Power Electronics

Exercise: Line-commutated rectifiers

2012
1 Theory

Line-commutated converters are very similar to diode rectifiers, the only difference is that thyristors are used instead of diodes. Via a pulse logic control pulses synchronously to the line frequency are generated. The thyristors are fired periodically by these pulses (leading to the name line-commutated converters). The firing angle is measured from the point of the natural commutation. It can, also for three-phase circuits (M3, B6), basically be varied in the range

\[ 0^\circ \leq \alpha \leq 180^\circ \] (1.1)

If a pure resistor \( R \) is connected to such a rectifier, the flowing DC current consists of truncated sinusoidal half waves. Hence, such a kind of control is also referred to as phase control. In order to show the basic functional principle, a B2 circuit was simulated with different loads and different firing angles. In fig. 1.1 the simulation model is shown. For each one the three circuits (pure \( R \) load, \( RC \) load and \( RL \) load) three simulations with the firing angles 30°, 90° and 150° were made. The parameters were chosen as in the previous exercises:

\[
V = 230 \, \text{V} \\
\eta = 50 \, \text{Hz} \\
R = 100 \, \Omega \\
C = 50 \, \mu\text{F} \\
L = 50 \, \text{mH}
\]

In fig. 1.2 the current and voltage trajectories for a firing angle \( \alpha = 30^\circ \) are shown, in fig. 1.3 the firing angle is 90°, in fig. 1.4 150°.

The ideal DC voltage \( V_{di0} \) can be decreased to \( V_{di\alpha} \) by increasing the firing angle \( \alpha \). For a pure \( R \) load the ideal DC voltage dependent on the firing angle can be calculated to

\[
V_{di\alpha} = 2 \cdot \frac{1}{2\pi} \int_{\alpha}^{\pi} \dot{V} \sin(\omega t) \, d\omega t = \frac{\dot{V}}{\pi} (1 + \cos \alpha) = \frac{\pi}{2} V_{di0} \cdot \frac{1}{\pi} (1 + \cos \alpha) = V_{di0} \cdot \frac{1 + \cos \alpha}{2} \] (1.2)

![Fig. 1.1: PSIM@model of the B2 circuit with thyristors](image)
Fig. 1.2: Current and voltage trajectories for $\alpha = 30^\circ$

Fig. 1.3: Current and voltage trajectories for $\alpha = 90^\circ$
Fig. 1.4: Current and voltage trajectories for $\alpha = 150^\circ$

Fig. 1.5: Characteristic line of a B2 circuit for pure ohmic load
The characteristic obtained via equation 1.2 is also referred to as characteristic line for pure ohmic load. It shows the output voltage dependent on the firing angle \( \alpha \). The characteristic line for pure ohmic load can be seen in fig. 1.5.

As it can be seen in the figures 1.2, 1.3 and 1.4, the current and voltage trajectories are very similar to the ones of diode rectifiers. The only difference is that in this case the load voltage drop only occurs when the thyristors have been fired. This leads to a voltage peak at the firing time point. Considering a pure \( R \) load, the current trajectory results from the applied voltage, multiplied with the factor \( \frac{1}{\pi} \). Considering an \( RC \) load, a very high current peak results since the capacitor current is proportional to the derivation of the capacitor voltage. If an \( RL \) load is used, the current is again smoothened, i.e. it shows \( PT_1 \) behavior.

For \( RL \) loads the calculation of the ideal DC voltage for firing angles \( \alpha > 0^\circ \) is more difficult: As already mentioned, the current is still flowing, although the thyristor voltage has already become negative. This is due to the energy which is still stored in the inductor. If, however, the inductor is so large that the current does not become zero anymore, the thyristors are conducting for \( 180^\circ \) (B2 circuit) and the ideal DC voltage dependent on the firing angle can again be calculated easily:

\[
V_{\text{dia}} = 2 \left( \frac{1}{2\pi} \int_{\alpha}^{\alpha+\pi} \dot{V} \sin(\omega t) \, d\omega t \right) = \frac{2\sqrt{2}}{\pi} \dot{V} \cos \alpha = V_{\text{d.io}} \cos \alpha
\]

The control characteristic for inductive loads with nonzero load current is shown in fig. 1.6. It has to be noted that for firing angles \( \alpha > \frac{\pi}{2} \) the voltage \( V_{\text{dia}} \) will become negative. The

![Control characteristic of a B2 circuit for inductive loads with nonzero load current](image)

Fig. 1.6: Control characteristic of a B2 circuit for inductive loads with nonzero load current

current direction does not change, hence the direction of energy flow changes. For a nonzero load current firing angles \( \alpha > \frac{\pi}{2} \) do only make sense if a voltage source which should delivers energy into the AC grid is connected to the DC side. The converter works for firing angles \( 0 \geq \alpha < \frac{\pi}{2} \) in rectifier mode, for \( \frac{\pi}{2} < \alpha < \pi \) in inverter mode. This is also the case for circuits with a higher number of pulses and for three-phase circuits (as it can be seen from equation 1.4).

For circuits with \( p \) pulses \( (p \geq 2) \) and a nonzero load current the ideal average DC voltage
dependent on the firing angle $\alpha$ can be calculated as follows:

$$V_{die} = \frac{p}{2\pi} \int_{\frac{\pi}{p} + \alpha}^{\frac{3\pi}{2} + \alpha} \hat{V} \cdot \cos(\omega t) \, d\omega t = \ldots \hat{V} \cdot \left( \frac{P}{\pi} \right) \cdot \sin \left( \frac{\pi}{p} \right) \cdot \cos \alpha = V_{di0} \cdot \cos \alpha$$ (1.4)
2 Exercises

Draw

a) for an M2 circuit,

![M2 circuit diagram](image)

Fig. 2.1: M2 circuit

b) for a B2 circuit,

![B2 circuit diagram](image)

Fig. 2.2: B2 circuit

c) for an M3 circuit and

d) for a B6 circuit

the natural firing point in the corresponding graphs and draw the load voltage trajectory $u_d(t)$, the voltage drop $u_{T1}(t)$ across thyristor 1 and the semiconductor current trajectories $i_{T2}(t)$ for $\alpha = 30^\circ$ and $\alpha = 150^\circ$. In this case the load current $i_d(t)$ can be assumed to be constant, i.e. $i_d(t) = I_d = \text{const}$. Commutation losses can also be neglected.
Fig. 2.3: M3 circuit

Fig. 2.4: B6 circuit
a) M2 circuit:

\[ \alpha = 30^\circ \quad \text{M2} \quad \alpha = 150^\circ \]

\[ 2u_b1 = u_{b1} - u_{b2} \]

\[ i_{T1} \quad i_{T2} \]
b) B2 circuit:

\[
\alpha = 30^\circ \quad \text{**B2**} \quad \alpha = 150^\circ
\]

\[
\alpha
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\alpha
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\alpha
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\alpha
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\alpha
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\alpha
\]
c) M3 circuit:

\[ \alpha = 30° \quad \text{M3} \quad \alpha = 150° \]

\[ \begin{array}{ccc}
\text{u}_d & \alpha & 1 \quad 2 \quad 3 \\
\text{u}_{T1} & & 12 \quad 13 \\
\text{i}_{T1} & & 12 \quad 13 \\
\text{i}_{T2} & & 12 \quad 13 \\
\text{i}_{T3} & & 12 \quad 13 \\
\end{array} \]
d) B6 circuit:
2.1 Solution

a) M2 circuit:

\[ \alpha = 30^\circ \quad \textbf{M2} \quad \alpha = 150^\circ \]

\[ 2u_{s1} = u_{s1} - u_{s2} \]
b) B2 circuit:

\[ \alpha = 30^\circ \quad \textbf{B2} \quad \alpha = 150^\circ \]
c) M3 circuit:

\[ \alpha = 30^\circ \quad \text{M3} \quad \alpha = 150^\circ \]

\[ u_d \]

\[ u_{T1} \]

\[ i_{T1} \]

\[ i_{T2} \]

\[ i_{T3} \]

\[ T_1 \]

\[ T_2 \]

\[ T_3 \]
d) B6-Schaltung:

\[ \alpha = 0^\circ \]

\[ u_I \]

\[ u_{II} \]

\[ u_d = u_I - u_{II} \]

\[ u_{T1} \]

\[ i_{s1} \]

\[ i_{s2} \]

\[ i_{s3} \]