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ELECTRICAL POWER ENGINEERING

LABORATORY I

Experiment 8:

DC-DC Converter

(Buck-, Boost-Converter)

1 Introduction and Objective of the Experiment

In many applications, a constant dc voltage source is utilized to supply dc loads. The load does not always match to the available dc source, such that it could be supplied directly by the source. In general, the specifications of the load have to be taken into account. One example is the CPU inside a laptop computer with a core-voltage of 1.8 V ±20 mV. For the functionality of the CPU, it is important to keep this voltage within the limits, no matter what the state of the CPU is (sleep, speed-step or full-load mode).

In order to fulfil this requirement, an additional component is inserted between the source and the load, which absorbs the voltage difference between the source and the load. A resistance represents a simple technical solution. It lowers the voltage at the load. However, it causes high losses at high power levels. Furthermore, the load voltage is load dependent.

Using a transistor instead of the resistor, at least the second disadvantage can be avoided, since the voltage between collector and emitter of the transistor can be adjusted continuously. This solution is commonly used up to power levels of approximately 100 W in power supplies, where a load-independent output voltage being as constant as possible is desired. Such a constant voltage regulator is commonly called a series regulator or linear regulator. (see Figure 1.1)

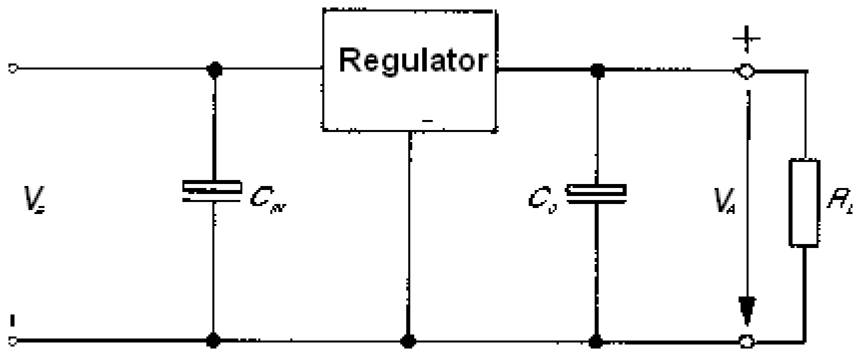

Figure 1.1: Linear regulator

For large voltage differences between the supply voltage and the output voltage, and concurrently high load currents, the entire power difference has to be transformed into heat within the linear regulator.

Example: Supply voltage (battery) 12 V, load voltage (CPU) 1.8 V, load current 10 A, load power 18 W

Thermal power in the linear regulator: (12 V-1.8 V)*10 A = 102 W

Power efficiency of the regulator: $\eta = \frac{P_{\text{ab}}}{P_{\text{auf}}} = 15\%$

Therefore, at higher power levels, the solution of a component with less power loss between source and load is desired. A portion of the input voltage is "extracted" by means of an electronic switch, such that the load obtains a lower average voltage than the input voltage supplied by the dc source. In the simplest form, this "extraction" can be achieved by means of a buck converter (or step-down converter) (see Figure 1.2).

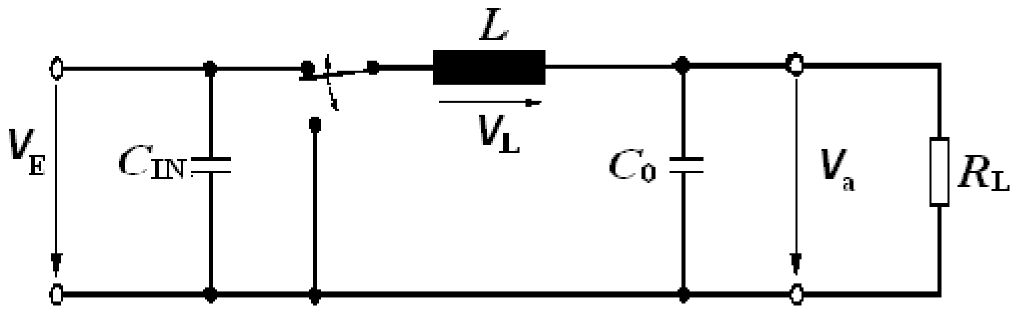

Figure 1.2: Basic configuration of a buck converter

The electrical effect of the inductor can be compared to the mechanical effect of a flywheel in a car engine. The flywheel takes care that the energy generated from short-time combustion processes are distributed evenly, so that the power transferred to the drive train does not fluctuate with high ripples.

This principle can be applied to the following examples:

- for the local CPU voltage supply (several 10 W)
- in switch-mode power supplies or battery-driven electric tools (several 100 W)
- for the control of dc machines (drives, forklift trucks) (several kW)
- in electric vehicles (electric cars) (several 10 kW)

Due to innovations and new developments, the applications of one-quadrant choppers have changed fundamentally.

Nowadays, new drive concepts have replaced the dc-motors almost completely. However, buck converter with a high efficiency ($\eta \geq 90\%$), low output voltages (V_A = 0.7...12 V) and medium currents (I_A = 0.1...400 A) have gained importance, especially in grid independent devices. No transmitting stage in a mobile phone, no processor, no background lighting in a laptop or palmtop computer, pager, no home PC can work without a discrete decentralized high-efficient dc-dc converter.

The CPUs, which constantly become more powerful, determine the requirements of the dc-dc converter. In the next CPU generation, core voltages of between 0.7 V and 1.4 V at currents of 50 A to 400 A are required. In addition, CPUs demand a high dynamic voltage supply: Within a few cycles, the CPU can go from sleep-mode to full load. Therefore, the dc-dc converter must be able to supply a rated current within a few µs, while the output voltage must not exceed the limits.

In order to justify the requirements of dc-dc converter and the new technology, in this experiment the principle function of the buck converter should be discussed. Starting from a classic buck converter with freewheeling diode, the synchronous rectifier and the principle of the boost converter are developed. Based on the basics, which are explained in detail in "Power Electronics Lecture Companion" [Doncker03], certain devices of a buck converter should be designed considering the physical limits. The design will be verified by the experimental measurements.

2 The Principle of Buck Converters

2.1 Buck Converter with idealized Devices

The basic function of a buck converter can be seen from the circuit diagram in Figure 2.1. The load, in this case a resistor is supplied via the circuit shown in the Figure 2.1. It consists of a switching semiconductor *T*, an inductance *L* for storing energy, an output capacitor C_0 and a freewheeling diode *D*.

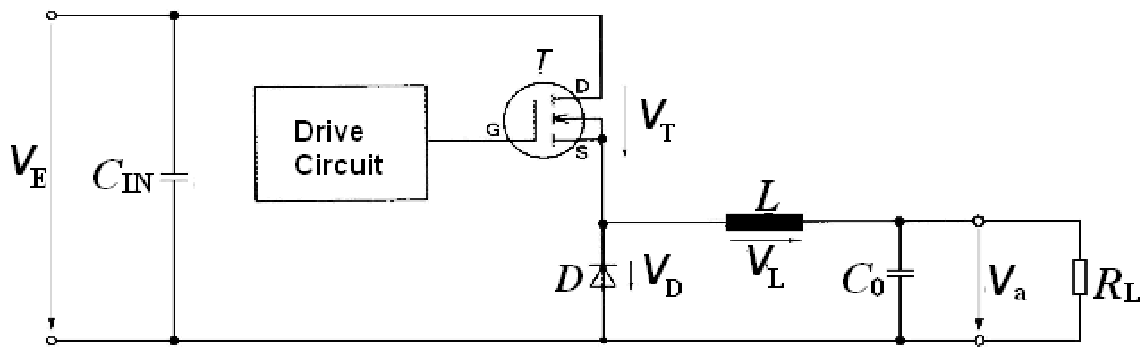

Figure 2.1: Principle configuration of a buck converter with MOSFET

First, we consider all devices to be ideal, i.e. the source has no internal resistance and provides a constant voltage, the output voltage is constant ($C_0 \rightarrow \infty$) and the semiconductors are either high-impedance (open-circuit in non-conducting mode) or without any impedance (ideally conducting). Furthermore, the inductance is considered very large, but still finite.

We consider steady state operation. We assume, that the current fed to the resistive load is equal to the average current flowing through the inductance. :

$$\bar{I}_{\mathrm{L}} = \frac{\bar{V}_{\mathrm{a}}}{R_{\mathrm{Load}}} = \bar{I}_{\mathrm{Load}}$$

2.1.1 Continuous-Conduction Mode

In order to determine the dependency of the output voltage on the input voltage and the duty cycle *a*, the two possible switching states will be explained.

Definition: The duty cycle a describes the turn-on time t_1 of the semiconductor switche T with respect to the cycle time $T = \frac{1}{f}$ (see Figure 2.4). The duty cycle a is adjusted by the control between $0 < a < 1$. How the instantaneous value of a is determined will be shown later.

a) MOSFET conducts :

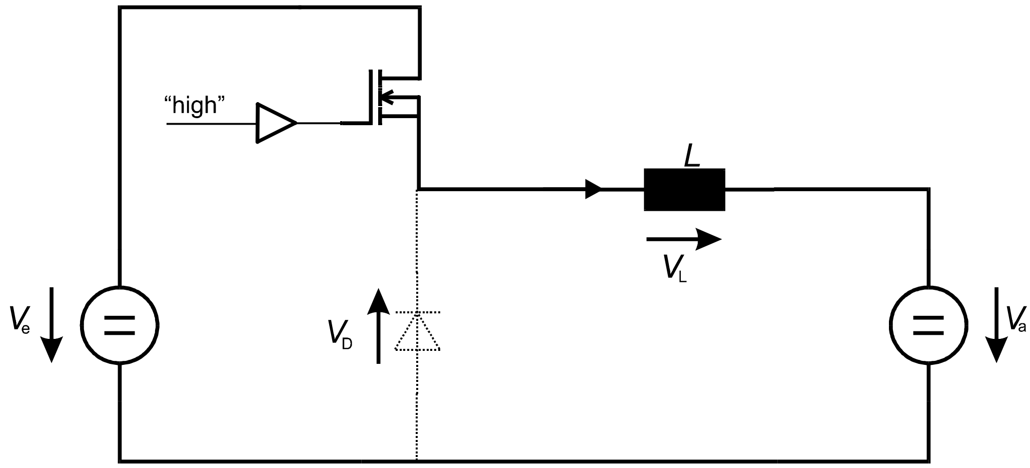

Figure 2.2: Buck converter, *T* turned on

As soon as the switch is turned on, the current flows without loss, i.e. without a voltage drop (ideal switch), through the switching device. The diode blocks, since the voltage V_D is negative. The voltage of the inductance is equal to the difference of input voltage and output voltage.

$$v_L = V_e - V_a \tag{2.1}$$

The current rise is limited by the inductance L and is proportional to the difference of input voltage and output voltage:

$$\frac{di_L}{dt} = \frac{V_e - V_a}{L} \tag{2.2}$$

This leads to the current waveform:

$$i_a(t) = i_a(t=0) + \frac{V_e - V_a}{L} \cdot t \tag{2.3}$$

b) MOSFET block:

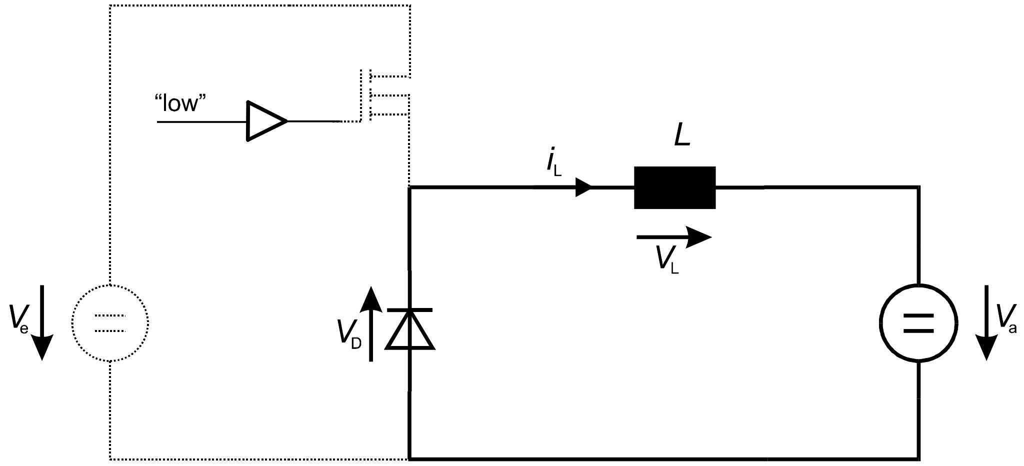

Figure 2.3: Buck converter, S turned off

As soon as the switch is turned off, the current can only remain flowing through the diode. In conducting state, there is no voltage drop across the ideal diode. Thus, the voltage drop across the inductance is equal to the negative output voltage.

$$v_{\mathrm{L}} = -V_{\mathrm{a}} \tag{2.4}$$

Hence, the current falls linearly:

$$v_L = L \cdot \frac{di_a}{dt} \quad \Rightarrow \quad i_a(t) = i_a(t = a \cdot T) - \frac{V_a}{L} \cdot (t - aT) \tag{2.5}$$

Assuming the average value of the current to be constant in the chosen stationary operational point, there cannot be an average voltage across the inductance. The positive and the negative volt-sec areas across the coil are equal, thus the following relation has to be satisfied:

$$\int_0^T v_L \cdot dt = \int_0^{aT} (V_e - V_a) \cdot dt + \int_{aT}^{T} -V_a \cdot dt = 0 \tag{2.6}$$

i.e.

$$i_{\mathrm{a}}(t = 0) = i_{\mathrm{a}}(t = T) \tag{2.7}$$

One obtains the solution of the integral:

$$(V_e - V_a) \cdot a \cdot T + (-V_a) \cdot (1 - a) \cdot T = 0 \tag{2.8}$$

After transformation, one obtains the following dependency of the output voltage on the input voltage and the duty cycle :

$$\boxed{V_a = a \cdot V_e} \tag{2.9}$$

According to the adjusted duty cycle, the source voltage V_e is transformed to the output side into a average voltage $\overline{V}_a$. The voltage is equal to the source voltage V_e for $a = 1$, i.e. if the switch is always in position 1 (according to the equivalent circuit in Figure 2.2 a), for $a < 1$ it is smaller respectively.

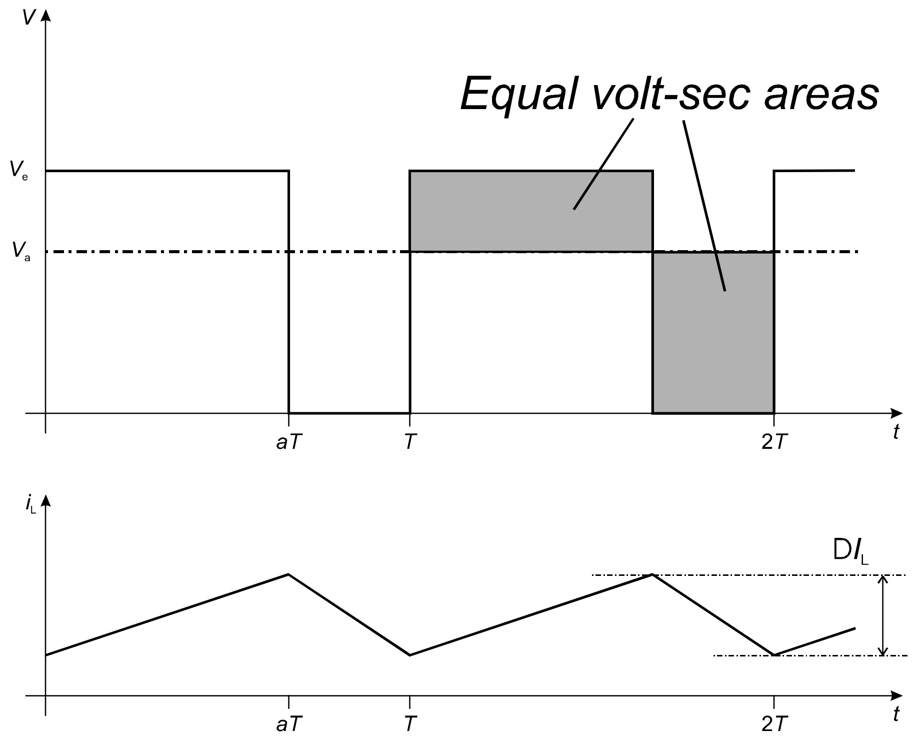

Figure 2.4: Voltage-time curves over L and current curves in continuous operation

Since there are no resistive loads inside the circuit, and the losses in the semiconductors are neglected, the consumed power at the input side is equal to the power delivered to the output side. Thus we obtain for the currents:

$$\boxed{\overline{I}_{\text{Load}} = \frac{1}{a} \cdot \overline{I}_{\text{e}}} \tag{2.10}$$

2.1.2 Current Ripple of the Inductor Current depending on the Duty Cycle

The maximum current ripple ΔI_{L} depends on the voltage V across the inductance, the inductance L and the time Δt. From

$$V = L \cdot \frac{di_L}{dt} = L \cdot \frac{\Delta i_L}{\Delta t} \tag{2.11}$$

follows:

$$\Delta I_L = \frac{V_e - V_a}{L} \cdot a \cdot T = \frac{V_a}{L} \cdot (1-a) \cdot T = \frac{V_e \cdot (1-a) \cdot a}{L} T \tag{2.12}$$

The maximum current ripple is obtained for a duty cycle of $a = 0.5$.

As an example, one obtains the following values for the maximum current ripple of a buck converter with an input voltage of $V_e = 12$ V and an inductance of $L = 10$ µH depending on the switching frequency f_s :

f_s	50 kHz	100 kHz	150 kHz
ΔI_L^{max}	6 A	3 A	2 A

Table 2.1: Current ripple at different switching frequencies

2.1.3 Discontinuous-Conduction Mode

So far, we assumed that the inductance current does not become zero at any point in time. This is only valid, if the average inductor current (=load current) is bigger than half the current ripple. If the average inductor current is exactly equal to half the current ripple (e.g. by means of increasing the load resistance, thus decreasing the output current), then the inductance current decays to zero for a short time. The mode of operation is called the boundary between continuous- and discontinuous-conduction mode (German: Lueckgrenze, hence Index LG). For V_e = constant, this yields:

$$\bar{I}_{L,LG} = \frac{1}{2} \cdot \Delta I_L = \frac{V_e}{2 \cdot L} \cdot (1-a) \cdot aT \qquad \textbf{(2.13)}$$

If the load current decreases further, the circuit operates in discontinuous-conduction mode (German: Lueckbetrieb, hence Index LB).

$$\bar{I}_{L,LG}^{max} = \frac{1}{2} \cdot \Delta I_L^{max} = \frac{V_e}{8 \cdot L} \cdot T \qquad \textbf{(2.14)}$$

The waveform depending on the duty cycle can be seen from Figure 2.5. For designing switch mode power supplies, the maximum current ripple has to be taken into account. It is also maximum for a=0.5, which can be seen from (2.13).

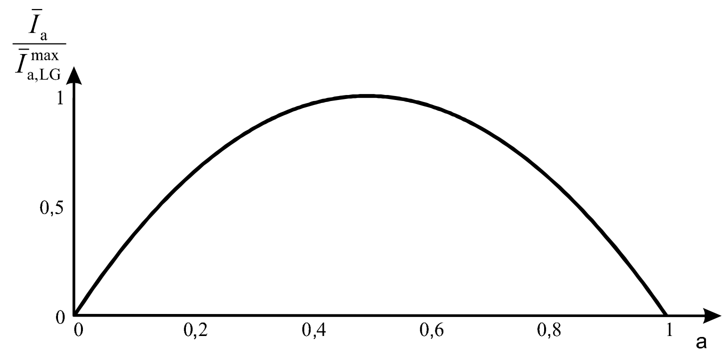

Figure 2.5: Current at the boundary between continuous- and discontinuous-conduction mode depending on the duty cycle a (V_e = const)

Note: Due to the mandatory minimum on-period of the devices, the usable duty cycle is normally between 5 and 95%.

2.1.4 Discontinuous-Conduction Mode with constant V_e , variable V_a

The current waveform is continuous or discontinuous depending on the parameters inductance, switching frequency and output voltage. If the current waveform is discontinuous, it is called discontinuous-conduction mode, in which one obtains :

$$a \cdot T + \varepsilon \cdot T < T \qquad \textbf{(2.15)}$$

where ε is defined by the falling time of the current.

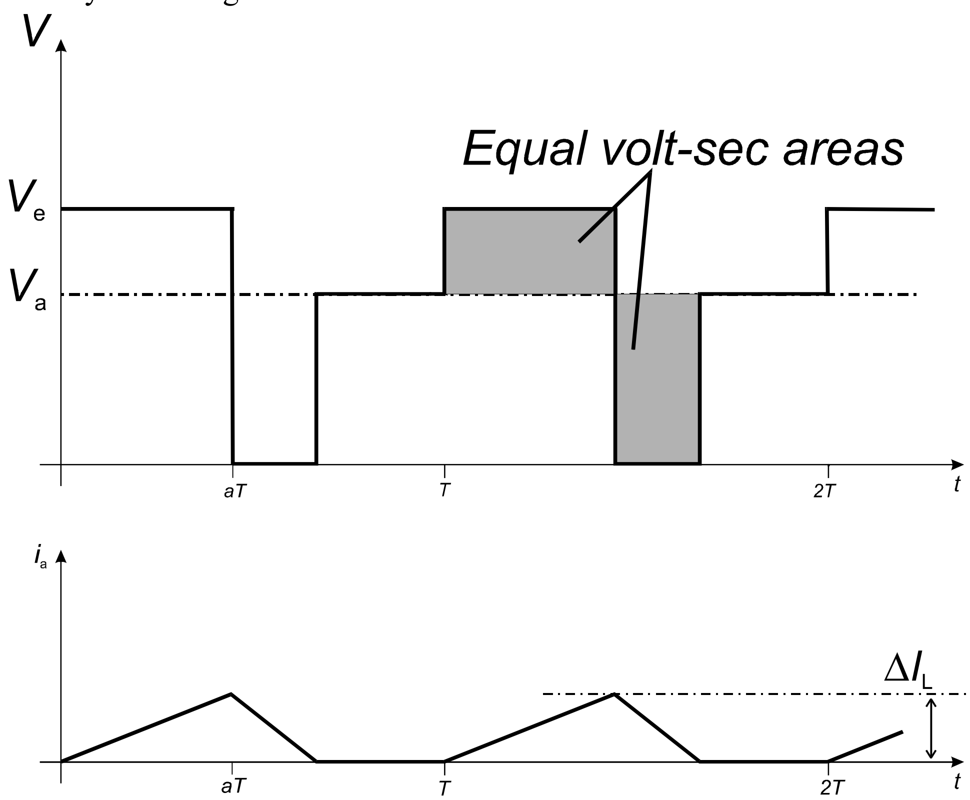

Figure 2.6: Volt-sec areas and current waveform in discontinuous-conduction mode

According to equations (2.9)-(2.13) one obtains for the voltages and currents in discontinuous-conduction mode:

$$\frac{V_a}{V_e} = \frac{a}{a+\varepsilon} \tag{2.16}$$

$$\bar{I}_{L,LB} = \frac{\hat{I}_{L,LB}}{2} \cdot (a+\varepsilon) = \frac{\varepsilon \cdot T \cdot V_a}{2 \cdot L} \cdot (a+\varepsilon) = \frac{V_e}{2 \cdot L} \cdot T \cdot a \cdot \varepsilon \tag{2.17}$$

(2.16) and (2.17) lead to

$$\frac{V_a}{V_e} = \frac{a^2}{a^2 + \frac{1}{4} \cdot \frac{\bar{I}_{L,LB}}{\bar{I}_{L,LG}^{\max}}} \tag{2.18}$$

Plotting the output voltage vs. the average output current (normalized to the input voltage and the maximum current at the boundary between continuous- and discontinuous-conduction mode) for both modes of operation (continuous- and discontinuous-conduction) with the duty cycle a as parameter and V_e = constant, one obtains the diagram shown in Figure 2.7. The area of discontinuous-conduction mode is shaded gray and separated from the area of continuous-conduction mode.

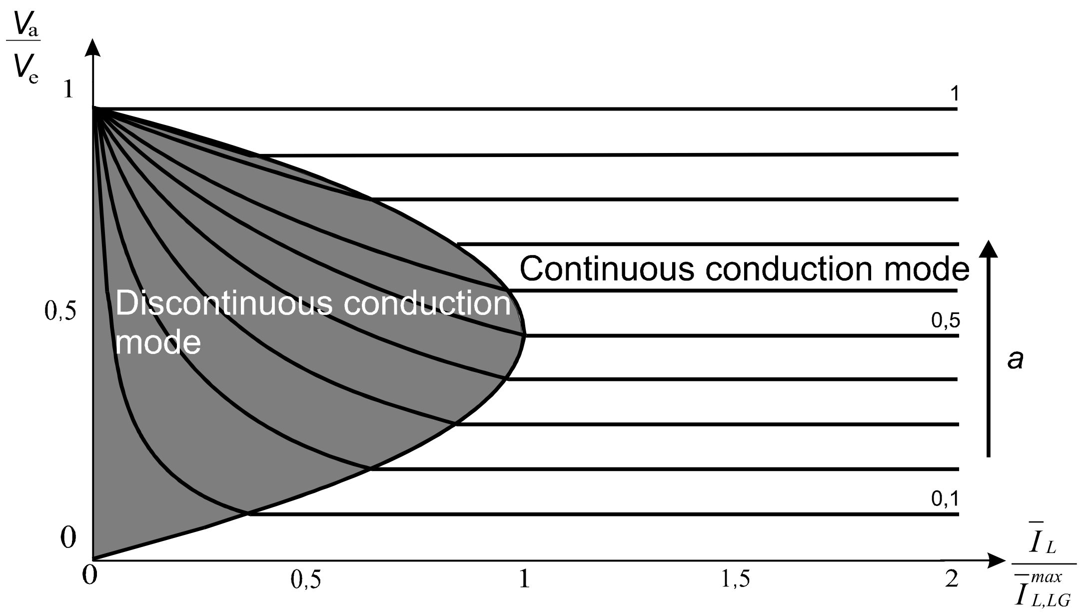

Figure 2.7: Operational diagram $V_a = f(\bar{I}_L)$ with duty cycle a as parameter and V_e=const

Note: In practice, discontinuous-conduction mode only means, that there is no longer a linear relationship between output voltage and duty cycle. This can lead to the effect, that the output voltage fluctuates more than desired, e.g. because the minimum on-periods of the devices have to be kept.

2.2 Ripple of the Output Voltage

The triangular ac current ½ · ΔI_L leads to an alternating charge ΔQ in the ideal, i.e. lossless output capacitance C_0. The charge and the discharge are equal (measured over one cycle), see Figure 2.6.

The triangular area equals:

$$2 \cdot \Delta Q = \frac{1}{2} \cdot \Delta I_{\mathrm{L}} \cdot \frac{T}{2} = \Delta I_{\mathrm{L}} \cdot \frac{T}{4} \qquad \textbf{(2.17)}$$

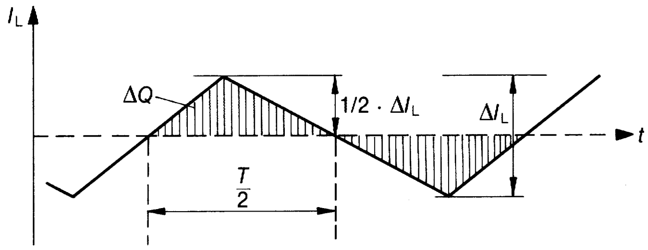

Figure 2.6: Ac current flow in the capacitance C_0

Commonly, the type of load (e.g. a CPU) determines how large the maximum ripple of the output voltage is allowed to be. Using the relationship $Q = C \cdot V$, one obtains:

$$C_0 \geq \frac{\Delta Q}{\Delta V_a} = \frac{\Delta I_L}{\Delta V_a} \frac{1}{8f} \qquad \textbf{(2.18)}$$

2.3 Synchronous Rectifier

For very large ratios of input voltage to output voltage (duty cycle *a* very small) and for very high output currents, the losses in one lumped element, the diode, become very high.

Example: Input voltage 12 V, output voltage 1.2 V (a=0.1), output current 10 A, output power 12 W

Diode forward voltage 0.7 V (conduction interval 90%)

$$P_{\mathrm{loss}} = 0.9 \cdot 10 \text{ A} \cdot 0.7 \text{ V} = 6.3 \text{ W}$$

This means, that half the output power is already consumed by one single element, due to the high forward voltage of the diode. In addition, the efficiency can never become higher than 65% in this case.

The synchronous rectifier represents a solution to this problem. For exactly the time interval, when the diode is conducting anyway, a MOSFET, connected in parallel having a very low R_{DSon} is triggered. Since the voltage drop across the MOSFET is significantly lower than the forward voltage of the diode, the diode does not become conductive. Thus, the losses are reduced.

In the example: R_{DSon} =0.010 Ohm V_{MOSFET} =0.1 V

$$P_{verl} = 0.9 \cdot 10\ \text{A} \cdot 0.1\ \text{V} = 0{,}9\ \text{W}$$

Only by this measure, the efficiency now becomes up to 93%.

Note: Actually, the MOSFET conducts the current in the inverse direction in this circuit. However, this does not represent a technical problem, since the actual MOS-channel is always bi-directional (only one type of charge carrier). Neither the parasitic body-diode in the MOSFET nor the diodes connected in parallel on the printed circuit board interfere in this case, because the forward voltage of the diode is not reached.

2.4 Boost-Mode

3 Preparation for the Experiment

Starting from the theoretical basics, some of the significant components of the converter have to be calculated. The following data are known:

Switching frequency: f = 50 kHz, 100 kHz, 150 kHz
Maximum input voltage: $V_{\mathrm{e\,max}}$ = 12 V
Maximum output voltage: $V_{\mathrm{a\,max}}$ = 6 V
Minimum output voltage: $V_{\mathrm{a\,min}}$ = 0.8 V
Maximum current at the output: $I_{\mathrm{Load\,max}}$ = 6 A

Calculate the minimum and the maximum on-periods of T for continuous-conduction mode from these data.

$t_{1\min} =$ $\qquad\qquad$ $t_{1\max} =$

3.1.1 Determination of the Inductor *L*

The inductance should be designed in a way, such that on the one hand the current ripple does not become too large (L as high as possible), but on the other hand such that the device stays as small and cheap as possible (L as low as possible).

For a given current ripple ΔI_L, we obtain from equation (2.12):

$$L = \frac{V_e \cdot (1-a) \cdot a}{\Delta I_L} T \tag{3.19}$$

Calculate the inductance L, under the assumption, that for f = 150 kHz and V_e = 12 V the current ripple should not exceed $\frac{1}{3} \cdot I_{\mathrm{Lmax}}$=2 A!

$L =$

What is the minimum current rating (peak value) of the coil?

$I =$

What happens to an inductor, if it has to conduct a higher current for a short time (instantaneously, before it is thermally overloaded)? Hint: Draw a hysteresis curve.

3.1.2 Determination of the Output Capacitance C_0

Calculate the minimum value for C_0, corresponding to the results from section 3.1.1, for $\Delta V_\mathrm{a} = 20\ \mathrm{mV}$:

C_0 =

4 Experimental Procedure

Turn the switches to "aus" (off), "buck" and "diode" accordingly (see photo).

Connect the assembled circuit as drawn:

Pay attention to the right polarity! Please note the maximum ratings of the printed circuit board and the recommended setting for the oscilloscope (Appendix A and B).

Foto Platine mit Beschriftung

Skizze Aufbau

Turn on the load and the power supply. Adjust the output voltage using the right regulator, the switching frequency using the left regulator, as well as the load current using the regulator (photos) of the load to the desired values.

Complete the following table with you measured values.

Measured Values:

f_{switch} in kHz	V_a in V	Duty Cycle a calculated	measured	Boundary dc-ccm calculated	measured	I_a in A (adjusted)	Delta I_a in A	Efficiency
150	2					1		
						2		
						3		
						4		
	6					1		
						2		
						3		
						4		
100	2					1		
						2		
						3		
						4		
	6					1		
						2		
						3		
						4		
50	2					1		
						2		
						3		
						4		
	6					1		
						2		
						3		
						4		

For the keen ones:

Synchronous Rectifier:

Repeat the measurements of the last experiment using the activated synchronous rectifier. You can activate the synchronous rectifier even during the experiment by switching from "Diode" to "SyncRect".

f_{switch} in kHz	V_a in V	Synchronous rectifier	I_a in A (adjusted)	Efficiency
50	2	Off (Freewheeling via Diode)	2	
		On (Freewheeling via MOSFET)	2	

Observe the improvement of the efficiency and explain it! What happens at I_a=0A? Why does the circuit not go into discontinuous-conduction mode?

BOOST-Mode

With activated synchronous rectifier, but at $I_a = 0$ A, the current flows alternating in both directions in the inductance. This means, that for constant input and output voltages there is energy delivered from the input to the output and from the output to the input (I_L negative).

The inductance is capable to maintain the stored current, even towards a higher voltage. This is the reason, why you can see a light arc if you turn off an inductance using a mechanical switch. This effect can be utilized to create a higher output voltage than the input voltage. Therefore the inductance is magnetized via the synchronous rectifier-MOSFET and demagnetized via the freewheeling diode by the original MOSFET.

Turn off the printed circuit board using the left switch

Connect the configuration as shown.

Turn the switch to "BOOST" and keep the switch "SyncRect" turned on.

Now, use a voltage of 6V and connect it at the right hand side (output) of the printed circuit board. If you turn on the control using the left switch again, the lamp glows.

Take a measurement of the voltage! It should be about 12V and fixed.

Skizze

Foto

5 Appendix

A: Absolute Maximum Ratings

B: Adjustments of the Oscilloscope

A: Maximum Ratings of the Printed Circuit Board

Supply: Nominal 12V, maximum 14 V, typ. 2A, maximum 4.2A*
Output: ca. 1.8 to 6V*, max. 5A*
Switching frequency: 50 kHz, 100kHz, 150 kHz.
Power efficiency: 95% (7V @ 2A) to 66% (2V @ 4A) in SyncRect-mode
Caution: The coil becomes very warm during the operation.
(*: please note overview of operational modes)

B: Adjustments of the Oscilloscope, Connections and PCB terminals

Time basis: typ: 4 us/div. Trigger to chanel 3 or 4 rising edge, all couplings DC, Hold-off minimum.Acquire-Menu: Sample-mode to "Sample"
Please: NO AUTOSETUP!

Nr:	Measured value	Socket on the board	Type of Cable	Vertical-Adjustment	Specialities
1	Current through MOSFET	1. SMC (left)	SMC->BNC	50mV DC	50 Ohm Connection in Oscilloscope, inverted, Bandwidth limitation of 20MHz
2	Duty Cycle (Gate Drives)	2. SMC (Middle)	SMC->BNC	2 V DC	-None-
3	Current through Freewheeling Diode	3. SMC	SMC->BNC	50mV DC	50 Ohm Connection in Oscilloscope, inverted, Bandwidth limitation of 20MHz
4	Current through Inductance	4. SMC	SMC->BNC	1 V DC	50 Ohm Connection in Oscilloscope, inverted, Bandwidth limitation of 20MHz
5	Output Voltage	5. SMC (Right)	SMC->BNC	100mV AC	AC-Coupling

Note: ALL measured values a referred to ground (GND of the power supply). Please avoid hum pick-up.

6 Literature

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Note: References marked with a *, are highly recommended.