Buck-converter

The **Buck-converter** converts an input voltage into a lower output voltage, it is also called **step-down converter**.

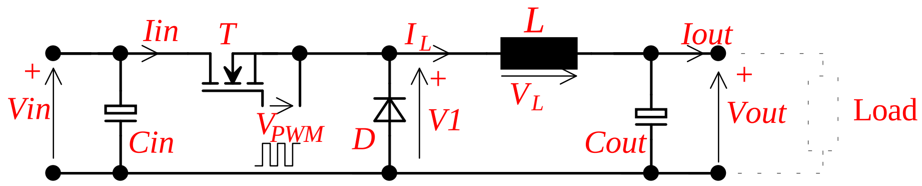

Figure1.1.1: Buck-converter

Figure 1.1.1 shows the circuit diagram of a Buck-converter. The transistor T operates as the switch, which is turned on and off by a pulse width modulated control voltage V_{PWM} with high frequency. The ratio $\frac{t_1}{T}$ between on-time t_1 to the period time T is called the **duty cycle**.

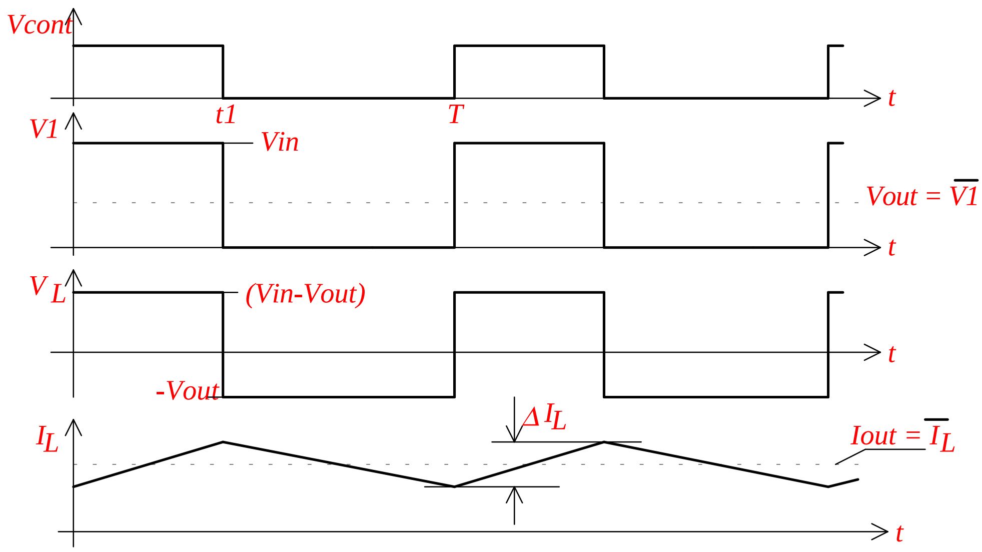

Figure 1.1.2: voltages and currents of the Buck-converter

In the following analysis it will be assumed that the conducting voltage drop of the transistor and the diode is zero.

During the on-time of the transistor the voltage V_1 is equal to V_{in}. When the transistor switches off (blocking phase) the inductor L continues to drive the current through the load in parallel with C_{out} and the diode, consequently the voltage V_1 becomes zero. The voltage V_1 stays at zero during the off-time of the transistor provided that the current I_L does not reduce to zero. This mode of operation is called **continous mode**. In this mode V_1 is a voltage which changes between V_{in} and zero, corresponding to the duty cycle of V_{cont},(see Figure 1.1.2).

The low-pass filter, formed by L und C_{out}, produces an average value of V_1, i.e. $V_{out} = \overline{V_1}$, therefore for continuous mode:

$$\boxed{V_{out} = \frac{t_1}{T} V_{in}}$$

- For the continuous mode the output voltage is a function of the duty cycle and the input voltage, it is independent on the load.

The inductor current I_L has a triangle shape, its average value is determined by the load. The peak-to-peak current ripple ΔI_L is dependent on L and can be calculated with the help of Faraday's Law:

$$V = L\frac{\mathrm{d}i}{\mathrm{d}t} \quad \rightarrow \quad \Delta i = \frac{1}{L} \cdot V \cdot \Delta t \quad \rightarrow \quad \Delta I_L = \frac{1}{L}(V_{in} - V_{out}) \cdot t_1 = \frac{1}{L} V_{out}(T - t_1)$$

For $V_{out} = \frac{t_1}{T} V_{in}$ and a switching frequency f it follows that for the continous mode:

$$\boxed{\Delta I_L = \frac{1}{L}(V_{in} - V_{out}) \cdot \frac{V_{out}}{V_{in}} \cdot \frac{1}{f}}$$

- The current ripple ΔI_L is independent of the load.
- The average of the current I_L is equal to the output current I_{out}.

At low load current, in case that $I_{out} \le \frac{\Delta I_L}{2}$, the current I_L becomes zero in every switching cycle. This mode is called **discontinous mode** and for this mode the calculations above are not valid.

Calculation of L and C_{out}:

To the calculate the value of L a realistic value of ΔI_L has to be selected. The problem is as follows: If ΔI_L is selected at a very low value, the value of L has to be relatively high and this would require ae very heavy and expensive inductor. If ΔI_L is selected at very high level the switch-off current of the transistor would be very high (this would result in high losses in the transistor). A good and usual compromise between these effects is: $\Delta I_L \approx 0.2\, I_{out}$

For L it follows:

$$\boxed{L = \frac{1}{\Delta I_L}(V_{in} - V_{out}) \cdot \frac{V_{out}}{V_{in}} \cdot \frac{1}{f}}$$

The maximum value of the inductor current is:

$$\hat{I}_L = I_{out} + \frac{1}{2}\Delta I_L$$

Assuming that the inductor ripple current is small compared to its dc current the RMS value of the current flowing through the inductor is given by:

$$I_{L(RMS)} \approx I_{out}$$

The capacitor C_{out} is chosen usually for a cut-off frequency of the LC_{out}-low-pass filter, which is approximately 100 to 1000 times lower than the switching frequency. An exact calculation of the capacitor depends on its maximum rating of the AC current and its serial equivalent impedance $Z_{\max}$, both can be verified from the relevant data sheet.
The current ripple ΔI_L causes a voltage ripple ΔV_{out} at the output capacitor C_{out}. For normal switching frequencies this voltage ripple is determined by the equivalent impedance $Z_{\max}$.

The output voltage ripple is given by Ohm's law:

$$\Delta V_{out} \approx \Delta I_L \cdot Z_{\max}$$

The choice of the output capacitor depends not on its capacitance, but on its series equivalent impedance $Z_{\max}$ at the switching frequency which can be verified from the capacitor data sheet.