7 Basics of power electronics for electric drives

The task of power electronics is to supply electrotechnical devices (e.g. drives) with electrical energy in such a way that they can be operated with optimum efficiency. Depending on the voltage source from which a device is supplied and with which voltages and currents this device is to be supplied, a distinction is made between

- **rectifiers**: AC voltage system at the input, DC voltage system at the output
- **inverters**: DC voltage system at the input, AC voltage system at the 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)

The following power electronics components are then required for electric drives:

- **DC servo motors** require variable DC voltage
  - Regulators with DC supply
  - Rectifiers with AC supply
- **Synchronous servomotors** require 3-phase variable AC voltage
  - 3-phase inverter with DC supply
  - 3-phase rectifier + 3-phase inverter with AC supply

Since power electronic devices usually control or regulate the flow of energy between supply and consumer, they often act in a control loop that is often closed. Figure 7.1 shows the basic structure of power electronic devices.
The power level is very low up to the control unit (μW...mW), whereas the power level in the control unit for large devices is already kW. In this block, the control

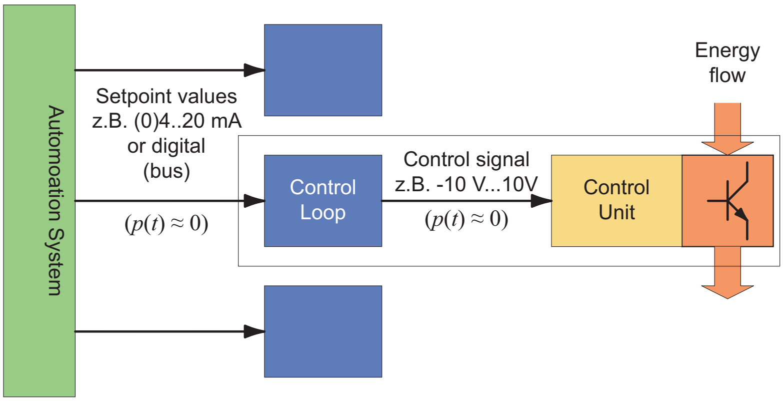


Figure 7.1: Basic structure of power electronic devices

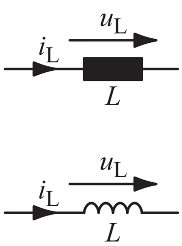
signals for the main switching elements are generated depending on the control variable. The actual control of the energy flow is carried out in the power unit, which means that the power level can reach the GW range.

The automation system consists of a process computer, which in large systems can consist of several processor modules that often interact with the field devices (drives, pneumatic elements, measuring transducers). At this point, however, the trend is clearly towards networking via bus systems (e.g. PROFIBUS DP, SERCOS, Interbus S, CAN bus or similar).

7.1 Passive components as energy storage

Although power electronics are based on active components, the passive components coil and capacitor play an indispensable role as energy storage in power electronic systems.

An **inductor (or coil)** stores energy in the form of magnetic field energy. The energy stored in the reactor is equal to the total work done, i.e. equal to the integrated instantaneous power $p(t)$:



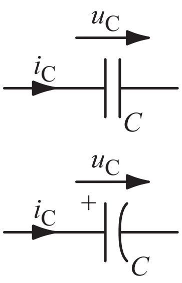
$$u_L(t) = L\frac{\mathrm{d}i_L}{\mathrm{d}t}$$

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

Figure 7.2: Voltage, current and energy of an inductor

The energy stored in the magnetic field changes with the square of the electric current. This magnetic energy stored in a coil means that the current cannot change abruptly when the voltage changes, but instead approaches its final value exponentially when the voltage changes abruptly. The voltage drop across an inductor is proportional to the change in current, i.e. if a pure direct current flows in the circuit, the voltage across a choke is equal to zero.

The second passive component that can be used to store energy is the **capacitor**. It consists of two mutually insulated surfaces that can absorb electrical charges. The different polarity of the charges on the two surfaces creates an electric field, so that an electric voltage results at the terminals. This voltage u_C is proportional to the total charge Q, but is smaller the larger the capacitor or the larger the capacitance.



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

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

Figure 7.3: Current, voltage and energy of a capacitor

Electrical energy can therefore be stored in the capacitor by „charging“ it with electrical charge carriers.

In summary, Figure 7.4 shows the relationships between current and voltage with periodic block pulse values:

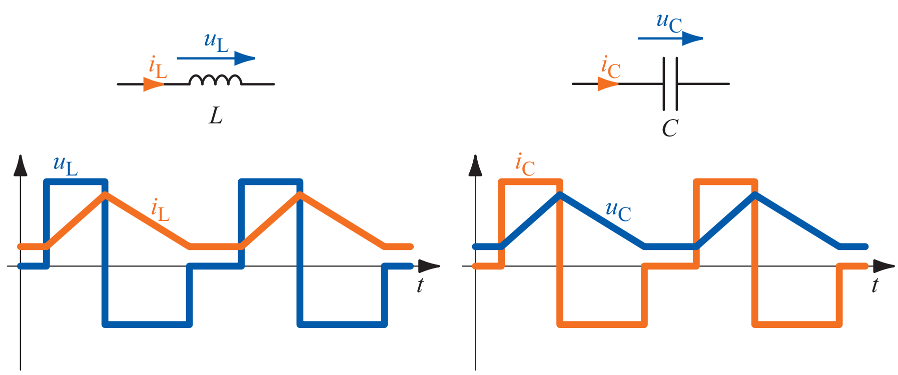


Figure 7.4: Current and voltage under pulsed operation

In the case of the inductor, the voltage is proportional to the change in current, whereas in the case of the capacitor, the current is proportional to the change in voltage. If an inductor or capacitor is operated in an AC network, there is a phase shift of 90 between voltage and current (Figure 7.5):

7.2 Active components of power electronics

Components in power electronics with which power flows can be controlled are also referred to as **valves**. A distinction is made here between non-controllable valves,

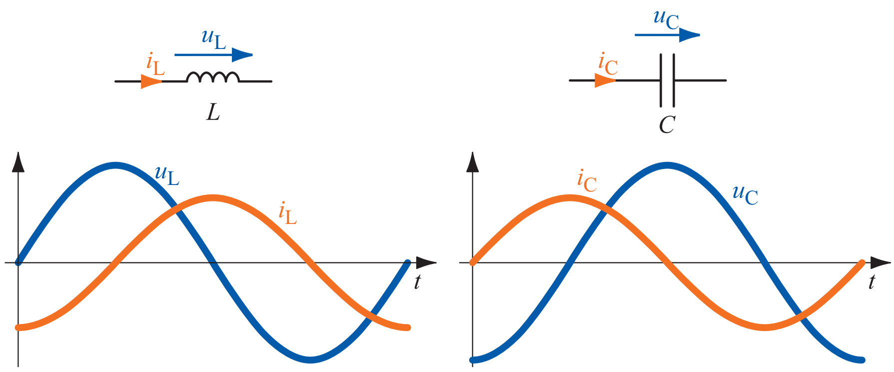


Figure 7.5: Current and voltage curves under sinusoidal operation

valves that can be switched on and valves that can be switched on and off.

Diodes are used e.g. for the rectification of AC voltages or to generate a DC voltage from an AC voltage network. The diode has no control input and is therefore a non-controllable valve. A diode only starts to conduct when the voltage U_{AK} (from the anode to the cathode) is positive (Figure 7.6).

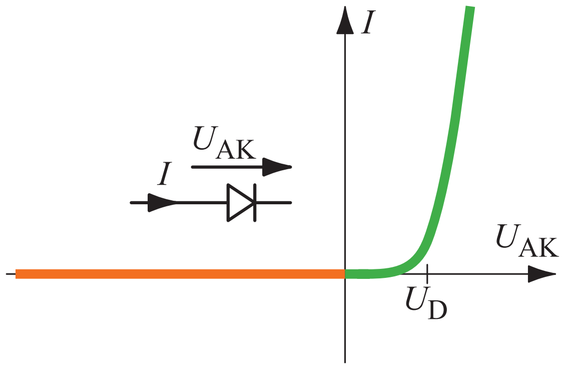


Figure 7.6: Diode characteristic

The thyristor is one of the valves that can be switched on. In contrast to the diode the thyristor also blocks in the initial state with a positive anode-cathode voltage U_{AK} (blocking state). If a positive current pulse is applied to the gate of the thyristor, the thyristor fires and remains conducting until either the anode current has fallen below a holding current I_{H} or a negative anode-cathode voltage U_{AK} is present. It cannot(!) be switched off from the outside, since the thyristor must first be brought into the blocking state before it can absorb a blocking voltage!
A thyristor can only carry a current in the direction from the anode to the cathode and behaves like a diode with a negative anode-cathode voltage U_{AK}, independent of the gate current.

It is important to comply with the cyclical sequence shown in Figure 7.8 forward blocking - conducting - reverse blocking - forward blocking - etc., since a positive voltage can only be blocked if the thyristor was previously in the blocking state. For this purpose, the external circuitry must ensure that before the blocking voltage is picked up, the current first extinguishes and then a negative voltage from the anode to the cathode must be present for a minimum period of time. For this reason, thyristors are mainly used in circuits that are fed from an AC voltage network.

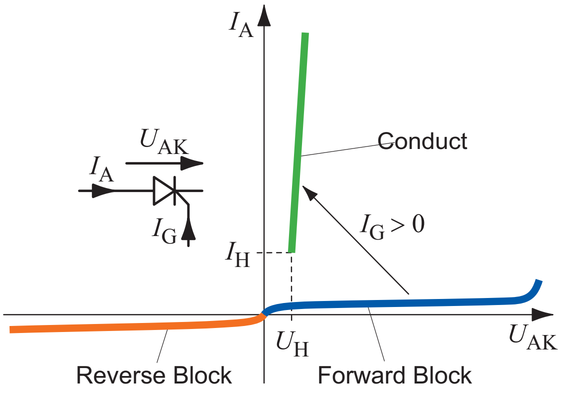


Figure 7.7: Comparison thyristor/modified non-return valve

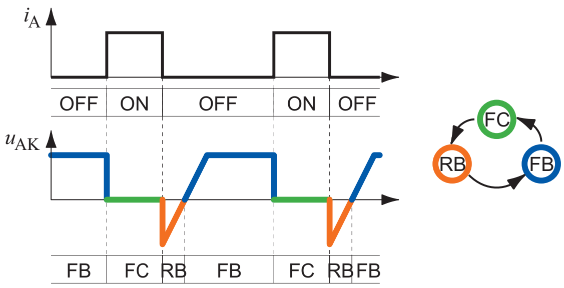


Figure 7.8: State diagram thyristor

The most important valves, which can not only be switched on but also switched off, are shown with their circuit diagrams Figure 7.9.

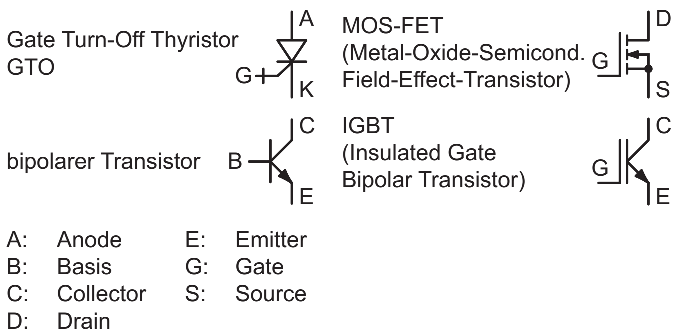


Figure 7.9: valves that can be switched on and off

These elements can be directly switched from the conducting state to the blocking state.

The GTO thyristor has a similar structure to a „normal“ thyristor, but can be switched off via a negative voltage pulse. GTOs were the first turn-off circuit switches, but they can only be used with switching frequencies of $200 \ldots 400\,\mathrm{Hz}$. Today, GTOs are only used for very high outputs (> $1\,\mathrm{MW}$).

Bipolar transistors are used in the first servo converters with powers of up to a few $10\,\mathrm{kW}$ with switching frequencies from initially $1.5\,\mathrm{kHz}$ to later $8\,\mathrm{kHz}$ (rarely until $20\,\mathrm{kHz}$) have been used. However, they are rarely used nowadays due to their high losses.

MOSFETs enable very high switching frequencies (> $50\,\mathrm{kHz}$) with, however, relatively low power ($U_{\mathrm{DS,max}} \approx 250\,\mathrm{V}$, $I_{\mathrm{D,max}} \approx 150\,\mathrm{A}$), so that they are primarily used in low voltage power supplies or in the automotive area.

The IGBT combines the advantages of a bipolar transistor (low conduction losses) with those of a MOSFET (practically powerless control), so that today it has already replaced the GTO on the market in the power range up to approx. $1\,\mathrm{MW}$.

State of the art are silicon-based valves. A few years ago, new developments brought about components based on silicon carbide technology SiC. SiC is characterized by a larger band gap, which is why they are significantly thinner and therefore have lower losses with the same dielectric strength. In addition, they have a faster switching capability and better temperature resistance than silicon components. It can be assumed that SiC will have a major impact on power electronics in a few years. Furthermore, new components based on galium nitrite, GaN for short, are currently entering the market. These components also have a large band gap and are of particular interest in the lower voltage range of up to approx. 600 V and can be operated at very high switching frequencies.

7.3 DC converters and pulse-controlled inverters

For electric drives, a variable DC converter is required to control DC servo motors. Pulse-controlled inverters are required to control synchronous servomotors with an AC voltage that can be changed in effective value and frequency. The needed configuration of power electronic switches and passive elements for these functions will be discussed now. For the following consideration, some idealizations are used (**idealized theory**):

- Considered semiconductor elements:
  - Only switches (IGBT/MOSFET) that can be switched on and off and diodes
  - Ideal switches (no voltage drop in the conducting state, absolutely currentless in the 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 the steady state is considered
  - $\Rightarrow$ Periodic time curves for current and voltage
  - $\Rightarrow$ Mean value of the inductor voltages and the capacitor currents is equal to zero!
- Inductors: initially an infinitely large inductance, i.e. practically $L \to \infty$
  - $\Rightarrow$ current through the inductor $i_\mathrm{L} = \mathrm{const.}$, i.e. without alternating component

These prerequisites are no longer permissible if power electronic circuits are to be developed. However, these strongly idealized prerequisites are absolutely permissible and very useful for explaining the basic concepts.

The step-down converter and the step-up converter are now explained as the two simplest DC converters. A combination of one variant of the step-down converter and the step-up converter results in the four-quadrant converter that is used for **DC servo motors**.

The four-quadrant converter can also be operated as a single-phase inverter. If you then combine three such single-phase inverters, you get an inverter with which a three-phase AC voltage system of variable voltage and frequency can be generated with suitable pulse modulation. These three-phase inverters are used as **actuators for synchronous servo motors**.

7.3.1 Step-down converter (buck converter)

The step-down converter is a DC converter that generates a pulsed output voltage $u_2(t)$ from a DC voltage U_1, the mean value of which U_2 is smaller than the input voltage. In the basic principle shown here, the switch S is periodically switched on and off, so that with a purely resistive load in Figure 7.10 the current $i_2(t)$ qualitatively has the same profile as the voltage $u_2(t)$ must have.

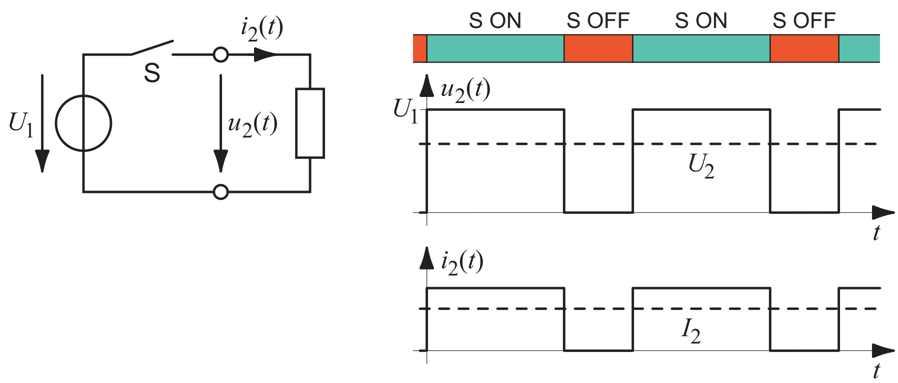


Figure 7.10: Basic principle step-down converter

When switching off mechanical switches, a switching spark can very often be observed, which increases with the size of the current to be switched off and the speed with which the current is switched off. A magnetic field is always associated with every current-carrying conductor, so that every cable represents an additional parasitic inductance. A wire of $10\,\mathrm{cm}$ length has an inductance of approximately $100\,\mathrm{nH}$. If a current of $100\,\mathrm{A}$ is switched off in this supply line within $100\,\mathrm{ns}$, then there is a voltage on this piece of wire during the switching process of

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

From this it follows that the load current cannot be abruptly reduced, particularly in the case of a load with an inductive component (this includes all electromechanical energy converters!). This problem can be solved in Figure 7.11 by a „**fly-back diode**“ connected in parallel to the load.
If the switch is opened, the circuit remains closed via the load and the fly-back diode. The energy stored in the inductance is dissipated in the resistor in the form of heat loss. Both the current increase when switching on and the current drop when switching off are exponential. If the diode were left out, the same course would result when switching on, but the abrupt switch-off would result in a very large voltage $u_2(t)$, which would inevitably destroy the electronic switch.
If a constant DC voltage U_2 is to be guaranteed at the output of the buck converter, a smoothing inductor L must be provided, as shown in Figure 7.12, which

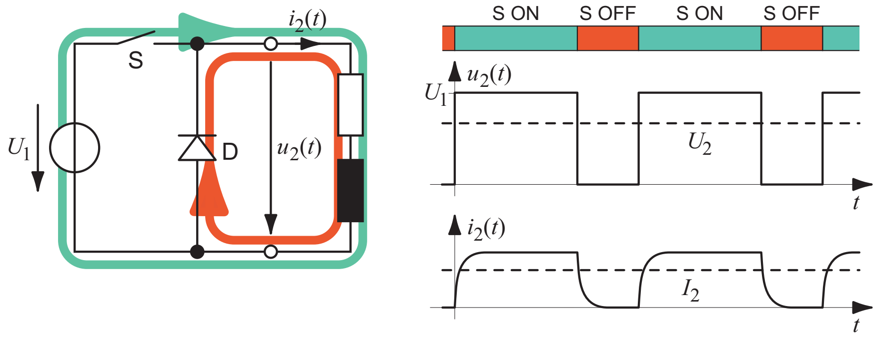


Figure 7.11: Basic principle step-down converter with fly-back diode

absorbs the harmonics of the voltage curve $u_\mathrm{D}(t)$. The mean value of the voltage $\overline{u_\mathrm{L}(t)}$ is zero, so that this measure definitely reduces the harmonic content of U_2.

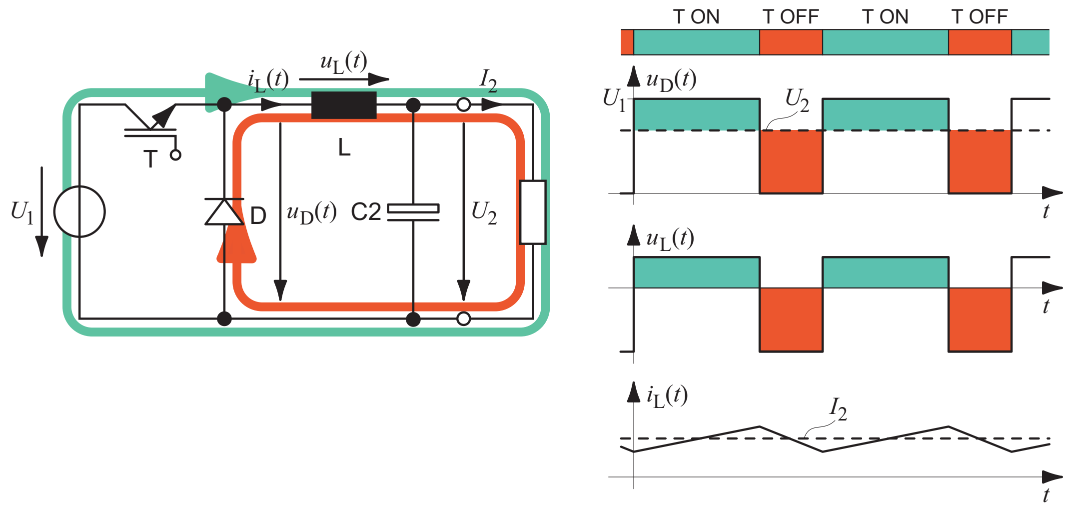


Figure 7.12: Step-down converter with fly-back diode and smoothing inductor and output capacitor

If the output current I_2 is also to remain constant, a capacitor C_2 is also required at the output to absorb the harmonics of $i_\mathrm{L}(t)$.
In the structure according to Figure 7.12, however, the voltage source U_1 is loaded with a pulsating current. As a rule, this is not permissible simply because of parasitic lead inductances. For this reason, an input capacitor C_1 must be provided for the buck converter, as in Figure 7.13, which absorbs the alternating component of the current $i_\mathrm{T}(t)$.

In order to also be able to describe the step-down converter quantitatively, the inductor L is assumed to be infinitely large, so that the current $i_\mathrm{L}(t)$ can be assumed to be constant. To discuss the circuit, node and mesh equations must be set up and evaluated, whereby a distinction must be made between two different states: T switched on or off.

With the transistor on, the inductor current flows through the transistor through the inductor and the load and then back to the source. Since the output current of the buck converter is greater than the input current, the difference is provided by the input capacitor C_1, the amount of charge of which is reduced by $(I_2 - I_1) \cdot t_\mathrm{ON}$.

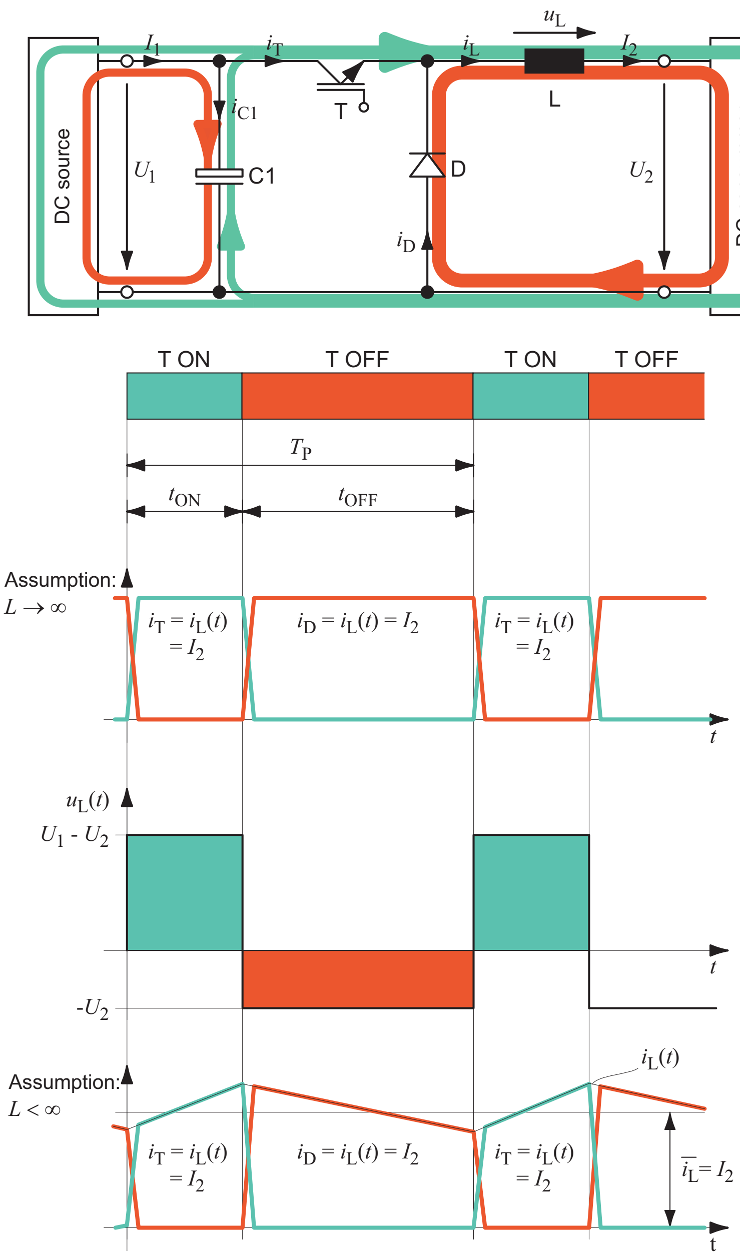


Figure 7.13: Step-down converter

If the transistor is switched off, the circuit closes through the fly-back diode D, so that the current i_L commutes to the diode immediately. During the time t_{OFF}, the capacitor C_1 is recharged with the input current I_1, so that the amount of charge is again increased by $I_1 \cdot t_{OFF}$. The charge dissipated during the time t_{ON} must be the same as the power dissipated during the time t_{OFF} so that the voltage U_1 can remain constant even with a very large capacitor C_1 :

$$(I_2 - I_1) \cdot t_{ON} = I_1 \cdot t_{OFF} \quad \Rightarrow \quad I_2 \cdot t_{ON} = I_1 \cdot (t_{ON} + t_{OFF}) \quad \Rightarrow \tag{7.1}$$

$$I_1 = I_2 \cdot \frac{t_{ON}}{T_P} \quad = \quad D \cdot I_2 \qquad\qquad D\text{: duty cycle}$$

The voltage drop across the inductor (T switched on) can be written from the mesh equation:

$$-U_1 + u_\mathrm{L}(t) + U_2 = 0 \quad \Rightarrow \quad u_\mathrm{L}(t) = U_1 - U_2 \tag{7.2}$$

If the transistor is then switched off, the inductor current cannot change under any circumstances because of the large inductance. Thus, after the transistor has been switched off, the inductor current must be „offered“ a new current path via the „fly-back diode“ D.

If this fly-back diode were not present, the inductor current would have to drop to zero very quickly. However, the magnetic energy stored in the inductor would have to be dissipated just as quickly.

However, there is no electrical consumer in the entire circuit that could dissipate this energy in the short time. A real implemented transistor does not switch on immediately from the conductive state to the blocking state, but during this state change the voltage between collector and emitter increases and the load current also flows. The resulting power loss (transistor current i_T · collector-emitter voltage u_CE) is then briefly so high that the transistor would be destroyed.

As soon as the transistor blocks and the fly-back diode must then conduct ($u_\mathrm{D} = 0$), the following equation applies:

$$u_\mathrm{L}(t) + U_2 = 0 \quad \Rightarrow \quad u_\mathrm{L}(t) = -U_2 \tag{7.3}$$

The mean value over time for the voltage at the inductor must be zero so that the current does not change even after a very long time:

$$(U_1 - U_2) \cdot t_\mathrm{ON} - U_2 \cdot t_\mathrm{OFF} = 0 \Rightarrow U_1 \cdot t_\mathrm{ON} = U_2 \cdot T_\mathrm{P} \Rightarrow U_2 = U_1 \cdot \frac{t_\mathrm{ON}}{T_\mathrm{P}} = D \cdot U_1 \tag{7.4}$$

The switch-on time $t_\mathrm{ON}/T_\mathrm{P}$ related to the period duration is referred to as the duty cycle D, so that with a duty cycle of $D = 0...1$ the output voltage U_2 can be continuously adjusted in the range of $0...U_1$.

Only ideal components are considered in this circuit, so that the power $U_1 \cdot I_1$ fed in at the input terminals must be equal to the power $U_2 \cdot I_2$ at the output. The following therefore applies:

$$U_1 \cdot I_1 = U_1 \cdot \overline{i_\mathrm{T}(t)} = U_2 \cdot I_2 \tag{7.5}$$

Only because of the capacitor C_1 at the input is it possible that the input current is a temporally constant direct current. If this capacitor were not present, the input current I_1 would have to pulsate, which would lead to voltage peaks with the always present supply line inductances.

If a finitely large inductor is now to be taken into account, the same mesh circuits and thus also the same voltage curves when the transistor is switched on and off result. Only the current curves have to be different now, since the change in current in an inductor is proportional to the applied voltage:

$$u_\mathrm{L}(t) = L \cdot \frac{\mathrm{d}i_\mathrm{L}}{\mathrm{d}t} \tag{7.6}$$

The voltage at an the inductor $u_\mathrm{L}(t)$ consists of individual pulse blocks of constant amplitude, so that the current curves must consist of straight sections. In addition, on the one hand the mean value of the current $i_\mathrm{L}(t)$ must remain the same because of the power balance and on the other hand the mean current must be constant because of the inductor. This means that the current curve can also be sketched for a inductor of finite size in the lower part of Figure 7.13.

7.3.2 Step-up converter (boost converter)

The step-up converter is also a DC converter that generates an output voltage $U_2 > U_1$ from an input voltage U_1. The smoothing inductor L is in the input circuit, so that the inductor current $i_L(t)$ either flows to ground when the transistor is switched on or when the transistor is switched off, via the diode to the load.

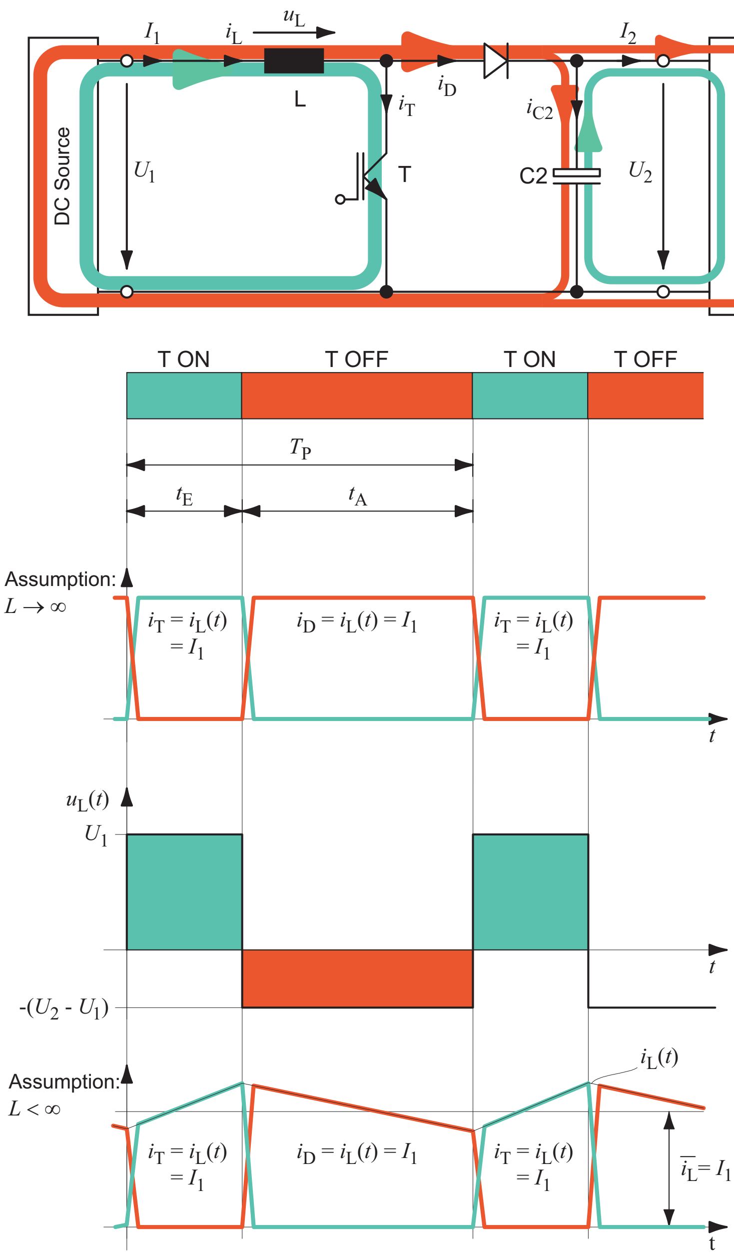


Figure 7.14: boost converter

If the smoothing reactor is infinitely (or very) large, the input variables U_1 and I_1 can actually be constant. However, since the diode only conducts a current when the transistor is blocking, a smoothing capacitor C_2 must be present at the output because of the pulsating diode current i_D.

During the time t_{ON} the amount of charge $I_2 \cdot t_{ON}$ is released from the capacitor

C_2 and during the time t_{OFF} the charge quantity $(I_1 - I_2) \cdot t_{\mathrm{OFF}}$ added. The mean value of the amount of charge absorbed is zero in the steady state:

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

$$\Rightarrow \qquad I_2 = I_1 \cdot \frac{T_{\mathrm{P}} - t_{\mathrm{ON}}}{T_{\mathrm{P}}} = (1 - D) \cdot I_1 \tag{7.7}$$

To determine $u_{\mathrm{L}}(t)$, the mesh equations for the state T ON and T OFF are set up:

$$\begin{aligned} \text{T ON:} \quad & -U_1 + u_{\mathrm{L}}(t) = 0 && \Rightarrow \quad u_{\mathrm{L}}(t) = U_1 \\ \text{T OFF:} \quad & -U_1 + u_{\mathrm{L}}(t) + U_2 = 0 && \Rightarrow \quad u_{\mathrm{L}}(t) = -(U_2 - U_1) \end{aligned}$$

The mean value of the inductor voltage $\overline{u_{\mathrm{L}}(t)}$ must be zero in the steady state:

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

$$\Rightarrow \qquad (U_2 - U_1) \cdot t_{\mathrm{OFF}} = U_1 \cdot t_{\mathrm{ON}}$$

$$\Rightarrow \qquad U_2 = U_1 \cdot \frac{t_{\mathrm{ON}} + t_{\mathrm{OFF}}}{t_{\mathrm{OFF}}} = \frac{T_{\mathrm{P}}}{t_{\mathrm{OFF}}} \cdot U_1 = \frac{1}{1 - D} \cdot U_1 \tag{7.8}$$

The same result is obtained if (7.7) is evaluated with a power balance.

As long as no limitations by the components used have to be taken into account, the output voltage can be set depending on the duty cycle $D = 0...1$, at least theoretically from $U_2 = U_1 ... \infty$. In practice, however, the output voltage cannot be chosen to be arbitrarily large due to the limited blocking voltages of the valves.

7.3.3 Buck-Boost Converter

The buck-boost converter is also a DC converter that can generate an inverse output voltage $U_2 > 0\,\mathrm{V}$ from an input voltage U_1 and acts like a series connection of a step-down converter (buck) and step-up converter (boost). It is therefore very well suited, for example, to stabilize a fluctuating supply voltage if the input and output sides do not have the same reference potential. The smoothing inductor L is now in the shunt branch so that the inductor current $i_{\mathrm{L}}(t)$ either flows through the switched-on transistor in the input circuit or through the diode in the output circuit.

Since both the current in the input circuit and in the output circuit are switched off, both an input capacitor C_1 to protect the transistor T and an output capacitor C_2 to protect the diode D are necessary.

If the smoothing inductor and the two capacitors are infinitely (or very) large, the input quantities U_1 and I_1 and the output quantities U_2 and I_2 can actually be constant quantities.

Just as with the step-down and step-up converters, the mean values of the capacitor currents must also be zero in the steady state. The charge that was absorbed (released) during the first phase of the pulse period $0...t_{\mathrm{ON}}$ must be released again

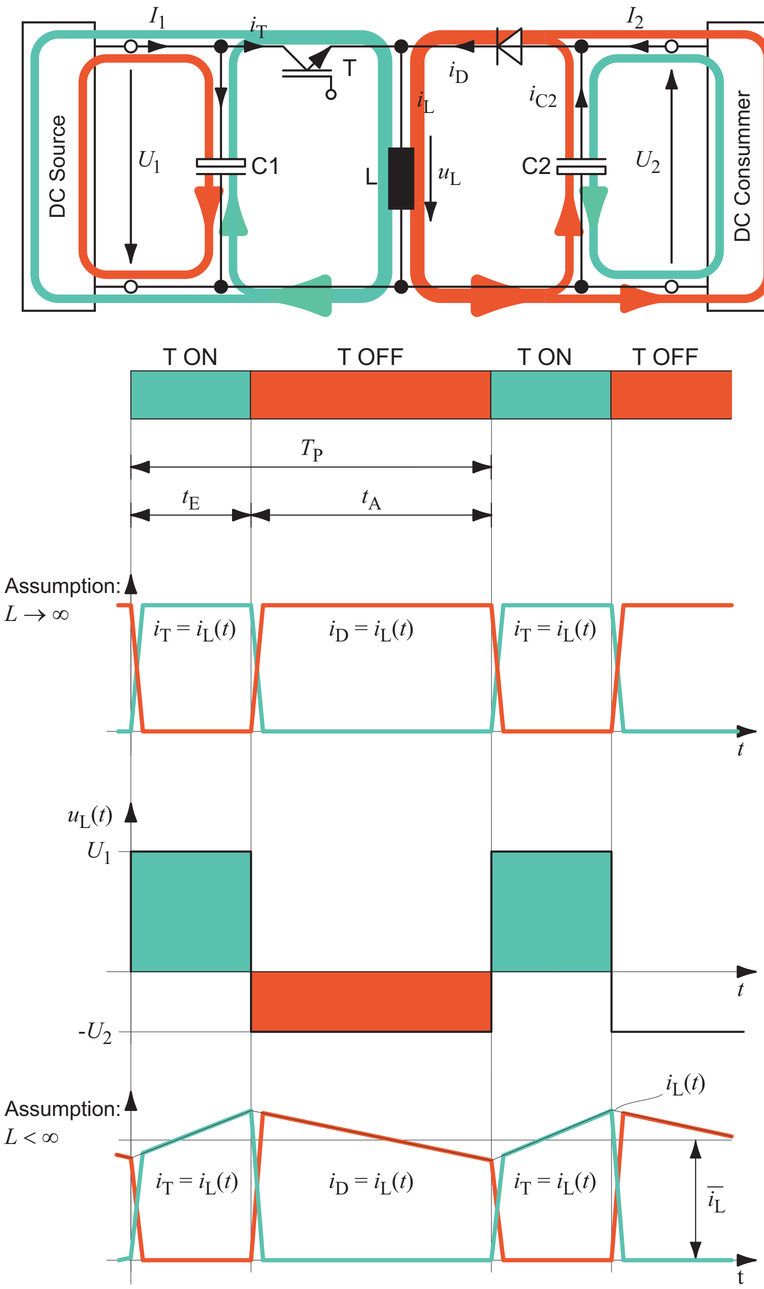


Figure 7.15: buck-boost converter

during the second phase of the pulse period $t_{ON} \ldots t_{OFF}$:

Input condensator C_1:

$$I_1 \cdot t_{OFF} = (\overline{i_L(t)} - I_1) \cdot t_{ON} \quad \Rightarrow \quad \overline{i_L(t)} = \frac{I_1 \cdot (t_{ON} + t_{OFF})}{t_{ON}} = \frac{I_1}{D}$$

Output condensator C_2:

$$I_2 \cdot t_{ON} = (\overline{i_L(t)} - I_2) \cdot t_{OFF} \quad \Rightarrow \quad \overline{i_L(t)} = \frac{I_2 \cdot (t_{ON} + t_{OFF})}{t_{ON}} = \frac{I_2}{1 - D}$$

$$\Rightarrow \quad \frac{I_1}{D} = \frac{I_2}{1 - D} \quad \text{bzw.} \quad I_2 = \frac{1 - D}{D} I_1 \tag{7.9}$$

To determine $u_\mathrm{L}(t)$, the mesh equations are set up:

$$
\begin{aligned}
&\texttt{T ON:} && -U_1 + u_\mathrm{L}(t) = 0 && \Rightarrow && u_\mathrm{L}(t) = U_1 \\
&\texttt{T OFF:} && -U_2 + u_\mathrm{L}(t) = 0 && \Rightarrow && u_\mathrm{L}(t) = -U_2
\end{aligned}
$$

The mean value of the inductor voltage $\overline{u_\mathrm{L}(t)}$ must be zero in the steady state:

$$
\begin{aligned}
&\overline{u_\mathrm{L}(t)} = 0 = \frac{U_1 \cdot t_\mathrm{ON} - U_2 \cdot t_\mathrm{OFF}}{T_\mathrm{P}} \\
\Rightarrow \quad & U_2 \cdot t_\mathrm{OFF} = U_1 \cdot t_\mathrm{ON} \\
\Rightarrow \quad & U_2 = \frac{t_\mathrm{ON}}{t_\mathrm{OFF}} \cdot U_1 = \frac{t_\mathrm{ON}}{T_\mathrm{P} - t_\mathrm{ON}} \cdot U_1 = \frac{D}{1-D} \cdot U_1
\end{aligned}
\tag{7.10}
$$

As long as no limitations by the components used have to be taken into account, the output voltage can be set depending on the duty cycle $D = 0...1$, at least theoretically from $U_2 = 0\,\mathrm{V}...\infty$. In practice, however, the output voltage cannot be chosen to be arbitrarily large due to the limited blocking voltages of the valves and the ever-increasing peak current.

7.3.4 Multi-quadrant controller

With the two converter circuits shown so far, neither the current nor the voltage direction at the output can be changed. In all circuits, the power is transferred from the input side to the output side. In DC motors, the voltage is a measure of the speed, while the current is a measure of the torque. It would only be possible to control a clockwise rotating motor with both of the converter circuits presented. Both circuits are therefore one-quadrant controllers (1QS).

For a controlled or regulated drive with both directions of rotation and the option of being able to brake electrically, both voltage and current directions are required. The power electronic converter required for such an application would then be a four-quadrant controller (4QS).

However, it is possible (see Figure 7.16) to create at least one two-quadrant converter with voltage reversal by slightly modifying the step-down and step-up converters. In both circuits, however, the direction of the current cannot yet be changed.

The disadvantage is that one of the two voltage sources in Figure 7.16 must be able to absorb power and two separate power supplies are required.

However, there are some similarities in both circuits in Figure 7.16 (arrangement of the capacitors and the inductor), so that both circuits can also be brought together used as in Figure 7.18.

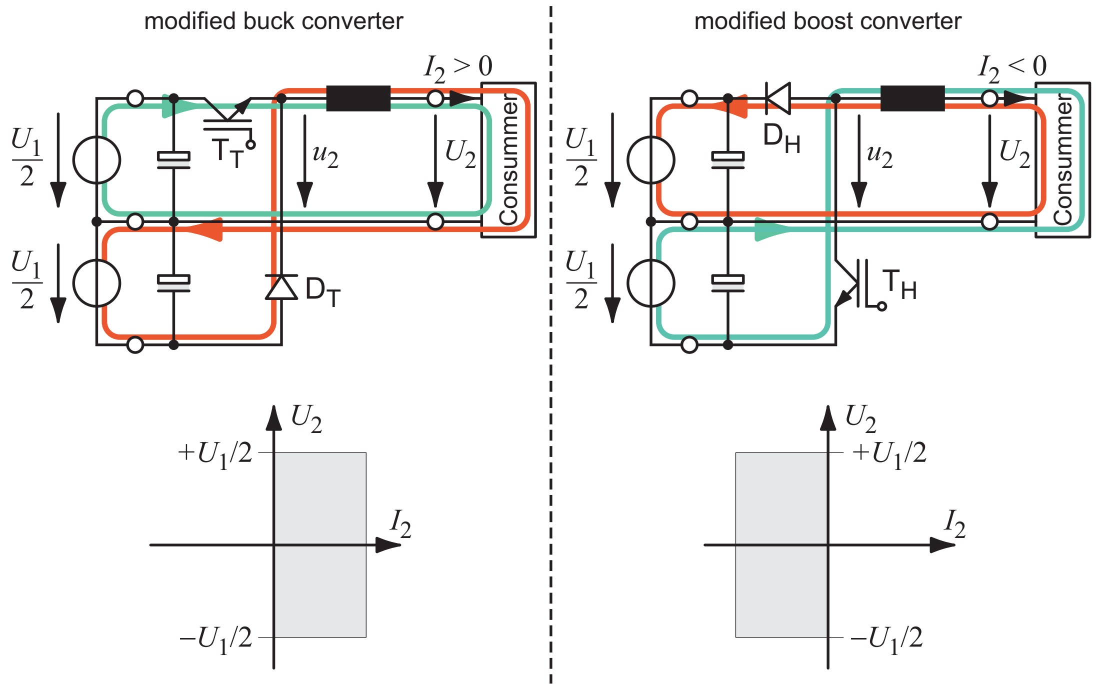
The two transistors are ignited alternately, so that the current can „find its way“ because of the anti-parallel diodes. If T_T is ignited, the current is routed via T_T for $I_2 > 0$ and otherwise via D_H (T_H blocks!). However, if T_H is ignited, the current is routed via T_H for $I_2 < 0$ and otherwise via D_T (T_T blocks!).

The disadvantage of this circuit is that a bipolar and regenerative power supply is required to operate this controller. Instead of the return via a center connection, a second half-bridge (see Figure 7.18) can also be provided.

Assuming that the current i_2 actually flows in the direction shown, when the transistors T_1 and T_2 are triggered, the current will also flow through these two transistors. However, if the transistors T_3 and T_4 are fired afterwards, the current cannot flow through these two transistors, but will flow through the fly-back diodes which are connected antiparallel to these two transistors (T_1/T_2 blocked!). The current direction does not need to be evaluated for the activation of the transistors.

If the supply voltage source is not able to absorb power, a braking resistor R_1 is needed, which can be switched on via a braking chopper. If the supply voltage cannot absorb energy that has been fed back, the capacitor will be charged by the current that has been fed back. As soon as the capacitor voltage exceeds a certain value, the transistor T_5 is switched on via a comparator circuit with hysteresis so that the capacitor can discharge again. If the value falls below a certain limit again, this transistor switches off again.

The load is therefore always supplied with either the full positive or negative voltage. If the transistors T_1 and T_2 are turned on for a period of time t_{ON} and then the transistors T_3 and T_4 are turned on for a period of time t_{OFF} with a temporally



$I_2 > 0$	$I_2 < 0$
T_T A: $u_2 = +\frac{U_1}{2}$	T_H ON: $u_2 = -\frac{U_1}{2}$
T_T OFF: $u_2 = -\frac{U_1}{2}$	T_H OFF: $u_2 = +\frac{U_1}{2}$
Lower voltage source: power consumption Upper power source: power delivery	Lower voltage source: power delivery Upper voltage source: power consumption

Figure 7.16: Two-quadrant controller with reversal of voltage direction

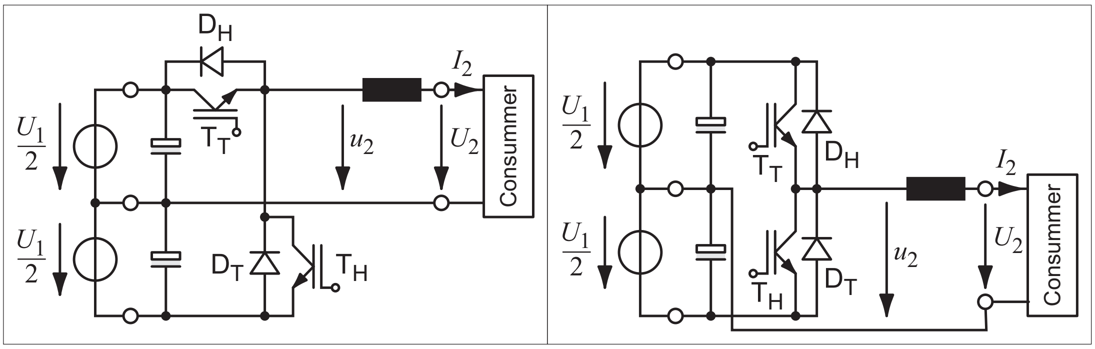


Figure 7.17: Four-quadrant controller (half bridge)

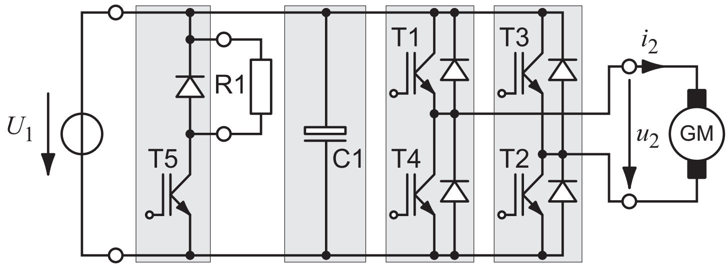


Figure 7.18: Four-quadrant controller (H-bridge)

constant pulse pattern, the following mean value for the output voltage results:

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

$$= \frac{2t_{\mathrm{ON}} - T_{\mathrm{P}}}{T_{\mathrm{P}}} \cdot U_1 = (2D-1) \cdot U_1 \tag{7.11}$$

$$D = 0...1: \; U_2 = -U_1... + U_1 \tag{7.12}$$

$$t_{\mathrm{ON}} = t_{\mathrm{E1}} = t_{\mathrm{E2}} = t_{\mathrm{A3}} = t_{\mathrm{A4}}$$

$$t_{\mathrm{OFF}} = t_{\mathrm{A1}} = t_{\mathrm{A2}} = t_{\mathrm{E3}} = t_{\mathrm{E4}}$$

7.3.5 Modulation and Inverter

The same power electronic circuits, the half and full bridge, can be used as inverter thanks to the pulse-width-modulation. The simplest method of generating a pulse pattern from a voltage setpoint is what is known as triangular modulation. To do this, the control voltage u_{Ct}, proportional to the setpoint voltage, is compared with a triangular signal from a function generator (Figure 7.19).

The sign of the difference between the control voltage and the triangular signal is evaluated via a comparator and passed on to the four transistors T1 to T4 as ignition signals.

Since time-variable voltages can be generated in this way, the same method can be used to control a pulse-controlled inverter. The control voltage u_{Ct} in Figure 7.20 is then a sinusoidal setpoint. Analyzing the periodic voltage curve u_2, the fundamental component has a peak value, which is actually proportional to the peak value of the control voltage u_{Ct}.

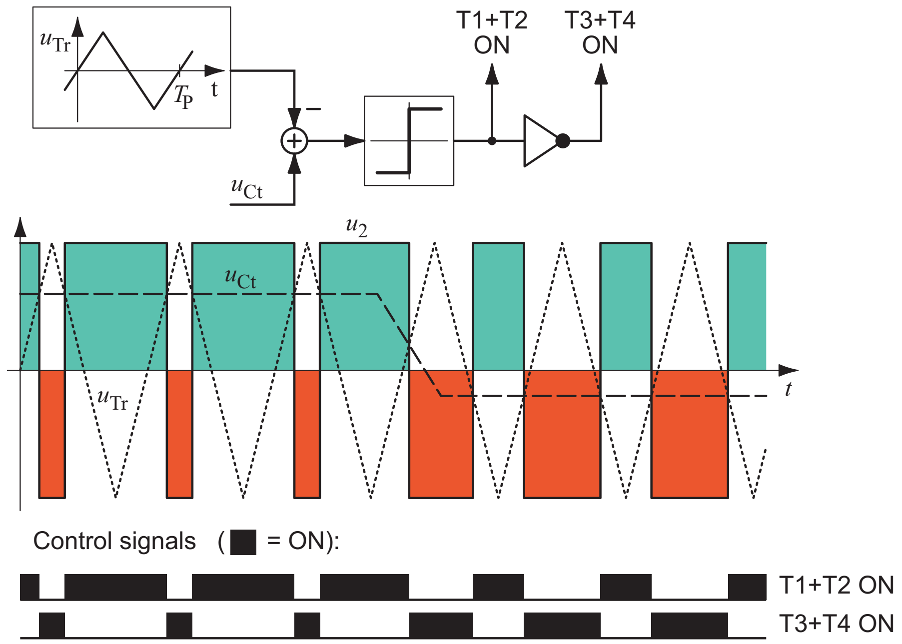


Figure 7.19: Triangle modulation principle

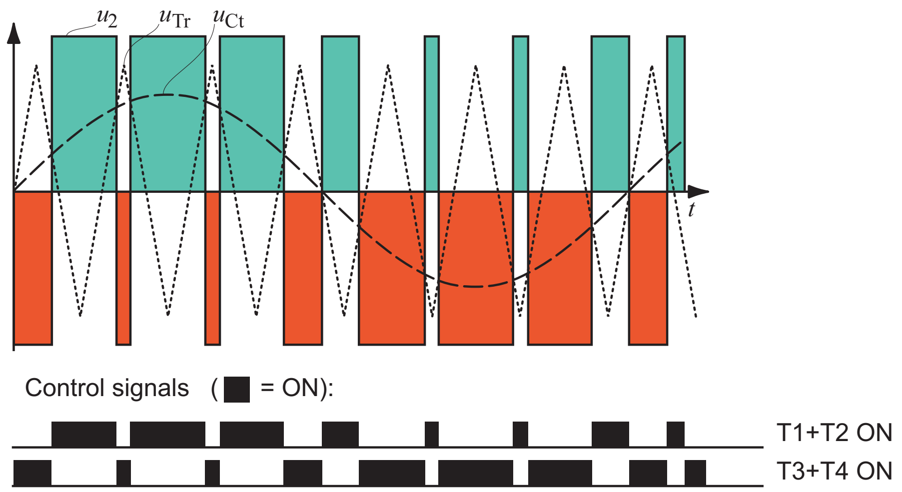


Figure 7.20: Inverter with triangle modulation

A three-phase inverter (see Figure 7.21), which is supplied from a DC voltage source, is often used to supply three-phase servo-drives with variable voltage and frequency. In terms of structure, it is similar to the power converter of a DC servo drive, except that instead of two half-bridges (= four-quadrant controller), three half-bridges are now used.

Three-phase drives are supplied with voltages and currents that are phase-shifted by $120°$, so that with a purely sinusoidal supply, the sum of the three phase current is always zero.
It is therefore not necessary to supply the inverter from a bipolar voltage source, since the middle point of the load is not connected anyway.

In principle, the pulse patterns for the three phases can be generated with a triangular modulation. However, it can be shown that with the so-called space

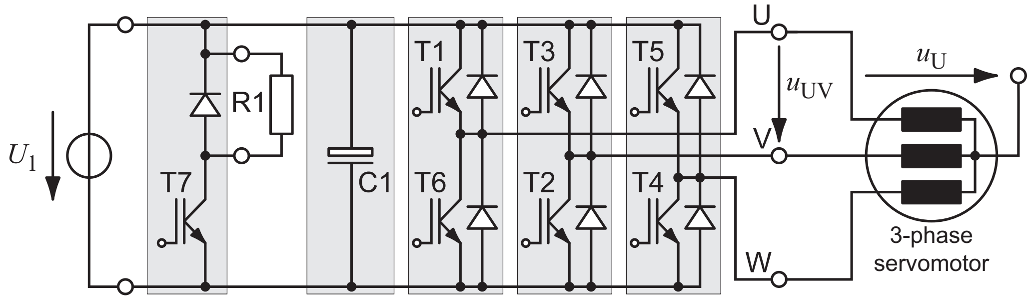


Figure 7.21: Three-phase inverter with three-phase machine as load

vector modulation with modulation of the d- and q-voltage, the fundamental voltage can be significantly increased.

In practice, the switching frequencies will be in the range of a few kHz (usually $16\,\mathrm{kHz)evenwithoutputsofupto500\,kW}$ to $20\,\mathrm{kHz)evenwithoutputsofupto500\,kW}$), in automotive applications for EMC reasons $22\,\mathrm{kHz}$), so that for the operating behavior of converter-fed drives, the inverter can be assumed to be a three-phase voltage system with variable amplitude and frequency.

7.4 Tasks

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.

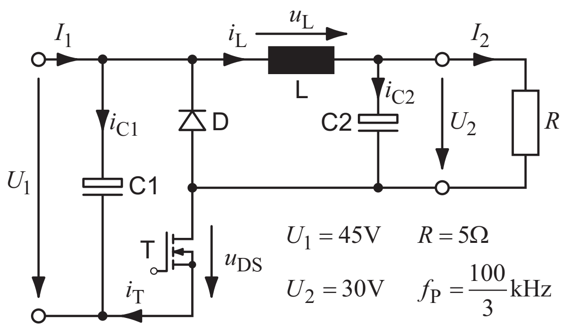


Figure 7.22: DC converter

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 currenti_L may only vary by $\pm 0.5\,\mathrm{A}$?

c) The resistance R is increased so that the current now gaps for $5\,\mu\mathrm{s}$. What is the output voltage U_2 now? State the same values as in point b) with the exception of L (value is not changed)!

Example 7-2: DC converter

Cornelius Löthilf wants to add a $-5\,\mathrm{V}$ connection to his $12\,\mathrm{V}$ power supply by adding the buck-boost converter outlined in Figure 7.23. The idealized theory is assumed with the exception of a finite inductor.

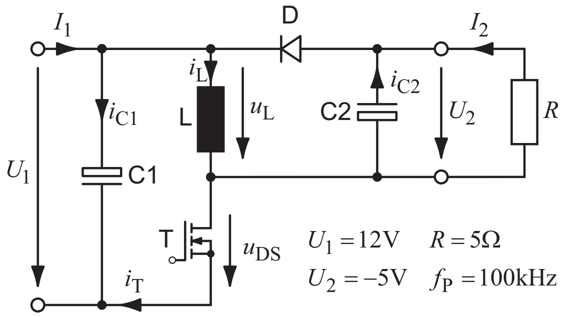


Figure 7.23: inverse converter

a) Is there a problem with this circuit? How would you solve it?
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 large is the inductor L if its current i_{L} is allowed to vary by $\pm 0.5\,\mathrm{A}$?
c) The resistance R is increased so that the current now gaps for $2\,\mu\mathrm{s}$. What is the output voltage U_2 now? State the same values as in point b) with the exception of L (value is not changed)!

Example 7-3: Sizing of a buck converter

The passive components for the buck converter in Figure 7.24 must be designed. Only the steady state is considered, whereby the two capacitors should initially be

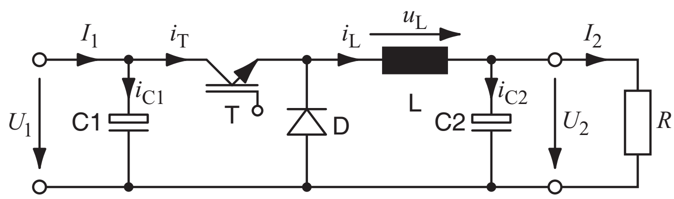


Figure 7.24: Step-down converter $U_1 = 14\,\mathrm{V},\ U_2 = 5\,\mathrm{V},\ R = 0.5\,\Omega,\ f_{\mathrm{P}} = 22\,\mathrm{kHz}$

assumed to be so large that the input and output voltages are constant.

a) What is the input and output current ($I_1,\ I_2$)?
b) Sketch the course of the voltage u_{L} across the inductor L! What is the on-time t_{ON} for the transistor T?
c) Determine the size of the inductor L so that its current i_{L} has a ripple of max. $0.5\,\mathrm{A}$ (peak-to-peak). !
d) Sketch the curves for the two capacitor currents i_{C1} and i_{C2}!

Furthermore, input and output voltages are no longer assumed to be constant. However, the effects on the current courses are so small that in the following you can continue working with the currents/current curves that have already been determined.

e) Dimension the output capacitor C_2 so that there is a maximum ripple of $100\,\mathrm{mV}$ (peak-peak) on the output voltage U_2!
f) Estimate the size of C_1 if, with a constant input current I_1, a voltage ripple of maximum $400\,\mathrm{mV}$ on the input voltage U_1 is allowed!
g) How would the values for L and C_2 change if you had a current ripple of $1\,\mathrm{A}$ instead of $0.5\,\mathrm{A}$ as in sub-item c, but requires the same voltage ripple on the output voltage as in sub-item e?

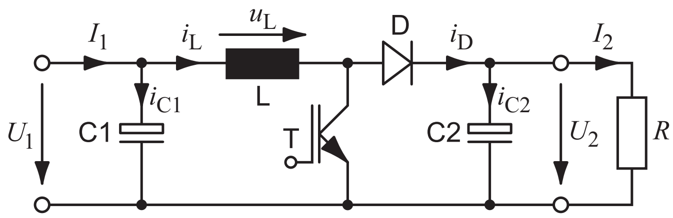
The load resistance R increases to $50\,\Omega$.

h) Sketch the course of the current i_L and the voltage u_L! How large is the on-time t_{ON} for the transistor T so that an output voltage of $5\,V$ still results?

i) What values for the output voltage and current would result if the transistor were operated in the same way as in sub-items a to g?

Example 7-4: Sizing of a step-up converter

The passive components for the step-up converter in Figure 7.25 must be designed. Only the steady state is considered, whereby the two capacitors should initially be



$U_1 = 5\,V,\ U_2 = 12\,V,\ R = 100\,\Omega,\ f_P = 22\,kHz$

Figure 7.25: boost converter

assumed to be so large that the input and output voltages are constant.

a) What is the input and output current ($I_1,\ I_2$)?

b) Sketch the course of the voltage u_L across the inductor L! What is the on-time t_{ON} for the transistor T?

c) Determine the size of the inductor L so that its current i_L has a ripple of max. $20\,mA$ (peak-to-peak)!

d) Sketch the curves for the two capacitor currents i_{C1} and i_{C2}!

Furthermore, input and output voltages are no longer assumed to be constant. However, the effects on the current curves are so small that you can continue to work with the currents/current curves that have already been determined.

e) Dimension the output capacitor C_2 so that there is a maximum ripple of $100\,mV$ (peak-peak) on the output voltage U_2!

f) Estimate the magnitude of C_1 if, with a constant input current I_1, a voltage ripple of maximum $200\,mV$ on the input voltage U_1 can be allowed!

g) How would the values for L and C_2 change for a current ripple of $40\,mA$ instead of $20\,mA$ in sub-item c? The same voltage ripple on the output voltage as in sub-item e can be assumed.

The load resistance R increases to $10\,000\,\Omega$.

h) Sketch the course of the current i_L and the voltage u_L! How large must the on-time t_{ON} for the transistor T be selected so that an output voltage of $12\,V$ still results?

i) Which values for the output voltage and current would result if the transistor were operated in the same way as in sub-items a to g?

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?

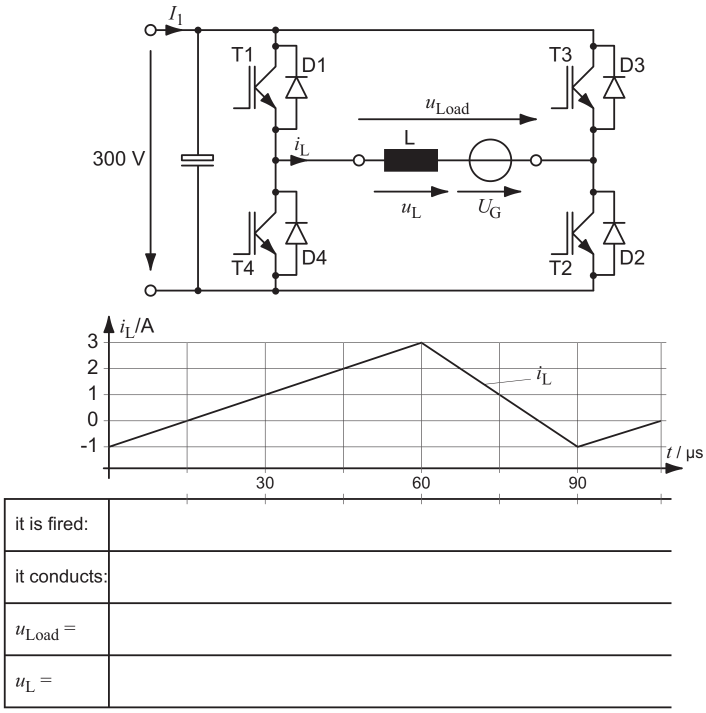


Figure 7.26: four-quadrant controller

Example 7-6: Half-Bridge

Given is the circuit specified in Figure 7.27, as well as the outlined current flow (time axis not to scale, pulse period $50\,\mu s$).

a) Correct the circuit error!
b) Fill out the given table! What is the resistance R? What is the current rise time t_1? What is the inductance L?
c) Can a current $I_2 < 0$ be set with a positive output voltage $U_2 > 0$ at the same time by changing the duty cycle? Why not?

Example 7-7: Half-bridge

Given is the circuit specified in Figure 7.28, which is periodically pulsed with a period of $30\,\mu s$, as well as the sketched current curve (not to scale!):

a) Fill out the given table!
b) What is the input current I_1, the current rise time t_1 and the inductance L?

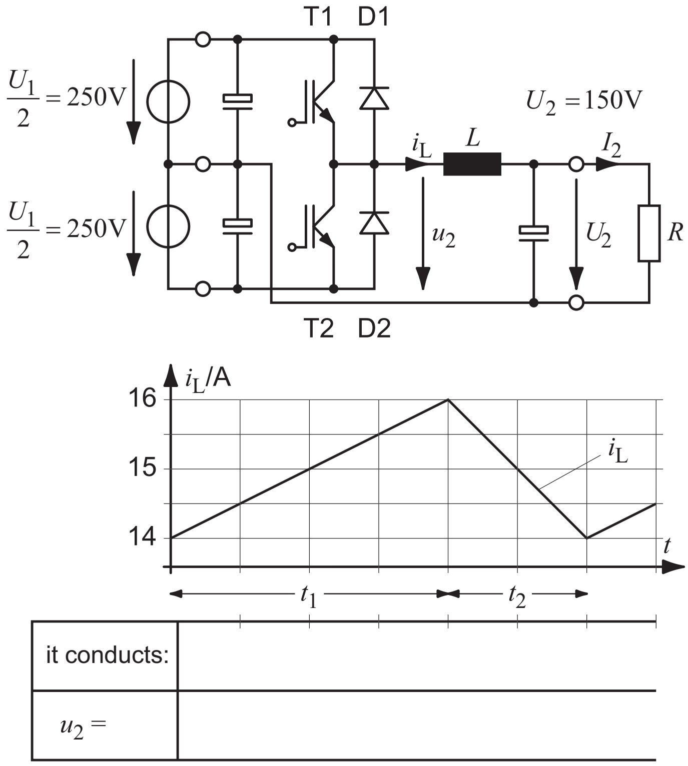


Figure 7.27: four-quadrant controller

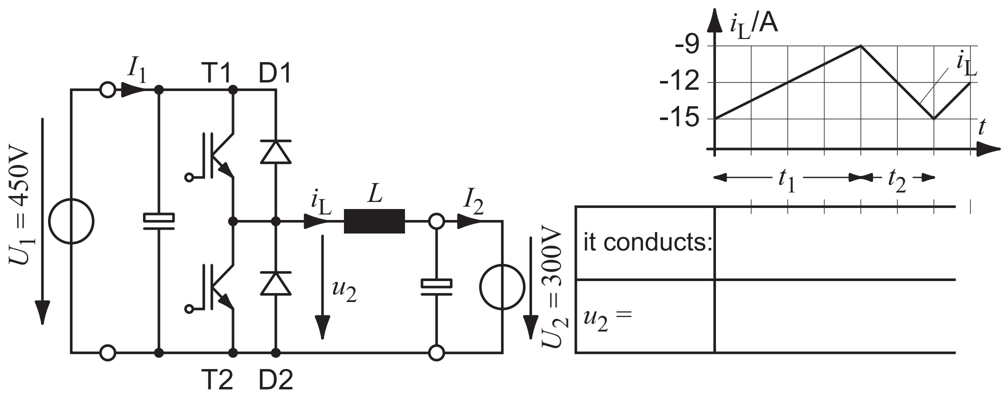


Figure 7.28: four-quadrant controller