Power Electronics

Exercise: Power supply circuits

2012
1 Exercises

1.1 Conventional power supply circuits

a) Draw the basic functional blocks of a conventional power supply circuit and explain roughly the functional principle of the units!

b) Draw the circuit of a linear voltage controller (with series resistor, collector resistor and emitter resistor) and explain its functional principle (the one of the resistors as well)! Which basic transistor circuit arrangement does this correspond to? Why is a Zener-diode used and not a resistor?

c) What are the advantages and drawbacks of conventional power supplies compared to switching power supplies (two advantages and two disadvantages)?

1.2 Switching power supplies

a) How can a DC voltage be converted with the help of switching devices? Explain this with a buck converter, first with a pure resistive load, then with a resistive inductive and then with a resistive inductive capacitive load!

b) How can such a switching device be controlled (two possibilities)? Explain these, their differences and their advantages and disadvantages!

c) A hysteresis control is an alternative to the two possibilities mentioned in exercise b). Explain its functional principle! Can the controlled variable be kept within the hysteresis bounds?

d) Draw the basic circuit diagram of a buck converter with smoothing capacitor! Calculate the ratio of the input and output voltage depending on the on and off times of the switch!

e) Draw the basic circuit diagram of a boost converter! Calculate the ratio of the input and output voltage depending on the on and off times of the switch!

f) Draw the basic circuit diagram of a buck-boost converter! Calculate the ratio of the input and output voltage depending on the on and off times of the switch!

g) Draw the basic circuit diagram of a Čuk converter! Calculate the ratio of the input and output voltage depending on the on and off times of the switch!
2 Solutions

2.1 Conventional power supply circuits

a) The basic functional blocks of a conventional power supply circuit can be seen in fig. 2.1. Function of the blocks:

![Diagram showing AC voltage, Rectifier, Voltage smoothing, Linear regulator leading to Load.]

Fig. 2.1: Basic functional principle of a conventional power supply circuit

b) The circuit diagram of a linear regulator can be seen in fig. 2.2.

![Diagram of a linear regulator.]

Fig. 2.2: Linear regulator

- The series resistor \( R_V \) is necessary for current limitation of the Zener-Diode (these devices can handle only small currents).
• The collector resistor \( R_C \) is necessary for the protection of the transistor in case of a short circuit \( (R_C \approx 10\,\Omega) \). Drawback: Stabilization is less effective!
• The emitter resistor \( R_E \) is necessary for tuning the operation point \( (R_E \approx 10\,k\Omega) \).

The basic transistor circuit arrangement is a collector circuit: The base is used as input, the emitter is the output. Hence, it is a collector circuit.

The basic functional principle of the circuit can be explained as follows: We assume that a certain resistor \( R_L \) is clamped at the output terminals, the circuit is furthermore in a stationary state. Now the resistor \( R_L \) becomes smaller. As the transistor is current controlled (the base current controls the emitter current), the emitter current will stay constant and hence the output voltage \( V_A \) will become smaller \( (V = R \cdot I) \). If we apply Kirchhoff’s voltage law,

\[
V_A - V_Z + V_{BE} = 0
\]

can be obtained. As the voltage drop \( V_Z \) across the Zener-Diode is constant, only the base emitter voltage \( V_{BE} \) can change. Hence, it rises. In fig. 2.3 the input characteristic of a transistor is shown. If \( V_{BE} \) rises, the base current \( i_B \) has to rise as well.

![Input characteristic of a bipolar transistor](image)

Fig. 2.3: Input characteristic of a bipolar transistor

For the emitter current

\[
i_E = \beta \cdot i_B
\]

can be obtained, whereas \( \beta \) is the current gain of the transistor. If the load current \( i_L \) rises, the load voltage rises until \( V_{BE} \) has reached its previous value. Hence, the output voltage \( V_A \) of the circuit stays constant. A linear regulator is a proportional controller, the reference value is \( V_Z - V_{BE} \), the actual value \( V_A \).

It is not possible to use a resistor instead of the Zener-Diode for stabilizing the output voltage \( V_A \):

• If the input voltage \( V_0 \) changes, the voltage drop across the resistor changes as well. This leads to a change in the output voltage \( V_A \).
• If the load changes, the base current \( i_B \) changes as well. Hence, even if ideal devices and an ideal voltage source would be used, the voltage drop across the resistor would change. This would lead to a change in the output voltage.

The Zener-Diode is absolutely necessary as a voltage reference in the circuit!

c) Conventional power supply circuits have the following advantages compared to switching power supplies:

• The output voltage ripple is much lesser than the one of switching power supplies (better voltage quality).
• A power factor correction (PFC) is normally not necessary.

Disadvantages compared to switching power supplies are:

• The efficiency of linear voltage regulators is much smaller than the one of switching power supplies.

• Much bigger transformers and heatsinks are necessary compared to switching power supplies.
### 2.2 Switching power supplies

a) A DC voltage can be stepped up or down with the help of a semiconductor switch by turning it on and off periodically. In fig. 2.4 the schematic circuit diagrams of a step-down converter for different loads are shown. For a pure resistive load it is enough to turn the switch $S$ on and off periodically in order to get an output voltage which is in the average smaller than the input voltage $V_0$. The output voltage can be calculated to

$$V_A = V_0 \cdot \frac{t_{on}}{t_{on} + t_{off}}$$

The switch $S$ is closed for $t_{on}$ and open for $t_{off}$.

If the load is, however, ohmic inductive, the switch alone is not enough anymore, as the inductor $L$ stores energy. If the switch would be opened, very high overvoltages would occur. In order not to harm the voltage source and especially the semiconductor switch, it is necessary to integrate a freewheeling diode $D$ into the circuit. In this way overvoltages across the inductor can be avoided.

For ohmic inductive and capacitive loads another problem occurs when closing the switch: The capacitor current is proportional to the derivation of the capacitor voltage. This leads to a very huge current peak. In order to damp this peak an inductor $L_D$ has to be integrated into the circuit.

As all practically realizable circuits have at least small parasitic inductances and capacitances, the integration of a freewheeling diode and of a choke for current limitation ($L_D$) is necessary. In order to smooth the chopped voltage, it also makes sense to integrate the capacitor $C$ into the circuit.

b) There are two possibilities to do the periodical switching:

Pulse width modulation (PWM): The period of one on- and off-cycle is constant, the time, in which the switch is on, can be varied. This leads to a constant switching frequency
and an optimization of the devices for this frequency is possible. A drawback of this
method is the higher effort for implementing it in an electronic circuit.

**Pulse frequency control (PFC):** The on period of the switch is constant, the period, during
which the switch is off, can be varied. Hence, the switching frequency is not constant.
Because of this no special adaptation of the devices to this frequency can be done. One
advantage is, however, that this kind of control can be realized easier in an electronic
circuit.

c) If a hysteresis or on-off control is implemented, the current or voltage which should be
controlled, is compared with an upper \( (V_{A_{\text{max}}}) \) and a lower boundary \( (V_{A_{\text{min}}}) \). If one of
the limits is exceeded, a switching state is selected which increases or decreases the current or
voltage again. As this does not happen continuously (only at the sampling time points),
the limits are normally always exceeded. As longer the sampling time is, as larger is the
violation of the hysteresis boundaries. The controlled variable could only be kept within
the boundaries if the sampling time would be infinitely high or a continuous-time controller
with infinitely small reaction time would be used!

d) The schematic circuit diagram of a buck-converter (with low-pass filter) can be seen in fig.
2.5. the inductor voltage \( v_L(t) \) is in the average equal to zero. Hence, the following can be

![Circuit diagram of a buck-converter](image)

**Fig. 2.5: Circuit diagram of a buck-converter**

stated for one period (turn-on and turn-off):

\[
\int_0^{t_{\text{on}}} v_L(t) \, dt + \int_{t_{\text{on}}}^{t_{\text{on}}+t_{\text{off}}} v_L(t) \, dt = 0
\]

If the switch S is closed, it can be stated that

\[ v_L = V_0 - V_A \]

If S is open,

\[ v_L = -V_A \]

is valid. Hence, it follows that

\[
(V_0 - V_A) \cdot t_{\text{on}} - V_A \cdot (t_{\text{on}} + t_{\text{off}} - t_{\text{on}}) = 0 \\
V_0 \cdot t_{\text{on}} - V_A \cdot t_{\text{on}} - V_A \cdot t_{\text{off}} = 0 \\
V_0 \cdot t_{\text{on}} - V_A \cdot (t_{\text{on}} + t_{\text{off}}) = 0
\]

This leads to the following ratio of the input and output voltage:

\[
\frac{V_A}{V_0} = \frac{t_{\text{on}}}{t_{\text{on}} + t_{\text{off}}}
\]
e) The circuit diagram of a boost converter can be seen in fig. 2.6. In this case the inductor voltage $v_L(t)$ is in the average equal to zero, too. For one period it can again be stated that

$$
\int_0^{t_{\text{on}}} v_L(t) \, dt + \int_{t_{\text{on}}}^{t_{\text{on}}+t_{\text{off}}} v_L(t) \, dt = 0
$$

If the switch $S$ is closed, it can be stated that

$$
v_L = V_0
$$

If the switch is open,

$$
V_0 - V_A - v_L = 0
$$

$$
v_L = V_0 - V_A
$$

is valid. Because of this it follows that

$$
V_0 \cdot t_{\text{on}} + (V_0 - V_A) \cdot t_{\text{off}} = 0
$$

$$
V_0 \cdot t_{\text{on}} + V_0 \cdot t_{\text{off}} - V_A \cdot t_{\text{off}} = 0
$$

$$
V_0(t_{\text{on}} - t_{\text{off}}) = V_A \cdot t_{\text{off}}
$$

Hence, the ratio of input and output voltage can be calculated to

$$
\frac{V_A}{V_0} = \frac{t_{\text{on}} + t_{\text{off}}}{t_{\text{off}}}
$$

f) The circuit diagram of a buck-boost converter is shown in fig. 2.7. It can again be stated
that
\[
\int_0^{t_{on}} v_L(t) \, dt + \int_{t_{on}}^{t_{on}+t_{off}} v_L(t) \, dt = 0
\]

If the switch is closed,
\[v_L = V_0\]
is valid, If the switch is opened,
\[v_L + V_A = 0\]
\[v_L = -V_A\]
is valid. Hence, it follows that
\[V_0 \cdot t_{on} - V_A \cdot t_{off} = 0\]
Then the ratio of the input and output voltage results to
\[
\frac{V_A}{V_0} = \frac{t_{on}}{t_{off}}
\]

g) The circuit diagram of a Čuk converter is shown in Fig. 2.8. In contrast to the other DC to

![](image)

**Fig. 2.8: Circuit diagram of a Čuk converter**

DC converters, in this case the voltages across both inductors are in the average equal to zero. Hence, it can be stated that
\[
\int_0^{t_{on}} v_{L0}(t) \, dt + \int_{t_{on}}^{t_{on}+t_{off}} v_{L0}(t) \, dt = 0
\]

If the switch S is closed, the following can be stated for the voltage \(v_{L0}\):
\[v_{L0} = V_0\]

For the open switch we get
\[V_0 - V_C - v_{L0} = 0\]
\[v_{L0} = V_0 - V_C\]
for $v_{L0}$. Hence, it follows that

\[
\begin{align*}
V_0 \cdot t_{on} + (V_0 - V_C) \cdot t_{off} &= 0 \\
V_0 \cdot t_{on} + V_0 \cdot t_{off} - V_C \cdot t_{off} &= 0
\end{align*}
\]

The voltage $v_{LA}$ can be calculated to:

\[
\begin{align*}
V_A - v_{LA} - V_C &= 0 \\
v_{LA} &= V_A - V_C
\end{align*}
\]

$v_{LA}$ results to

\[
v_{LA} = V_A
\]

if the switch is open. Hence it follows that

\[
\begin{align*}
(V_A - V_C) \cdot t_{on} + V_A \cdot t_{off} &= 0 \\
V_C \cdot t_{on} &= V_A \cdot (t_{on} + t_{off}) \\
V_C &= V_A \cdot \frac{t_{on} + t_{off}}{t_{on}}
\end{align*}
\]

If both resulting equations for $v_{L0}$ and $v_{LA}$ are replaced one into each other,

\[
\begin{align*}
V_0 \cdot (t_{on} + t_{off}) - V_A \cdot \frac{t_{off}}{t_{on}} (t_{on} + t_{off}) &= 0 \\
V_0 - V_A \cdot \frac{t_{off}}{t_{on}} &= 0
\end{align*}
\]

is obtained. Hence, the ratio of the input and output voltage results to

\[
\frac{V_A}{V_0} = \frac{t_{on}}{t_{off}}
\]