Fundamentals of power electronics for electric drives

Actuators - IRO6

Prof. Dr.-Ing. Mercedes Herranz Gracia

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

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  - 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 3-phase 1-phase

Use of power electronics

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

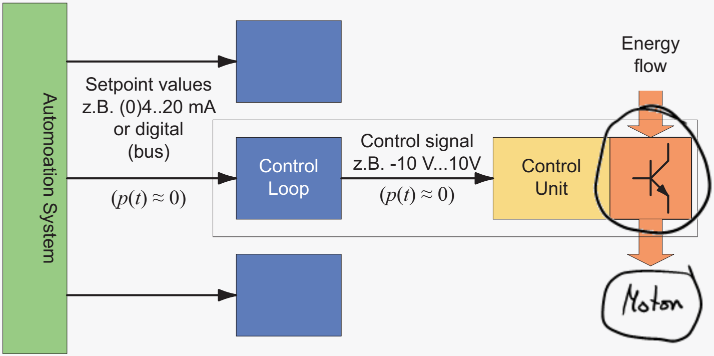

Figure Basic structure of power electronic devices

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Fundamentals of power electronics for electric drives

Capacitors, Inductors as energy storage to smooth the output values (current and voltage) of the circuit.

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Passive components: coil as energy storage

Energy is stored in a (magnetic) coil:

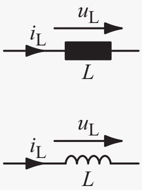

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Figure Voltage, current and energy of a coil

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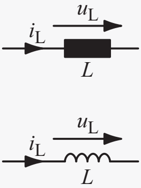

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$$W_{mag} = \int_{-\infty}^{t} p(\tau)\,\mathrm{d}\tau = \int_{-\infty}^{t} u_L(\tau)i_L(\tau)\,\mathrm{d}\tau = \int_{-\infty}^{t} L\frac{\mathrm{d}i_L}{\mathrm{d}\tau}i_L(\tau)\,\mathrm{d}\tau$$

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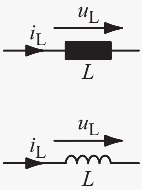

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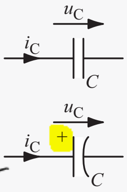
Passive components: capacitor as energy storage



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

$$W_{el} = \int_{-\infty}^{t} p(\tau)\,\mathrm{d}\tau = \int_{-\infty}^{t} i_C(\tau)u_C(\tau)\,\mathrm{d}\tau = \int_{-\infty}^{t} C\frac{\mathrm{d}u_C}{\mathrm{d}\tau}u_C(\tau)\,\mathrm{d}\tau$$

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Figure Current, voltage and energy of a capacitor

Electrolytic capacitor.
⇒ Fixed direction of charge (always check before connecting)
but with higher energy density (smaller for the same C)

Summary 1

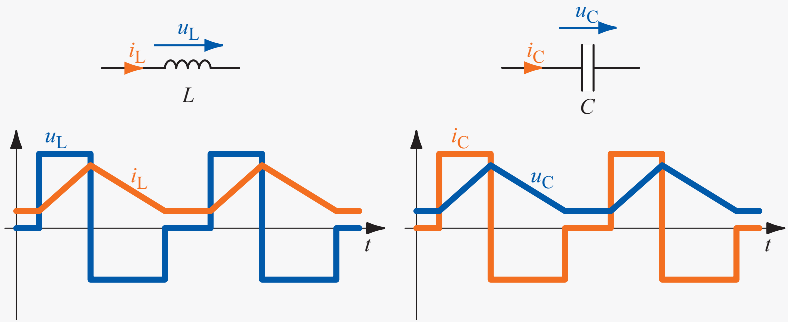

Figure Current and voltage curves with pulsed operation

Summary 2

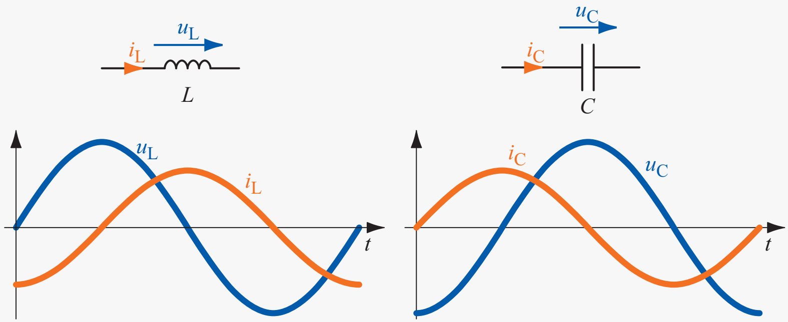

Figure Current and voltage curves with sinusoidal operation

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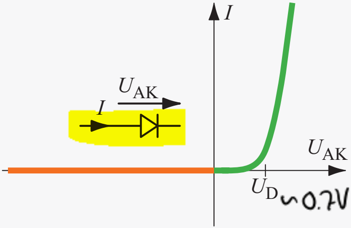

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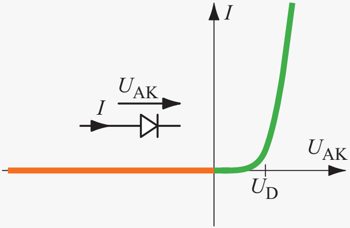
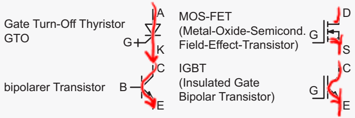


Figure Diode characteristic

Application: rectifier, fly-back diode

Active components: can be switched on and off



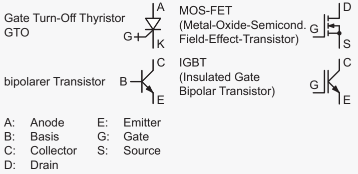
A: Anode
B: Basis
C: Collector
D: Drain
E: Emitter
G: Gate
S: Source

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

Active components: can be switched on and off



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  - similar to normal thyristor
  - can be switched off
  - switching frequencies 200...400 Hz
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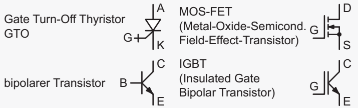

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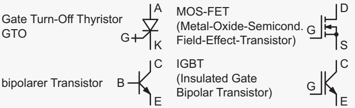

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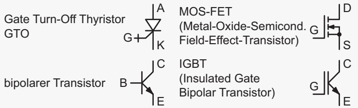

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- MOSFET ← for motor drives for voltages ≤ 100V
  - small forward resistance
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- IGBT ← for motor drives for voltages > 100V
  - greater dielectric strength
  - high voltage systems
  - outputs up to 2 MW

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  - ⇒ periodic time functions for current and voltage
  - ⇒ $\overline{u_L(t)} = 0$ and $\overline{i_C(t)} = 0$!

$u_L = L \cdot \frac{di_L}{dt} \qquad i_C = C \cdot \frac{du_C}{dt}$

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  - ⇒ $\overline{u_{\mathrm{L}}(t)} = 0$ and $\overline{i_{\mathrm{C}}(t)} = 0$!
- Inductivities: initially infinitely large, i.e. practical $L \rightarrow \infty$
  - ⇒ Current through the inductance $i_{\mathrm{L}} = \text{const.}$, i.e. without alternating component

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  - idealized study
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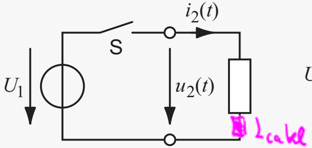
- half bridge
- four-quadrant controller (full bridge) $\Rightarrow$ DC servo controller
- (three-phase) inverter (inverter) $\Rightarrow$ AC servo controller

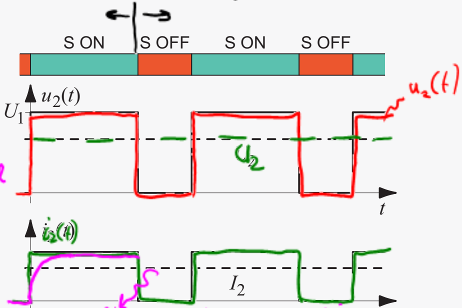
Fundamentals of power electronics for electric drives

Step-down converter

- Switch S on and off periodically

Changing the switching point changes U_2





Problems with this circuit

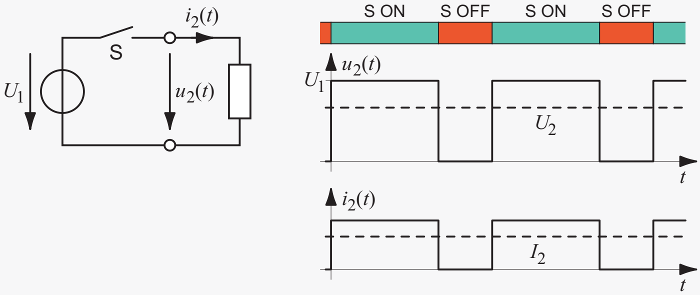
1. $u_2(t)$ pulsates
2. $i_2(t)$ pulsates
3. Parasitic inductance of cables

Voltage peak $u_L = L \cdot \frac{\Delta i_2}{\Delta t}$

Figure Basic principle step-down converter

Step-down converter

- Switch S on and off periodically
- DC voltage U_1 → pulsed output voltage $u_2(t)$



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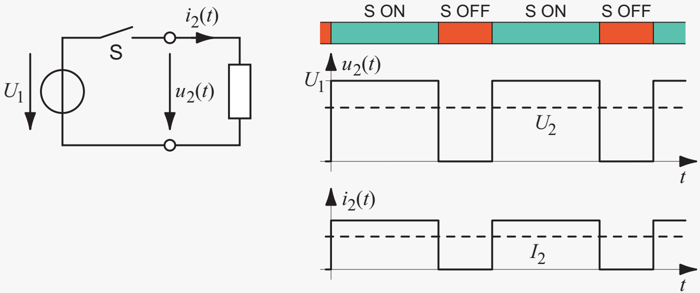

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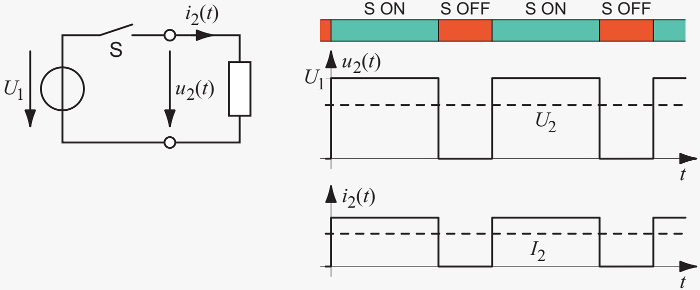
Step-down converter

- 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 $i_2(t) \sim u_2(t)$



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Mechanical switch: switching spark when switching off depends on

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- always has a magnetic field:
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Example: Power from $100\,A$ is cut off within $100\,ns$

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

$\Rightarrow$ Flyback diode to avoid this problem

Fly-back Diode

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

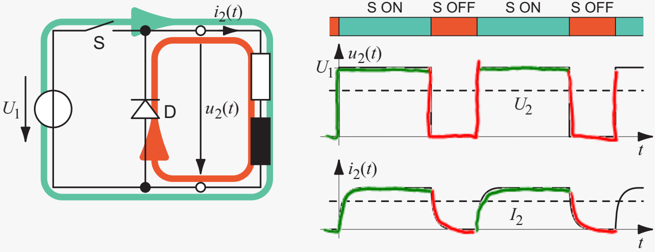

Figure Basic principle step-down converter with fly-back diode

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

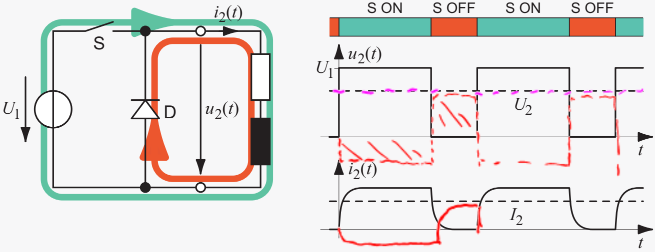


Figure Basic principle step-down converter with fly-back diode

Problems

L ← ① Pulsating voltage $u_2(t)$

C_2 ← ② Non-constant output current $i_2(t)$

- Switch opens:
  - ⇒ Circuit remains closed via load and fly-back diode

Fly-back Diode

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

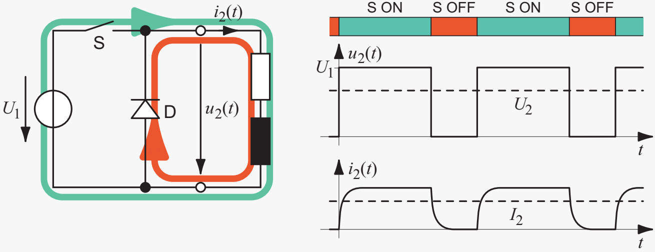


Figure Basic principle step-down converter with fly-back diode

- 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

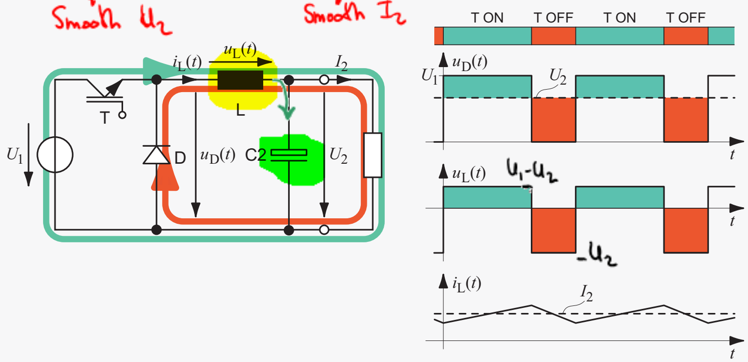


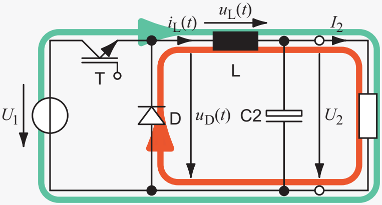
Figure Step-down converter with fly-back diode, smoothing inductance and output capacitor

$$u_D(t) = U_2 + u_L(t) \rightarrow u_L(t) = u_D(t) - U_2$$

$$T \text{ ON} \rightarrow u_D(t) = U_1 \rightarrow u_L(t) = U_1 - U_2$$

$$T \text{ OFF} \rightarrow u_D(t) = 0 \rightarrow u_L(t) = -U_2$$

Smoothing inductance and output capacitor



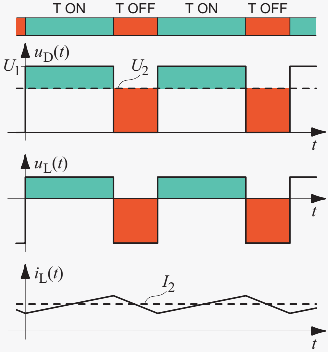


Figure Step-down converter with fly-back diode, smoothing inductance and output capacitor

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

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Smoothing inductance and output capacitor

Electrolytic capacitor (with fixed polarity)

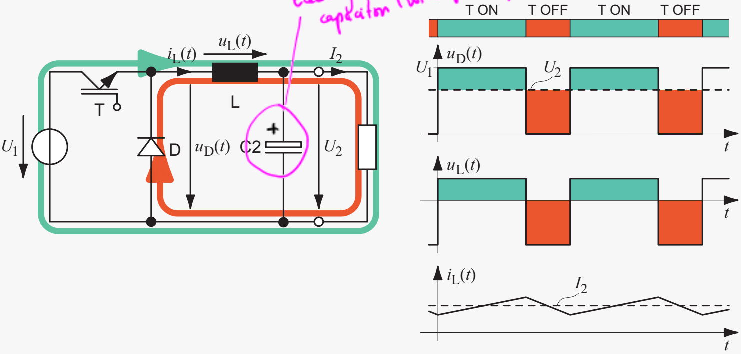

Figure Step-down converter with fly-back diode, smoothing inductance and output capacitor

- 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?

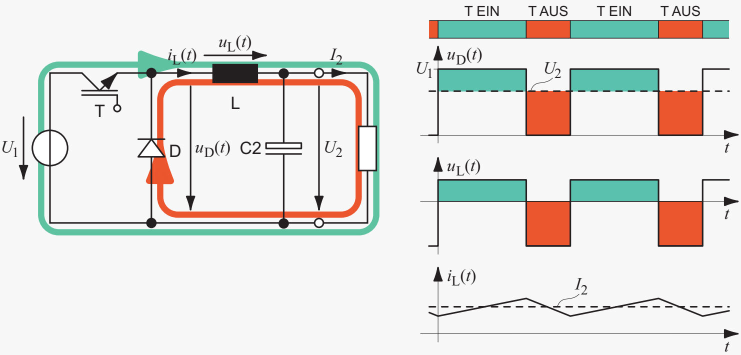

Figure Step-down converter with fly-back diode, smoothing inductance and output capacitor

Input Capacitor?

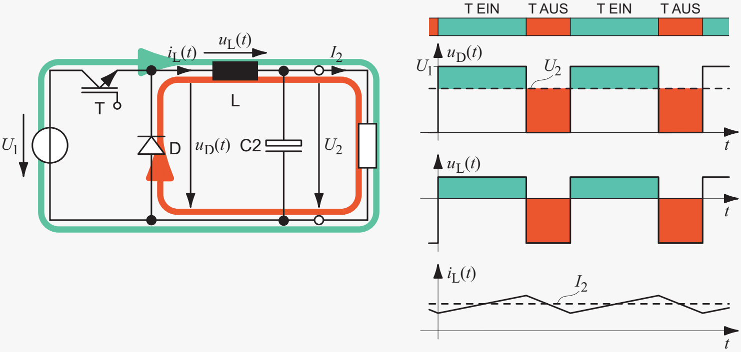

Figure Step-down converter with fly-back diode, smoothing inductance and output capacitor

- Collector current (= input current I_1) jumps!

Input Capacitor?

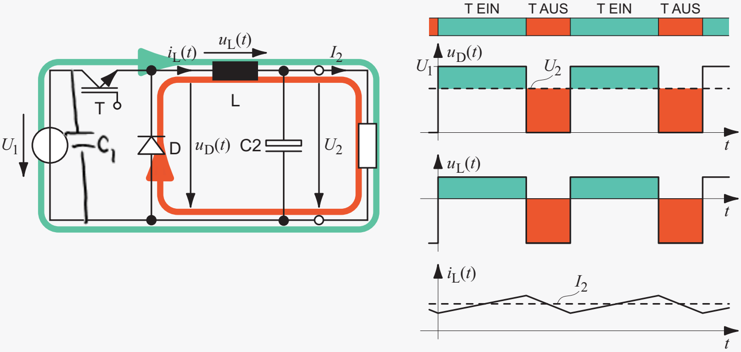

Figure Step-down converter with fly-back diode, smoothing inductance and output capacitor

- Collector current (= input current I_1) jumps!

⇒ Input capacitor to protect T necessary!

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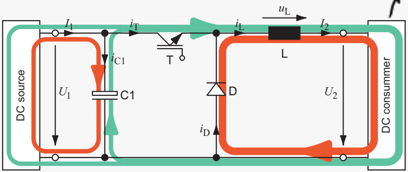
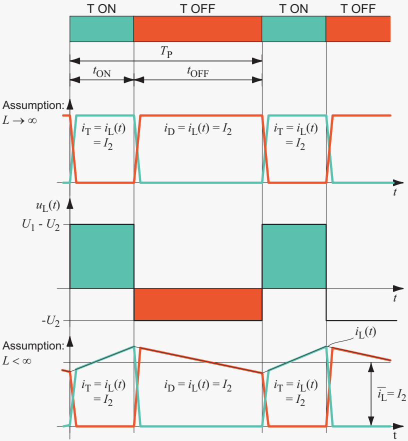
Step-down converter

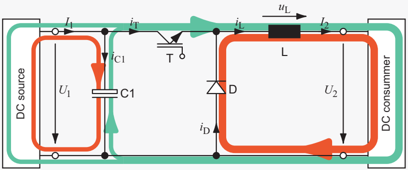
Including C_2





- $L \to \infty$: $i_L(t) = I_2 = \text{const.}$

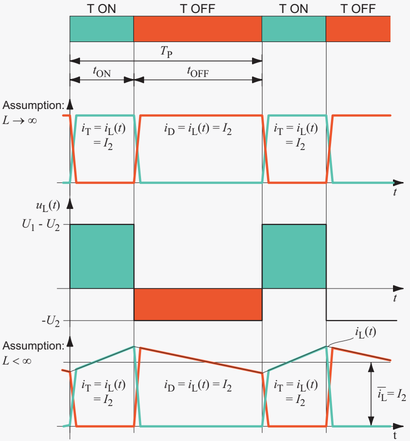
Step-down converter



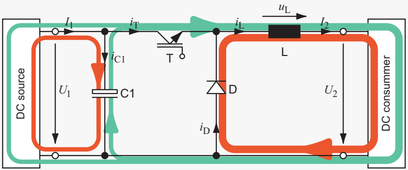
- $L \rightarrow \infty$: $i_L(t) = I_2$ = const.
- $U_2 \leq U_1$ or $I_2 \geq I_1$

Power balance: $U_1 \cdot I_1 = U_2 \cdot I_2$

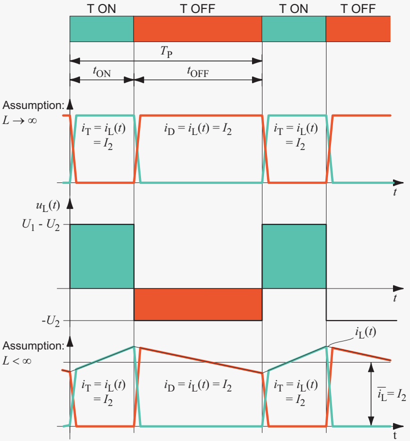
$\Rightarrow I_2 > I_1$



Step-down converter



- $L \rightarrow \infty$: $i_L(t) = I_2$ = const.
- $U_2 \leq U_1$ or $I_2 \geq I_1$
- ON state:
- OFF state:



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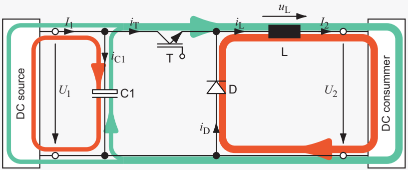
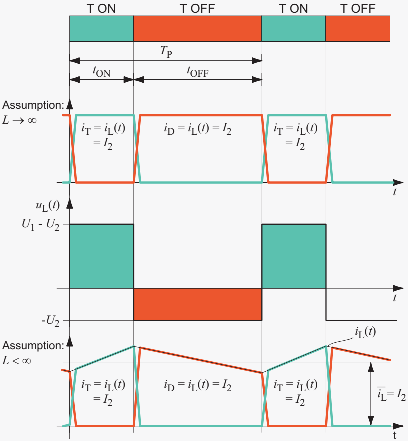
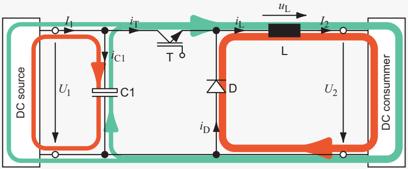
Step-down converter



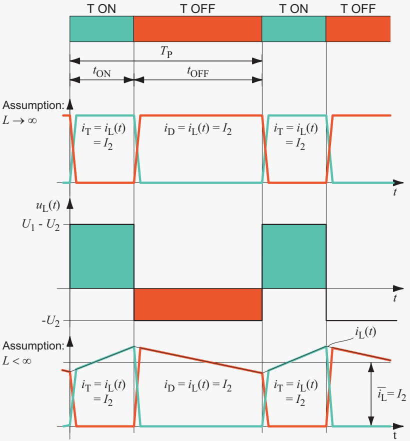


- $L \rightarrow \infty$: $i_L(t) = I_2 = \text{const.}$
- $U_2 \leq U_1$ or $I_2 \geq I_1$
- ON state: I_2
  - $I_1 - i_T = i_{C1} \rightarrow i_{C1} = I_1 - I_2 < 0$
- OFF state:

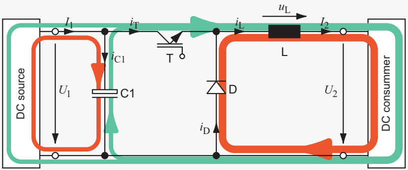
Step-down converter



- $L \rightarrow \infty$: $i_L(t) = I_2 = \text{const.}$
- $U_2 \leq U_1$ or $I_2 \geq I_1$
- ON state:
  - $I_1 - i_T = i_{C1} \rightarrow i_{C1} = I_1 - I_2 < 0$
- OFF state:
  - $I_1 - \cancelto{0}{i_T} = i_{C1} \rightarrow i_{C1} = I_1 > 0$

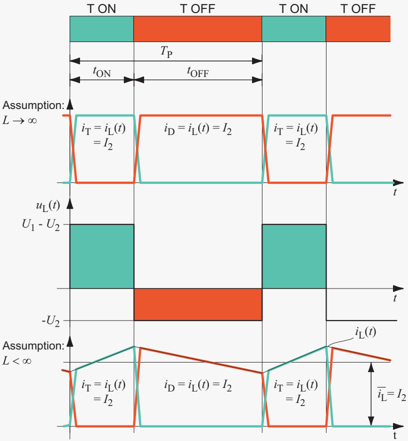


Step-down converter

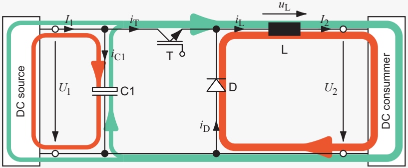


- $L \to \infty$: $i_L(t) = I_2 = \text{const.}$
- $U_2 \leq U_1$ or $I_2 \geq I_1$
- ON state:
  - $I_1 - i_T = i_{C1} \to i_{C1} = I_1 - I_2 < 0$
- OFF state:
  - $I_1 - i_T = i_{C1} \to i_{C1} = I_1 > 0$

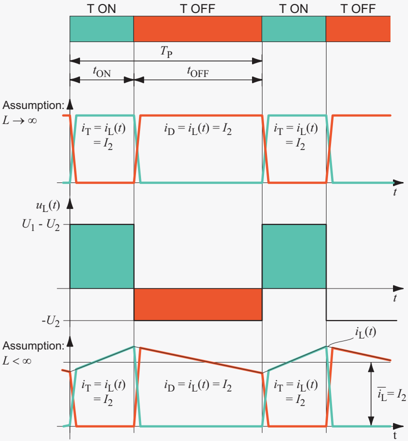
$\Rightarrow$ C_1 takes the charge $I_1 \cdot t_{OFF}$



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 $I_1 \cdot t_{OFF}$



Step-down converter

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

Step-down converter

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

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Step-down converter

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

" Duty cycle

↓ Relative ON-Time in a period

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

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

Step-down converter

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

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

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

Step-down converter

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

ON state ($u_D(t) = U_1$):

$$-U_1 + u_L(t) + U_2 = 0 \quad \Rightarrow \quad u_L(t) = U_1 - U_2$$

OFF state($u_D(t) = 0$):

$$u_L(t) + U_2 = 0 \quad \Rightarrow \quad u_L(t) = -U_2$$

$$\overline{u_L(t)} = 0 \quad \Rightarrow \quad (U_1 - U_2) \cdot t_{ON} - U_2 \cdot t_{OFF} = 0$$

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Step-down converter

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

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$$u_L(t) + U_2 = 0 \quad \Rightarrow \quad u_L(t) = -U_2$$

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Step-down converter

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

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$$u_L(t) + U_2 = 0 \quad \Rightarrow \quad u_L(t) = -U_2$$

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$$U_1 \cdot I_1 = U_1 \cdot \overline{i_T(t)} = U_2 \cdot I_2$$

Step-down converter

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

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

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

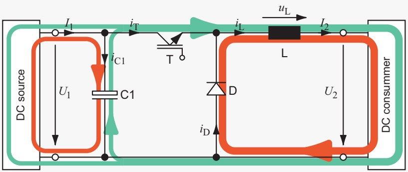
$$\overline{u_{\mathrm{L}}(t)} = 0 \quad \Rightarrow \quad (U_1 - U_2) \cdot t_{\mathrm{ON}} - U_2 \cdot t_{\mathrm{OFF}} = 0 \Rightarrow U_1 \cdot t_{\mathrm{ON}} = U_2 \cdot T_{\mathrm{P}} \Rightarrow \boxed{U_2 = U_1 \cdot \frac{t_{\mathrm{ON}}}{T_{\mathrm{P}}} = D \cdot U_1}$$

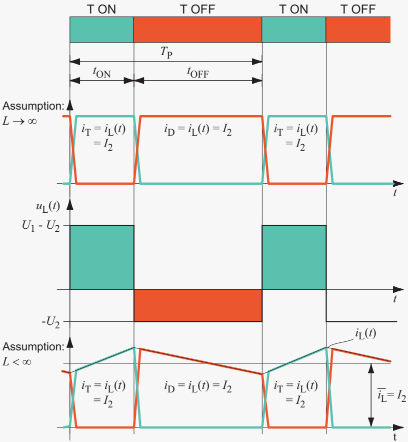
$$U_1 \cdot I_1 = U_1 \cdot \overline{i_{\mathrm{T}}(t)} = U_2 \cdot I_2$$

next step with $L < \infty$:

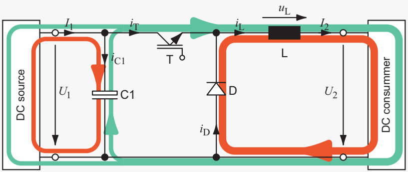
$$u_{\mathrm{L}}(t) = L \cdot \frac{\mathrm{d}i_{\mathrm{L}}}{\mathrm{d}t}$$

Step-down converter with $L < \infty$

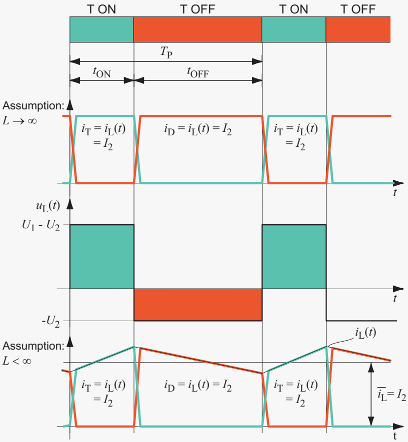




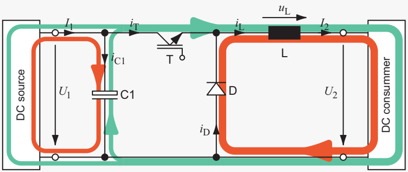
Step-down converter with $L < \infty$



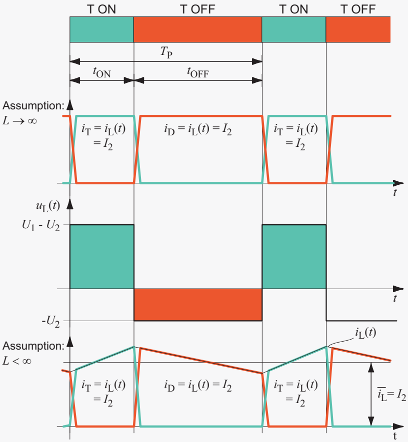
- ON state:



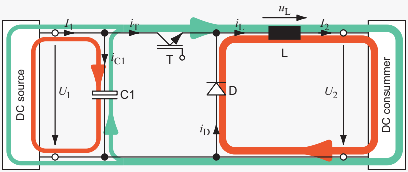
Step-down converter with $L < \infty$



- ON state:
  - $u_L(t) = U_1 - U_2 = L \cdot \frac{di_L}{dt}$

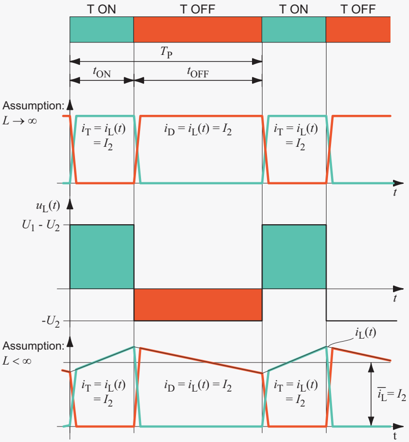


Step-down converter with $L < \infty$



- ON state:
  - $u_L(t) = U_1 - U_2 = L \cdot \dfrac{di_L}{dt}$

  $\Rightarrow \dfrac{di_L}{dt} > 0$ and constant



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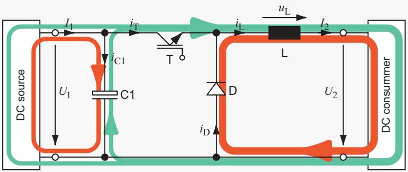
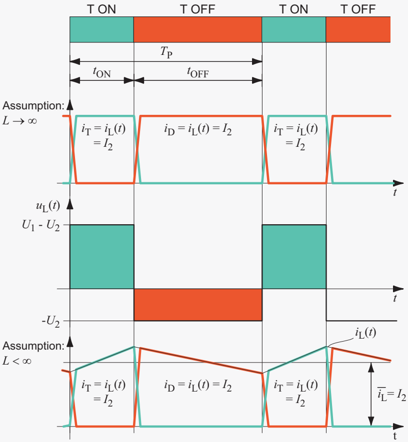
Step-down converter with $L < \infty$

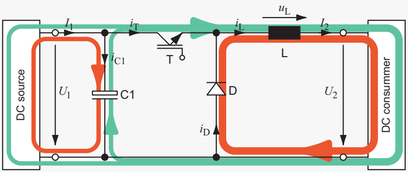




- ON state:
  - $u_L(t) = U_1 - U_2 = L \cdot \frac{di_L}{dt}$

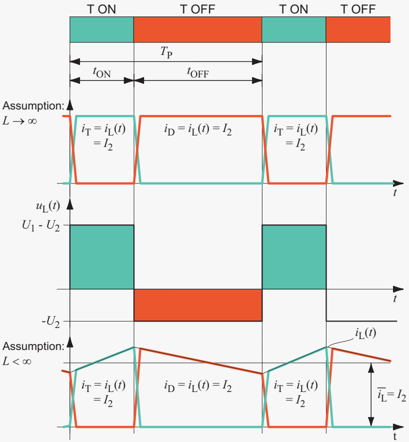
  $\Rightarrow \frac{di_L}{dt} > 0$ and constant
- OFF state:

Step-down converter with $L < \infty$

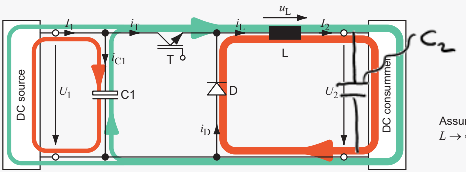


- ON state:
  - $u_L(t) = U_1 - U_2 = L \cdot \frac{di_L}{dt}$

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



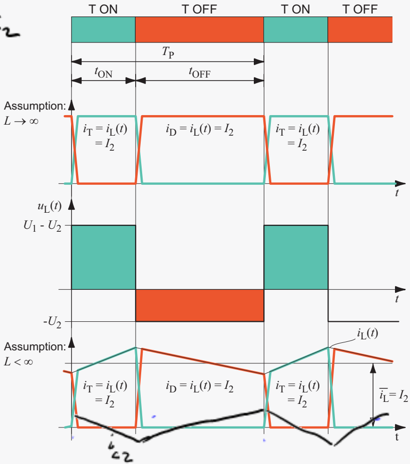
Step-down converter with $L < \infty$



- ON state:
  - $u_L(t) = U_1 - U_2 = L \cdot \frac{di_L}{dt}$

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

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



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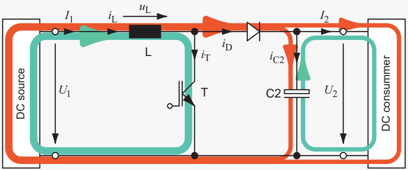
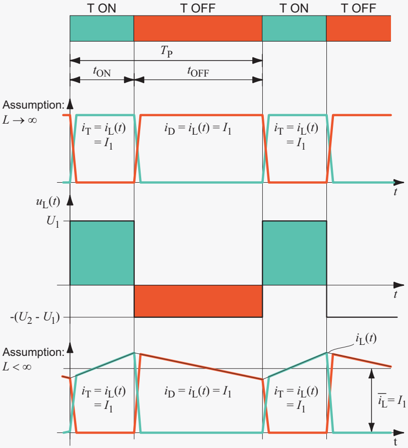
Fundamentals of power electronics for electric drives

Step-up converter



- $L \rightarrow \infty$: $i_L(t) = I_2$ = const.



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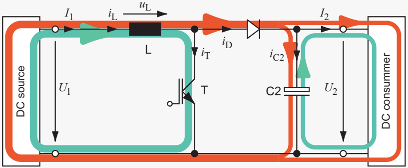
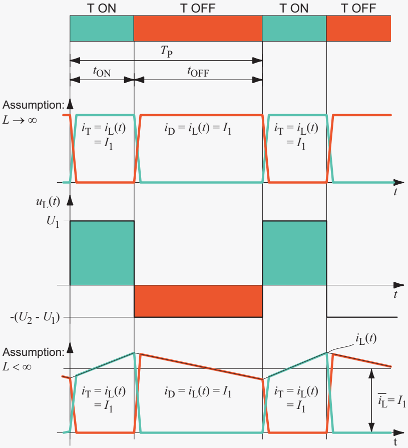
Step-up converter



- $L \to \infty$: $i_L(t) = I_2 = \text{const.}$
- $U_2 \geq U_1$ or $I_2 \leq I_1$

On the ON-State, L is charged.
On the OFF State L must
discharge ⇒ Increasing
the output voltage.



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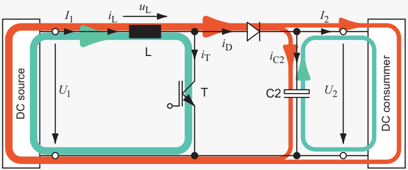

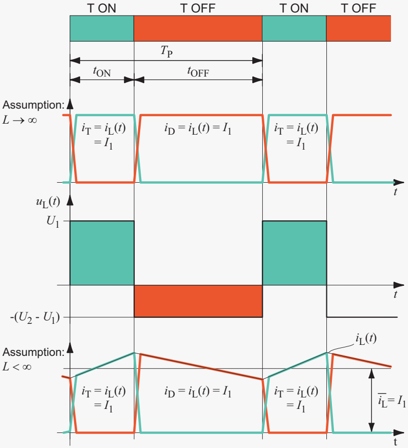

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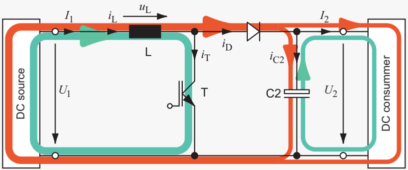
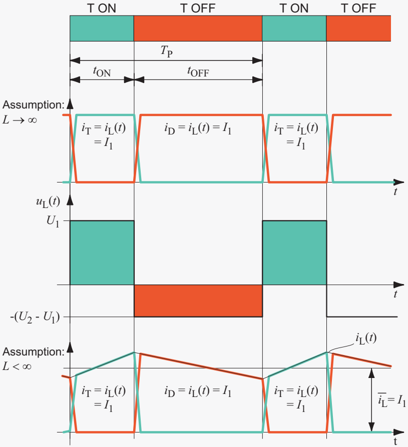
- $U_2 \geq U_1$ or $I_2 \leq I_1$
- ON state:
- OFF state:

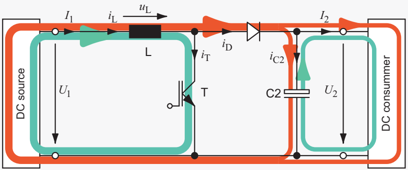
Step-up converter



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



Step-up converter



- $L \to \infty$: $i_L(t) = I_2 = \text{const.}$
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- ON state:
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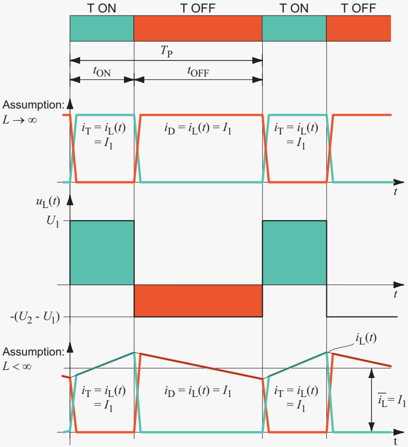
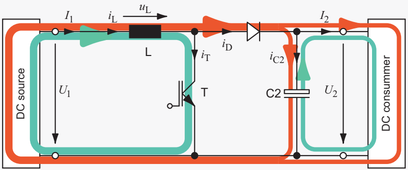
- OFF state:
  - $I_1 = I_2 + i_{C2} \to i_{C2} = I_1 - I_2 > 0$



Step-up converter



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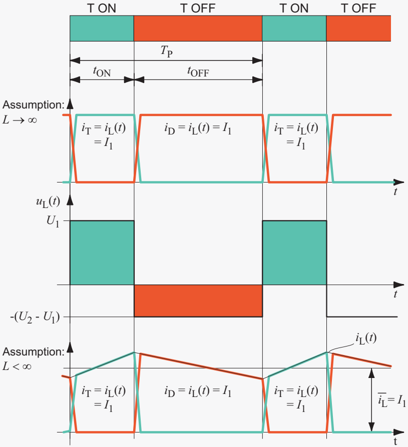
  $\Rightarrow$ C_2 takes up the charge $(I_1 - I_2) \cdot t_{OFF}$



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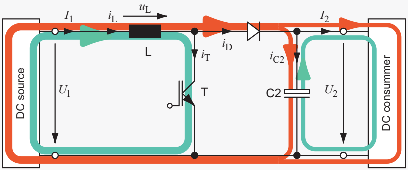
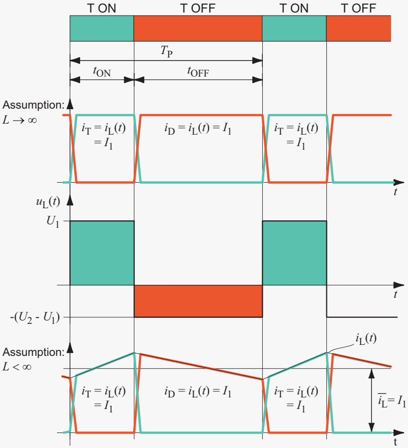
Step-up converter



- $L \to \infty$: $i_L(t) = I_2 =$ 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 $(I_1 - I_2) \cdot t_{OFF}$



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Step-up converter

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

Step-up converter

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

Step-up converter

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

Step-up converter

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

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

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Step-up converter

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

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Step-up converter

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

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

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

$0 < D < 1$

$U_1 < U_2 < \infty \leftarrow$ Only in theory. Components limit the output voltage

Step-up converter

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

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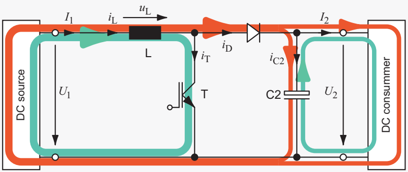
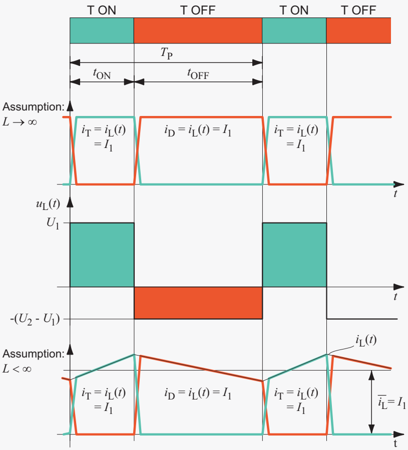
next step with $L < \infty$: $\quad u_{\mathrm{L}}(t) = L \cdot \frac{\mathrm{d}i_{\mathrm{L}}}{\mathrm{d}t}$

Step-up converter with $L < \infty$





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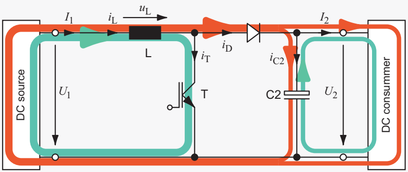
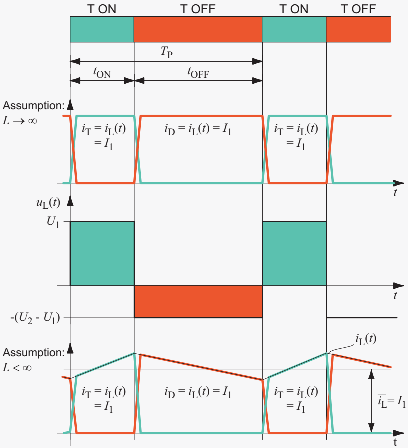


- State ON:



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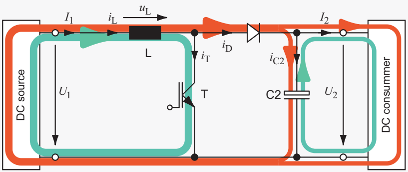
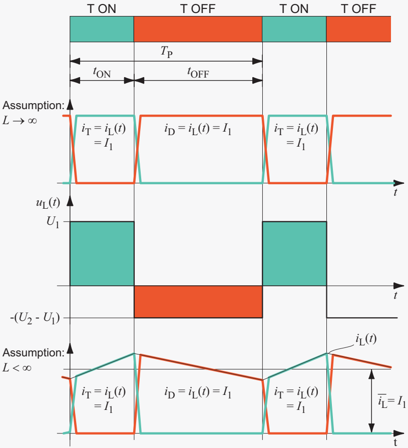
Step-up converter with $L < \infty$



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



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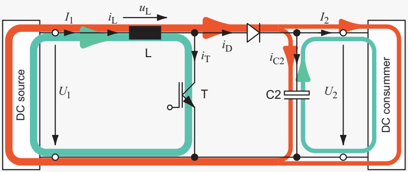
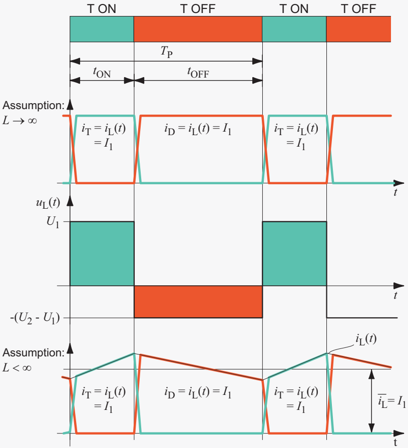


- State ON:
  - $u_L(t) = U_1 = L \cdot \dfrac{di_L}{dt}$

$\Rightarrow \dfrac{di_L}{dt} > 0$ and constant



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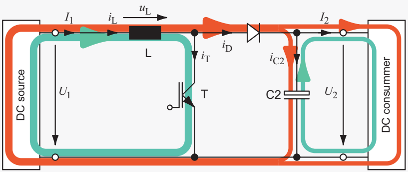

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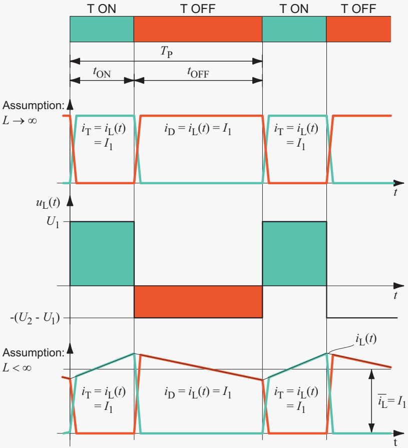

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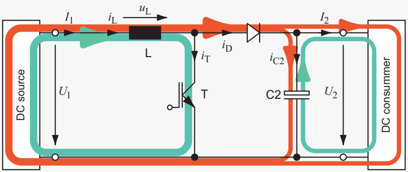
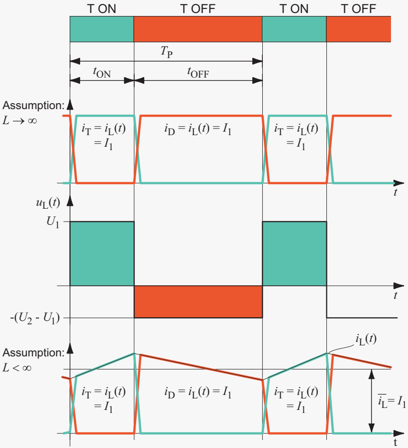


- State ON:
  - $$u_L(t) = U_1 = L \cdot \frac{di_L}{dt}$$
  - $$\Rightarrow \frac{di_L}{dt} > 0 \text{ and constant}$$
- OFF state:
  - $$u_L(t) = -(U_2 - U_1) = L \cdot \frac{di_L}{dt}$$



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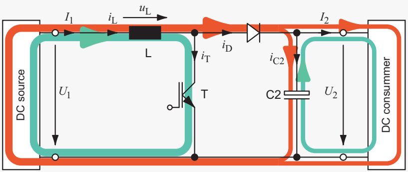

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  - $u_L(t) = U_1 = L \cdot \frac{di_L}{dt}$

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- OFF state:
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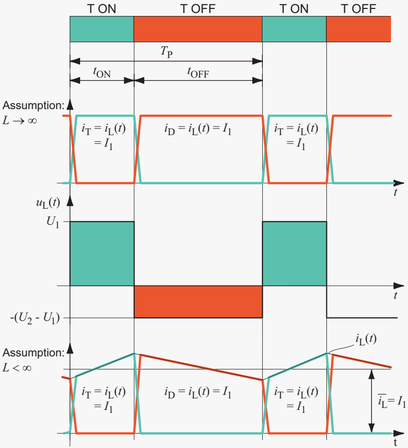
  $\Rightarrow \frac{di_L}{dt} < 0$ and constant



Fundamentals of power electronics for electric drives

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

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- Voltage = measure of speed
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⇒ with step-down or step-up converter only clockwise rotating motor operation

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

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- if both directions of rotation and torque are needed:
  - ⇒ both voltage AND both current directions necessary!

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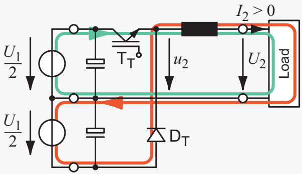
- if both directions of rotation and torque are needed:
  - ⇒ both voltage AND both current directions necessary!
  - ⇒ Four-quadrant controller (4QC)

2 x two-quadrant controllers...

modified step-down converter



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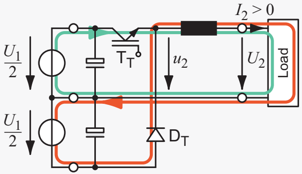
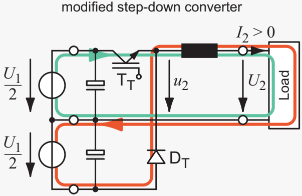
modified step-down converter



$I_2 > 0$

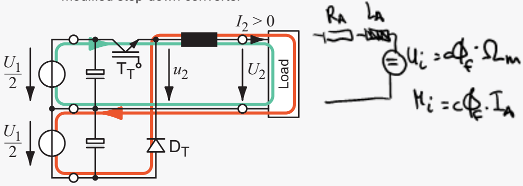
2 x two-quadrant controllers...

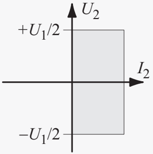


$$I_2 > 0: \quad U_2 = -\frac{U_1}{2} \ldots + \frac{U_1}{2} \quad (D = 0 \ldots 1)$$

2 x two-quadrant controllers...

modified step-down converter





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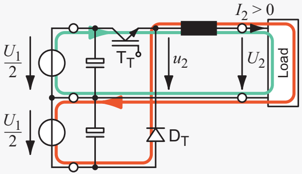
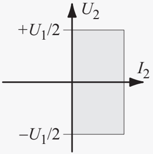
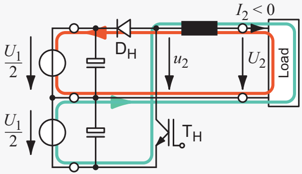




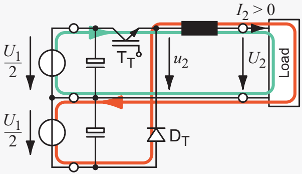
modified step-up converter

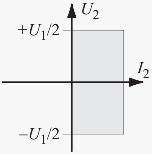


$$I_2 > 0: \quad U_2 = -\frac{U_1}{2} \ldots + \frac{U_1}{2} \quad (D = 0 \ldots 1) \quad I_2 < 0$$

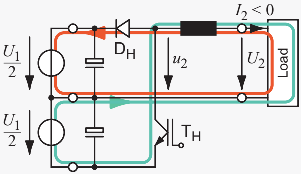
2 x two-quadrant controllers...

modified step-down converter





modified step-up converter



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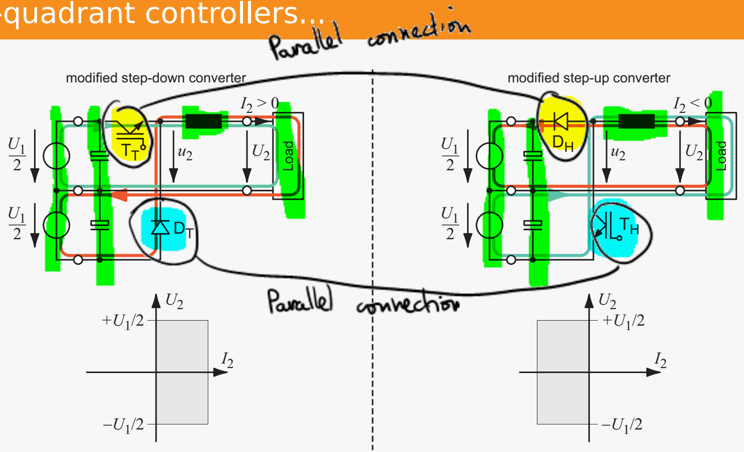
2 x two-quadrant controllers...



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

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

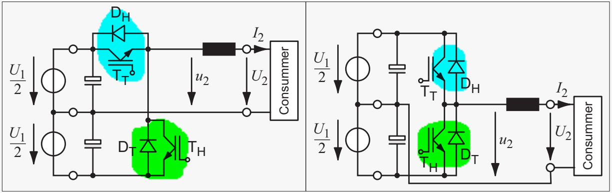


Figure Four-quadrant controller (half bridge)

- Transistors are fired alternately
- Current „finds“ its way

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T: Step-down converter ("Tief")
H: Step-up " ("Hoch")

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

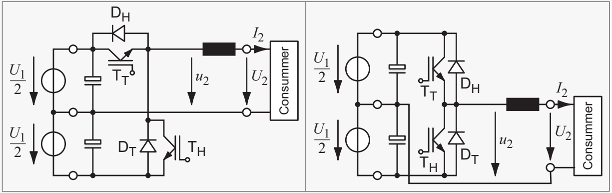

Figure Four-quadrant controller (half bridge)

- Transistors are fired alternately
- Current „finds“ its way

- T_T fired: $U_2 > 0$
- T_H fired: $U_2 < 0$

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

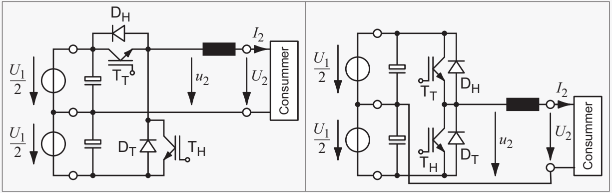

Figure Four-quadrant controller (half bridge)

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

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

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

Already 4QC
but with 2
problems:
- We need
two voltage
sources
- Voltage source
must be able to absorb current

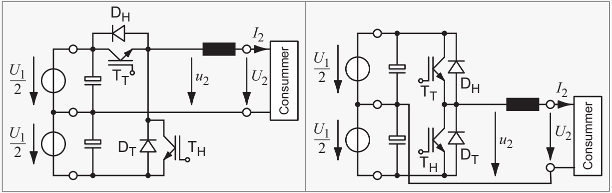
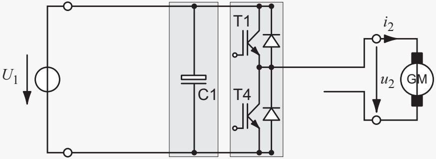


Figure Four-quadrant controller (half bridge)

- 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

2 x half-bridge = 1 x H-bridge



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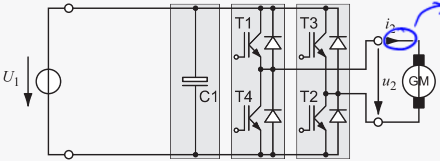
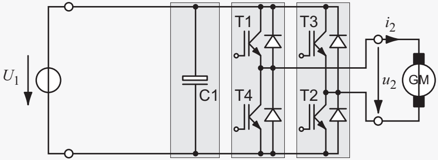
2 x half-bridge = 1 x H-bridge



Why not a smoothing coil?
Armature inductance is often enough
(Value of L influences
Δi → current ripple)

- Transistors are fired in pairs (T1/T2) vs. (T3/T4).
- $i_2 > 0$: T1/T2 (drive) or D3/D4 (fly-back)

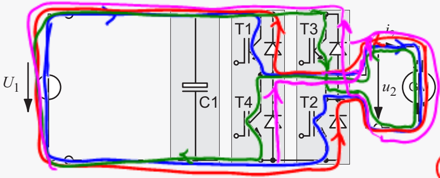
2 x half-bridge = 1 x H-bridge



- 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)

ttz-emo.thws

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)

U_M n

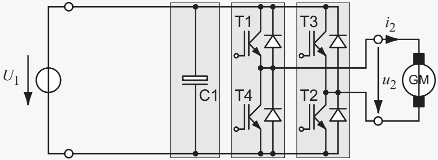
② T_1 & T_2 ON D_1 & D_2 conduct	① T_1 & T_2 ON T_1 & T_2 conduct
③ T_3 & T_4 ON T_3 & T_4 conduct	④ T_3 & T_4 ON D3 & D4 ON

M s I

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

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

2 x half-bridge = 1 x H-bridge

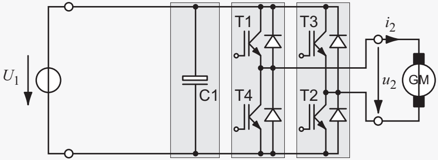


- Transistors are fired in pairs (T1/T2) vs. (T3/T4).
- $i_2 > 0$: T1/T2 (drive) or D3/D4 (fly-back)
- $i_2 < 0$: T3/T4 (drive) or D1/D2 (fly-back)

$$\overline{u_2(t)} = \frac{t_{ON}}{T_P} \cdot U_1 - \frac{t_{OFF}}{T_P} \cdot U_1 = \frac{t_{ON}}{T_P} \cdot U_1 - \frac{T_P - t_{ON}}{T_P} \cdot U_1 = \frac{2t_{ON} - T_P}{T_P} \cdot U_1$$

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

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)

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

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

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

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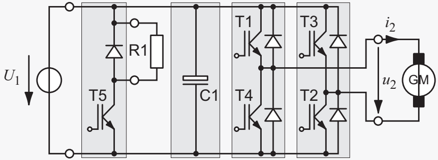
2 x half-bridge = 1 x H-bridge



- 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

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

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

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

Fundamentals of power electronics for electric drives

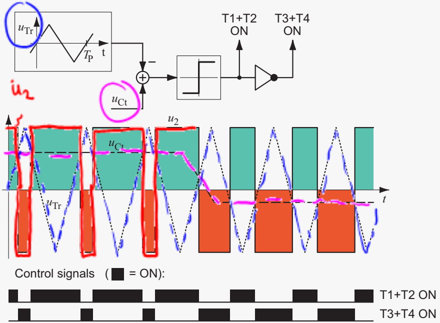
Modulation as basis for inverting

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)

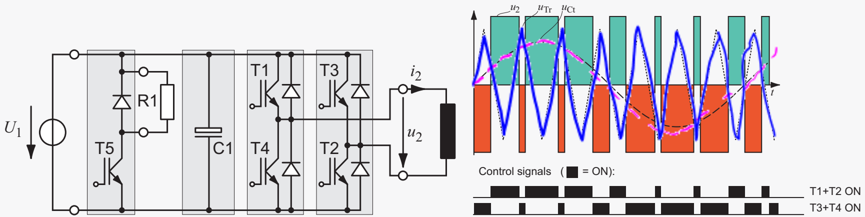


Figure Inverter with triangle modulation

Modulation of single-phase inverters (H-bridge)

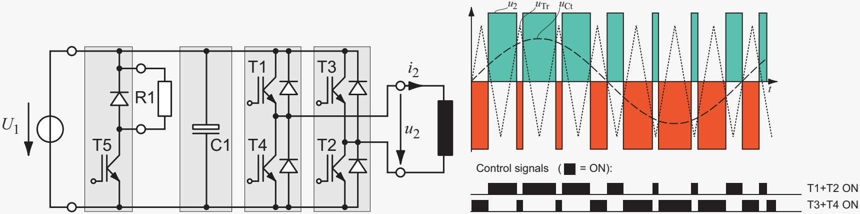


Figure Inverter with triangle modulation

- u_2 with fundamental component proportional to control voltage u_{Ct}.

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Modulation of single-phase inverters (H-bridge)

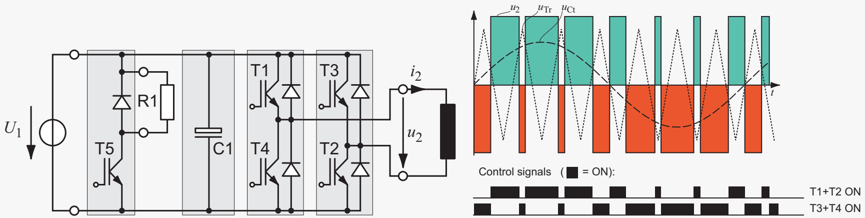


Figure Inverter with triangle modulation

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

Modulation of single-phase inverters (H-bridge)

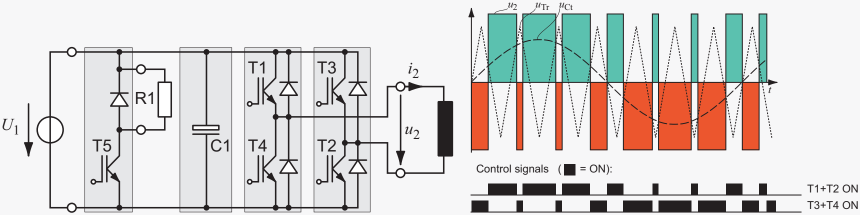


Figure Inverter with triangle modulation

- 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

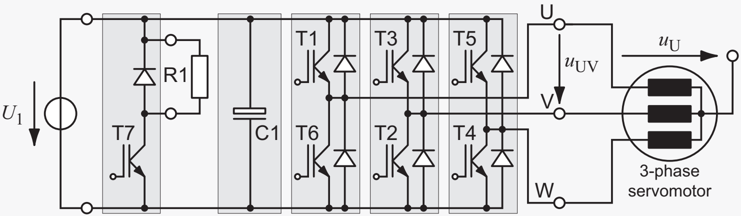


Figure Three-phase inverter with three-phase machine as load

Three-phase inverter

Supply of three-phase drives: three-phase inverter

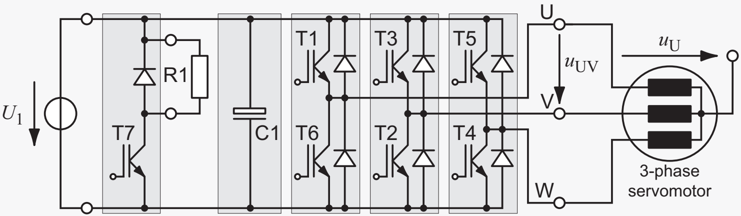


Figure Three-phase inverter with three-phase machine as load

- 120° offset on the voltages and currents

Three-phase inverter

Supply of three-phase drives: three-phase inverter

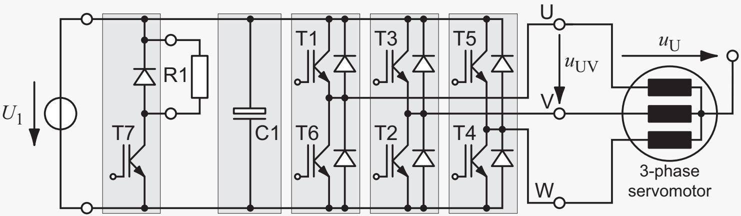


Figure Three-phase inverter with three-phase machine as load

- 120° offset on the voltages and currents
- Sum of phase currents always zero ⇒ only half bridges required

Three-phase inverter

Supply of three-phase drives: three-phase inverter

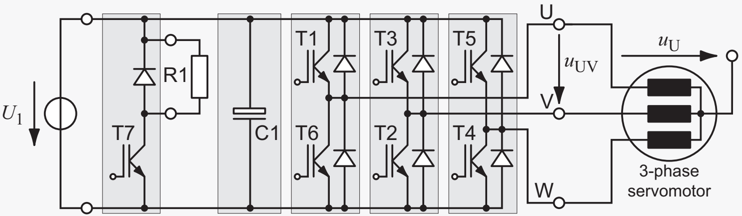


Figure Three-phase inverter with three-phase machine as load

- 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

Three-phase inverter

Supply of three-phase drives: three-phase inverter

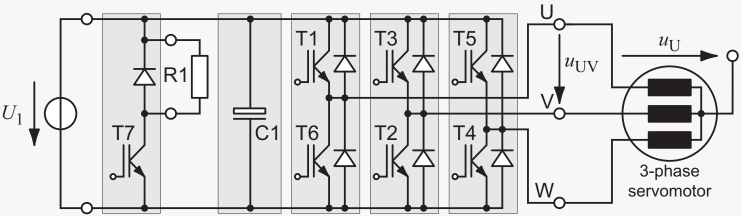


Figure Three-phase inverter with three-phase machine as load

- 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

Example 7-1: DC converter

Given the circuit and values in Figure 7.22. The idealized theory is assumed with the exception of a finitely large inductor.

U_2, I_2, U_1, I_1 are constants

i_L is not a constant

$\bar{u}_L = 0$, $\bar{i}_c = 0$

T ON: $U_1 = u_L + U_2$

$\Rightarrow u_L = U_1 - U_2 = 15V$

T OFF: $0 = u_L + U_2$

$u_L = -U_2 = -30V$

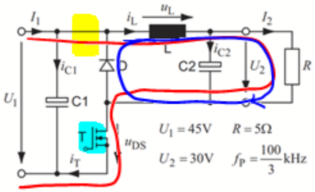


Figure 7.22: DC converter

a) Which basic converter type corresponds to this circuit? How was it varied?

b) Determine the DC input current I_1, the DC output current I_2, the on-time t_{ON} and the off-time t_{OFF} for the MOSFET T. How big is the inductor L if its current i_L may only vary by ± 0.5 A?

a) Buck or Step-down converter

- $U_2 < U_1$
- T is in series and D in parallel

Difference? T is in series with the negative terminal instead of with the positive

b) I_1? I_2? t_{on}? t_{off}?

$$I_2 = \frac{U_2}{R_2} = \frac{30V}{5\Omega} = \underline{\underline{6\,A}}$$

No losses in the circuit $\Rightarrow$ $U_1 \cdot I_1 = U_2 \cdot I_2$

$$I_1 = \frac{U_2 I_2}{U_1} = \frac{30V \cdot 6A}{45V} = \underline{\underline{4A}}$$

$$D = \frac{U_2}{U_1} = \frac{I_1}{I_2} = \frac{30V}{45V} = 2/3 = \frac{t_{ON}}{T_p} = t_{ON} \cdot f_p$$

Equation only valid for step-down converter

$$t_{ON} = 2/3 \cdot \frac{1}{f_p} = 2/3 \cdot \frac{1}{100/3\ kHz} = 20\mu s$$

$$\left(T_p = \frac{1}{f_p} = \frac{1}{100/3\ kH} = 30\mu s\right) \quad t_{OFF} = T_p - t_{ON} = T_p(1-D) = 10\mu s$$

T ON: $U_1 = u_L + U_2$

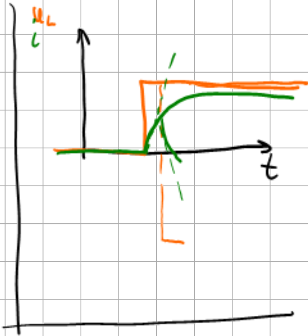
$\Rightarrow u_L = U_1 - U_2 = 15V$

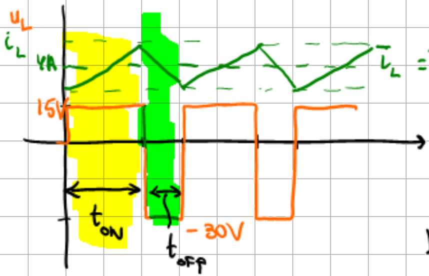
T OFF: $0 = u_L + U_2$

$u_L = -U_2 = -30V$

$$u_L = L \cdot \frac{di_L}{dt}$$

$$u_L = L \cdot \frac{\Delta i_L}{\Delta t}$$





$i_L = I_2 \Rightarrow \Delta i_L = \pm 0.5A = 1A$

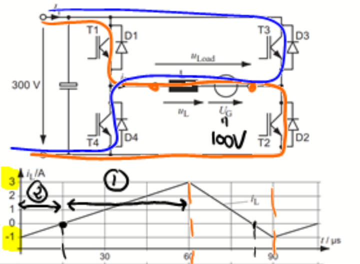
$$L = \frac{u_L \cdot \Delta t}{\Delta i_L} = \frac{15V \cdot 20 \cdot 10^{-6} s}{1A} = \frac{-30V \cdot 10 \cdot 10^{-6} s}{-1A}$$

$L = 0.3 mH$

Example 7-5: H-bridge

Given is the four-quadrant controller shown in Figure 7.26 with an oscillographed current curve.

a) Fill in the table!
b) What is the counter induced voltage U_G and the inductor L?



it is fired:		T1/T2	T3/T4	
it conducts:	D1 + D2	T1 + T2	D3+D4	$\longrightarrow T_3+T_4$
u_{Load} =		+ 300V	− 300V	
u_L =		+ 200V	− 400V	

Figure 7.26: four-quadrant controller

$$u_L = L\frac{di_L}{dt} = L\frac{\Delta i_L}{\Delta t}$$

if: $\frac{\Delta i_L}{\Delta t} > 0 \rightarrow u_L > 0$

T1 & T2 ON

if $i_L > 0$ $T_1 \& T_2$ conduct

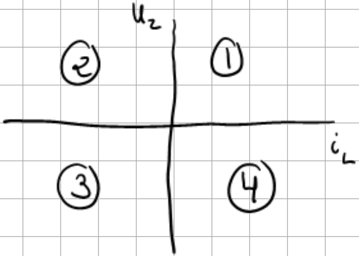
$i_L < 0$ $D_1 \& D_2$ conduct

$\frac{\Delta i_L}{\Delta t} < 0 \rightarrow u_L < 0$

T3 & T4 ON

if $i_L < 0$ $T_3 \& T_4$ conduct

$i_L > 0$ $D_3 \& D_4$ conduct



$$u_L = u_{Load} - U_G \quad \rightarrow \quad U_G ?$$

$$\underbrace{\bar{u}_L}_{0} = \bar{u}_{Load} - U_G \quad \rightarrow \quad U_G = \bar{u}_{Load} = \frac{1}{90\mu s} \cdot (300V \cdot 60\mu s - 300V \cdot 30\mu s)$$

$$= 100V$$

$$u_L = L \cdot \frac{\Delta i_L}{\Delta t} \quad \rightarrow \quad L = \frac{200V \cdot 60\mu s}{4A} = \underline{\underline{3mH}}$$