and diodes
  - ideal switches
    ($u_V(t) = 0$ in the conducting state, $i_V(t) = 0$ in blocking state),
  - Switching times are negligible (i.e. sudden commutation)
- Internal resistances and impedances are neglected
- Input voltage U_1 and output voltage U_2 are constant
- Only steady state
  - ⇒ periodic time functions for current and voltage
  - ⇒ $\overline{u_L(t)} = 0$ and $\overline{i_C(t)} = 0$!
- Inductivities: initially infinitely large, i.e. practical $L \rightarrow \infty$
  - ⇒ Current through the inductance $i_L = \text{const.}$, i.e. without alternating component

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Idealized Theory

- Usual procedure for sizing of power electronic devices:
  - idealized study
    $\rightarrow$ ideal switches, $L, C \rightarrow \infty$
  - simplified study
    $\rightarrow$ switches with forward voltage and resistance, $L, C < \infty$
  - detailed study
    $\rightarrow$ switch with real characteristic, $L, C < \infty, L = f(I)$

Next content:

- buck converter
- boost converter
- inverse converter (buck/boost converter)
- half bridge
- four-quadrant controller (full bridge) $\Rightarrow$ DC servo controller
- (three-phase) inverter (inverter) $\Rightarrow$ AC servo controller

Step-down converter

- Switch S on and off periodically
- DC voltage $U_1 \rightarrow$ pulsed output voltage $u_2(t)$
- Average output voltage $U_2 = \overline{u_2(t)}$ < Input voltage U_1
- with a purely resistive load $i_2(t) \sim u_2(t)$

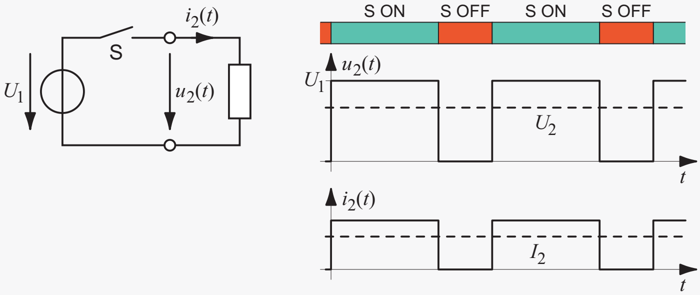

Figure Basic principle step-down converter

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Trouble switching off

Mechanical switch: switching spark when switching off depends on

- size of the current to be switched off
- speed of switching off

Current-carrying conductor:

- always has a magnetic field:
  E.g. wire: inductance of approx. $10\,nH/cm$

Example: Power from $100\,A$ is cut off within $100\,ns$

$$u_{\text{wire}} = L \cdot \frac{\mathrm{d}i_{\text{wire}}}{\mathrm{d}t} = 100\,nH/cm \cdot \frac{100\,A}{100\,ns} = 100\,V/cm$$

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Fly-back Diode

- Loading with an inductive part
  - ⇒ Load current cannot be abruptly reduced
  - ⇒ **Fly-back diode** in parallel with the load for protection:

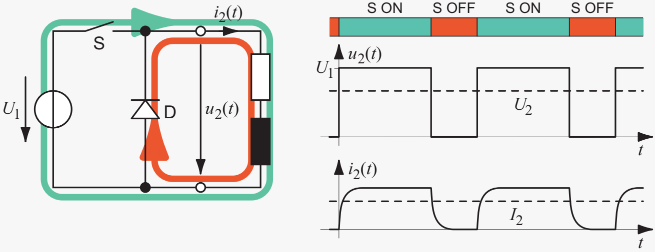


Figure Basic principle step-down converter with fly-back diode

- Switch opens:
  - ⇒ Circuit remains closed via load and fly-back diode
  - ⇒ Energy stored in inductor → Heat loss in the resistor

Smoothing inductance and output capacitor

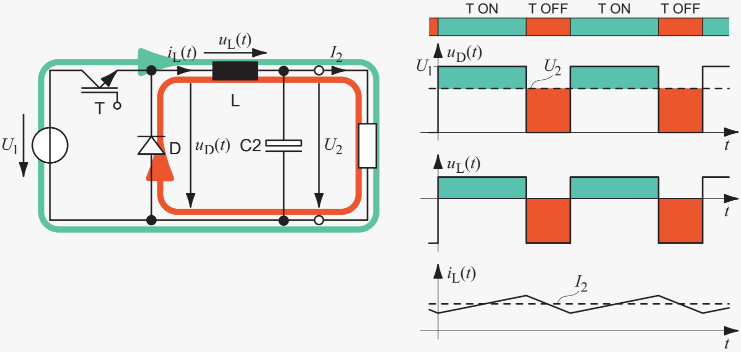


Figure Step-down converter with fly-back diode, smoothing inductance and output capacitor

- L takes up the alternating part of $u_D(t)$: $\overline{u_D(t)} - U_2 = u_L(t)$
- C_2 takes up the alternating part of $i_L(t)$: $\overline{i_L(t)} - I_2 = i_{C2}(t)$

Input Capacitor?

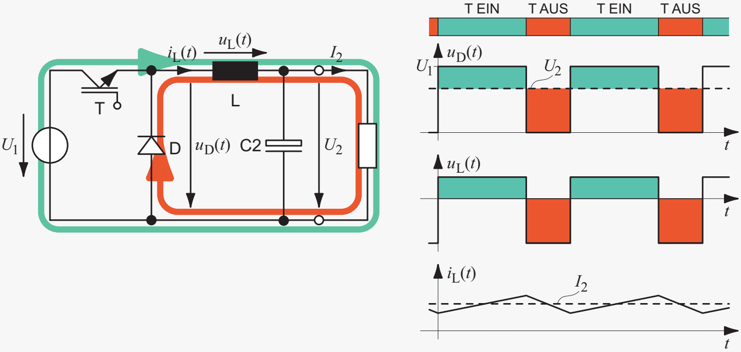
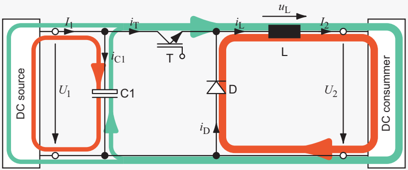


Figure Step-down converter with fly-back diode, smoothing inductance and output capacitor

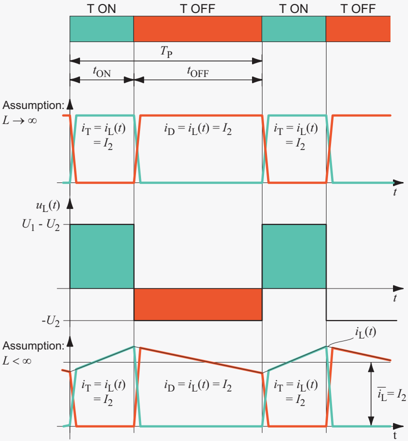
- Collector current (= input current I_1) jumps!

⇒ Input capacitor to protect T necessary!

Step-down converter



- $L \to \infty$: $i_L(t) = I_2 = \text{const.}$
- $U_2 \leq U_1$ or $I_2 \geq I_1$
- ON state:
  - $I_1 - i_T = i_{C1} \to i_{C1} = I_1 - I_2 < 0$
  - $\Rightarrow$ C_1 gives the charge $(I_2 - I_1) \cdot t_{ON}$
- OFF state:
  - $I_1 - i_T = i_{C1} \to i_{C1} = I_1 > 0$
  - $\Rightarrow$ C_1 takes the charge $I_1 \cdot t_{OFF}$



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Step-down converter

$$(I_2 - I_1)\cdot t_{\mathrm{ON}} = I_1 \cdot t_{\mathrm{OFF}} \quad \Rightarrow \quad I_2 \cdot t_{\mathrm{ON}} = I_1 \cdot (t_{\mathrm{OFF}} + t_{\mathrm{ON}}) \;\Rightarrow\; I_1 = I_2 \cdot \frac{t_{\mathrm{ON}}}{T_{\mathrm{P}}} = D \cdot I_2$$

ON state ($u_{\mathrm{D}}(t) = U_1$):

$$-U_1 + u_{\mathrm{L}}(t) + U_2 = 0 \quad \Rightarrow \quad u_{\mathrm{L}}(t) = U_1 - U_2$$

OFF state($u_{\mathrm{D}}(t) = 0$):

$$u_{\mathrm{L}}(t) + U_2 = 0 \quad \Rightarrow \quad u_{\mathrm{L}}(t) = -U_2$$

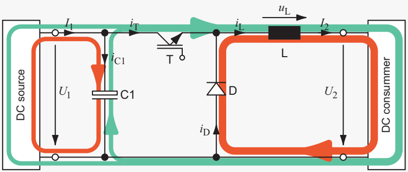
$$\overline{u_{\mathrm{L}}(t)} = 0 \quad \Rightarrow \quad (U_1 - U_2)\cdot t_{\mathrm{ON}} - U_2 \cdot t_{\mathrm{OFF}} = 0 \;\Rightarrow\; U_1 \cdot t_{\mathrm{ON}} = U_2 \cdot T_{\mathrm{P}} \;\Rightarrow\; U_2 = U_1 \cdot \frac{t_{\mathrm{ON}}}{T_{\mathrm{P}}} = D \cdot U_1$$

$$U_1 \cdot I_1 = U_1 \cdot \overline{i_{\mathrm{T}}(t)} = U_2 \cdot I_2$$

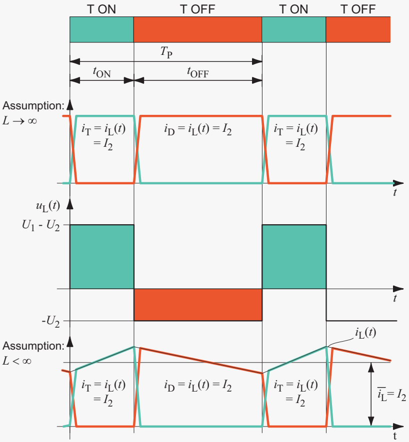
next step with $L < \infty$:

$$u_{\mathrm{L}}(t) = L \cdot \frac{\mathrm{d}i_{\mathrm{L}}}{\mathrm{d}t}$$

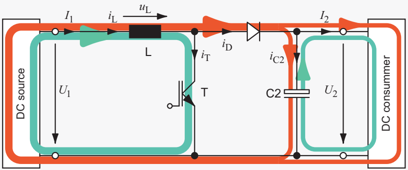
Step-down converter with $L < \infty$



- ON state:
  - $$u_L(t) = U_1 - U_2 = L \cdot \frac{di_L}{dt}$$
  - $$\Rightarrow \frac{di_L}{dt} > 0 \text{ and constant}$$
- OFF state:
  - $$u_L(t) = -U_2 = L \cdot \frac{di_L}{dt}$$
  - $$\Rightarrow \frac{di_L}{dt} < 0 \text{ and constant}$$



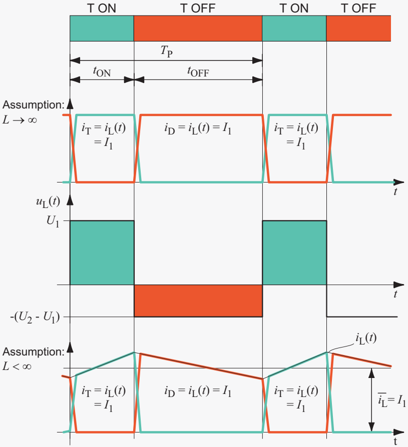
Step-up converter



- $L \to \infty$: $i_L(t) = I_2 = \text{const.}$
- $U_2 \geq U_1$ or $I_2 \leq I_1$
- ON state:
  - $0 = I_2 + i_{C2} \to i_{C2} = -I_2 < 0$

  $\Rightarrow$ C_2 gives off the charge $I_2 \cdot t_{ON}$
- OFF state:
  - $I_1 = I_2 + i_{C2} \to i_{C2} = I_1 - I_2 > 0$

  $\Rightarrow$ C_2 takes up the charge $(I_1 - I_2) \cdot t_{OFF}$



Step-up converter

$$I_2 \cdot t_{\mathrm{ON}} = (I_1 - I_2) \cdot t_{\mathrm{OFF}} \quad \Rightarrow \quad I_1 \cdot t_{\mathrm{OFF}} = I_2 \cdot (t_{\mathrm{ON}} + t_{\mathrm{OFF}})$$

$$\Rightarrow \quad I_2 = I_1 \cdot \frac{T_{\mathrm{P}} - t_{\mathrm{ON}}}{T_{\mathrm{P}}} = (1 - D) \cdot I_1$$

ON state ($u_{\mathrm{CE}}(t) = U_1$):

$$-U_1 + u_{\mathrm{L}}(t) = 0 \quad \Rightarrow \quad u_{\mathrm{L}}(t) = U_1$$

OFF state ($u_{\mathrm{CE}}(t) = U_2$):

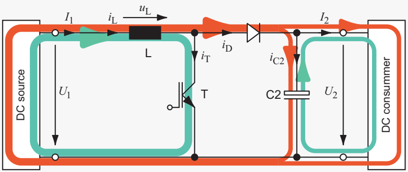
$$-U_1 + u_{\mathrm{L}}(t) + U_2 = 0 \quad \Rightarrow \quad u_{\mathrm{L}}(t) = -(U_2 - U_1)$$

$$\overline{u_{\mathrm{L}}(t)} = 0 = \frac{U_1 \cdot t_{\mathrm{ON}} - (U_2 - U_1) \cdot t_{\mathrm{OFF}}}{T_{\mathrm{P}}} \quad \Rightarrow \quad (U_2 - U_1) \cdot t_{\mathrm{OFF}} = U_1 \cdot t_{\mathrm{ON}}$$

$$\Rightarrow \quad U_2 = U_1 \cdot \frac{t_{\mathrm{OFF}} + t_{\mathrm{ON}}}{t_{\mathrm{OFF}}} = \frac{T_{\mathrm{P}}}{t_{\mathrm{OFF}}} \cdot U_1 = \frac{1}{1 - D} \cdot U_1$$

next step with $L < \infty$: $\quad u_{\mathrm{L}}(t) = L \cdot \frac{\mathrm{d}i_{\mathrm{L}}}{\mathrm{d}t}$

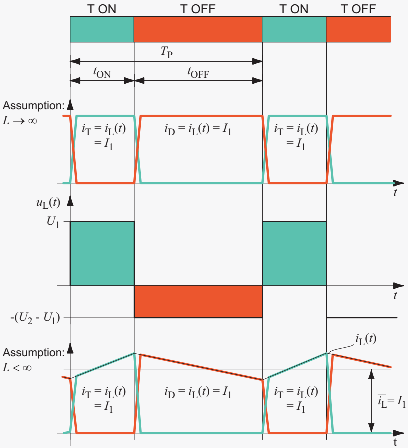
Step-up converter with $L < \infty$



- State ON:
  - $u_L(t) = U_1 = L \cdot \frac{di_L}{dt}$

    $\Rightarrow \frac{di_L}{dt} > 0$ and constant
- OFF state:
  - $u_L(t) = -(U_2 - U_1) = L \cdot \frac{di_L}{dt}$

    $\Rightarrow \frac{di_L}{dt} < 0$ and constant



Multi-quadrant controller

Step-down and step-up converters:

- Current direction at the output cannot be changed
- Voltage direction at the output cannot be changed
  - ⇒ Power can only be transferred from input to output

DC motor:

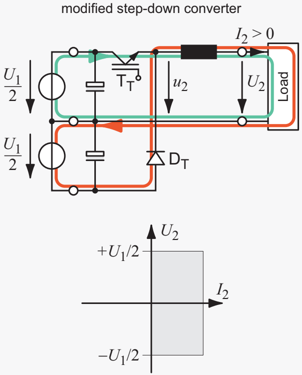
- Voltage = measure of speed
- Current = measure of torque

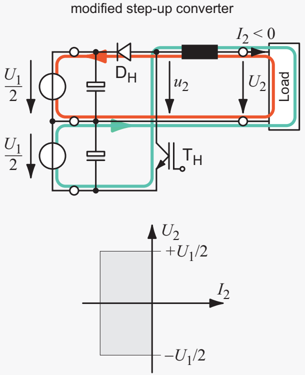
⇒ with step-down or step-up converter only clockwise rotating motor operation

  - ⇒ step-down or step-up converter = One-quadrant controller (1QC)

- if both directions of rotation and torque are needed:
  - ⇒ both voltage AND both current directions necessary!
  - ⇒ Four-quadrant controller (4QC)

2 x two-quadrant controllers...





$$I_2 > 0 : \quad U_2 = -\frac{U_1}{2} \ldots + \frac{U_1}{2} \quad (D = 0 \ldots 1) \quad I_2 < 0 : \quad U_2 = +\frac{U_1}{2} \ldots - \frac{U_1}{2} \quad (D = 0 \ldots 1)$$

… = 1 x four-quadrant controller (half bridge)

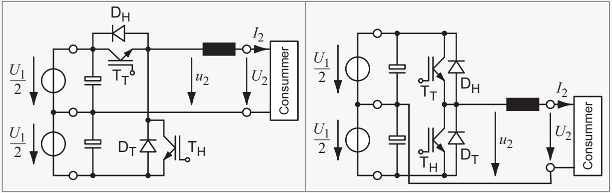


Figure Four-quadrant controller (half bridge)

- Transistors are fired alternately
- Current „finds“ its way
- „Drive“ ($u_L > (<) 0$, $i_L > (<) 0$):
  $\Rightarrow$ Transistor conducts
- „Fly-back“ ($u_L > (<) 0$, $i_L < (>) 0$):
  $\Rightarrow$ Diode conducts

- T_T fired: $U_2 > 0$
  - $I_2 > 0$: Current via T_T
  - $I_2 < 0$: Current via D_H
- T_H fired: $U_2 < 0$
  - $I_2 < 0$: Current via T_H
  - $I_2 > 0$: Current via D_T

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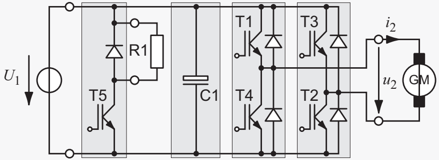
2 x half-bridge = 1 x H-bridge



- Transistors are fired in pairs (T1/T2) vs. (T3/T4).
- $i_2 > 0$: T1/T2 (drive) or D3/D4 (fly-back)
- $i_2 < 0$: T3/T4 (drive) or D1/D2 (fly-back)
- Voltage source must be regenerative or a brake chopper is needed

$$\overline{u_2(t)} = \frac{t_{\mathrm{ON}}}{T_{\mathrm{P}}} \cdot U_1 - \frac{t_{\mathrm{OFF}}}{T_{\mathrm{P}}} \cdot U_1 = \frac{t_{\mathrm{ON}}}{T_{\mathrm{P}}} \cdot U_1 - \frac{T_{\mathrm{P}} - t_{\mathrm{ON}}}{T_{\mathrm{P}}} \cdot U_1 = \frac{2t_{\mathrm{ON}} - T_{\mathrm{P}}}{T_{\mathrm{P}}} \cdot U_1 = (2D-1) \cdot U_1$$

$$D = 0 \ldots 1: \; U_2 = -U_1 \ldots + U_1$$

$$(t_{\mathrm{ON}} = t_{\mathrm{ON1}} = t_{\mathrm{ON2}} = t_{\mathrm{OFF3}} = t_{\mathrm{OFF4}} \quad \text{or} \quad t_{\mathrm{OFF}} = t_{\mathrm{OFF1}} = t_{\mathrm{OFF2}} = t_{\mathrm{ON3}} = t_{\mathrm{ON4}})$$

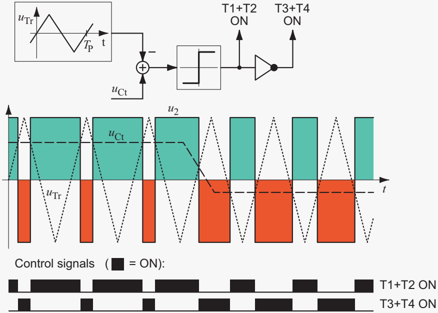
Modulation as basis for inverting

So far only „regulator " (DC voltage in input and output) considered.

Same circuit (H-bridge) for inverting?

Pulse width modulation (PWM) ⇒ any form of output voltage

Triangle modulation: the simplest type of modulation



Modulation of single-phase inverters (H-bridge)

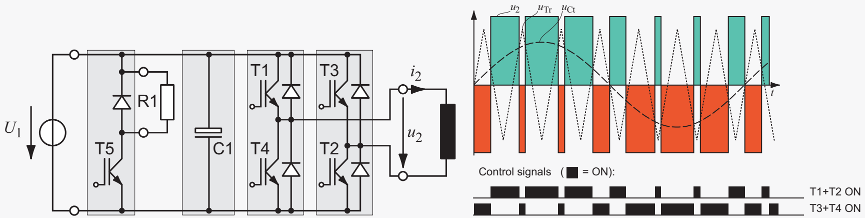


Figure Inverter with triangle modulation

- u_2 with fundamental component proportional to control voltage u_{Ct}.
- How to reduce harmonics in u_2? ⇒ Increase (pulse) switching frequency
- Limited by switching losses in the transistors

Three-phase inverter

Supply of three-phase drives: three-phase inverter

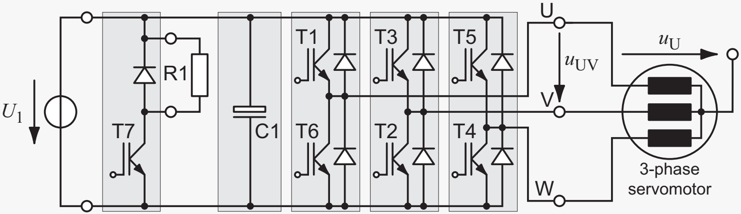


Figure Three-phase inverter with three-phase machine as load

- 120° offset on the voltages and currents
- Sum of phase currents always zero ⇒ only half bridges required
- Switching frequency mostly 4 kHz to 16 kHz
- Space vector modulation (voltage in d and q axis) instead of triangular modulation (phase voltages) ⇒ higher output voltage