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ELECTRICAL POWER ENGINEERING

LABORATORY I

Experiment 7:

Line-Commutated Converters

1 Characteristics of Line-Commutated Converters

A converter is a power conversion stage for control and conversion of electrical energy, which utilizes power semiconductor devices (= electronic switches, e.g., thyristors, transistors) controlled by signal electronics.

In contrast to forced-commutated converters, line-commutated converters (naturally commutated converters) do not require active turn-off semiconductor switches but can use thyristors, which can only be forced to turn on. Thyristors operate in single-phase as well as in three-phase ac power grids in which the current in one thyristor becomes zero before another thyristor is turned on (discontinuous operation), or the thyristor current is forced to zero by turning on another thyristor, because the load current changes from one thyristor to the other one (commutation).

A converter which is used to convert single-phase or three-phase ac voltage to dc voltage is called a rectifier. There are two kinds of rectifiers, controllable and uncontrollable rectifiers. A rectifier is controllable, if the electric valves can be forced to turn on by control signals i.e., thyristors are also called Silicon Controlled rectifiers (SCRs). A rectifier whose electric valves are all diodes is an uncontrollable rectifier. Using controlled rectifiers, the output quantities can be adjusted. A controlled rectifier can also be used to convert energy from dc voltage to a single-phase or three-phase ac grid. In this case the rectifier is operating in the inverting mode.

The instant of natural conduction refers to the instant at which the electrical valves begin to conduct the current, with the assumption that the electrical valves are diodes or thyristors whose gate currents are continuously applied. The firing angle or the delay angle a is defined with respect to this instant of natural conduction.

There are different topologies for line-commutated converters. The most important topologies are bridge topologies and center-tap topologies.

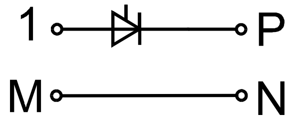
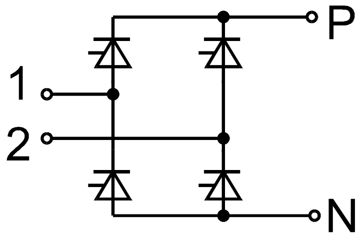
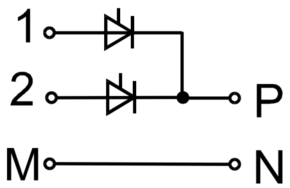
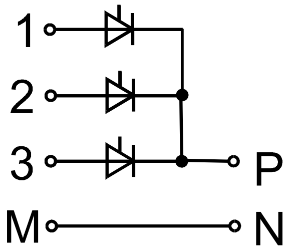
In bridge topologies (abbreviated by B), the converter terminals connected to the ac power grid conduct ac currents. The terminals of the electrical valves on the dc side which have the same polarity, are connected together and used as dc terminals.

In center-tap topologies (abbreviated by M), the converter terminals connected to the ac power grid conduct currents only in one direction. All terminals of the electrical valves on the dc side are connected together and used as one dc terminal. The other dc terminal is the neutral of the single-phase or three-phase ac system.

An important feature of the bridge and the center-tap topologies is the pulse number p. It is the ratio of the fundamental frequency of ac component in the rectified dc voltage to the lines frequency, when the converters are operated at minimum a.

Pulse numbers are important features and are applied to identify converters, for example, the two pulse-bridge topology can be abbreviated as B2. However, the behavior of the line-commutated converters is still not completely described by this abbreviation. It should be noted that the behavior of the converter can also be influenced by the dc-link or load connected to the converter depending on its design and characteristics.

Table 1 illustrates the most commonly used bridge and center tap topology. Topologies with higher pulse number (p=6) and converters with special feature (current reverse in dc-link) can be built by using the combination of these given basic configuration.

<table>
<tr><th></th><th>Bridge</th><th>Center tap</th></tr>
<tr><td>p = 1</td><td>——</td><td>M1 
</td></tr>
<tr><td>p = 2</td><td>B2 
</td><td>M2 
</td></tr>
<tr><td>p = 3</td><td>——</td><td>M3 
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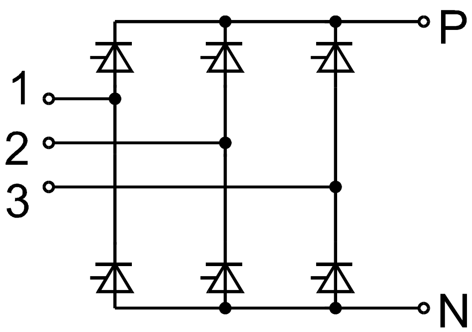
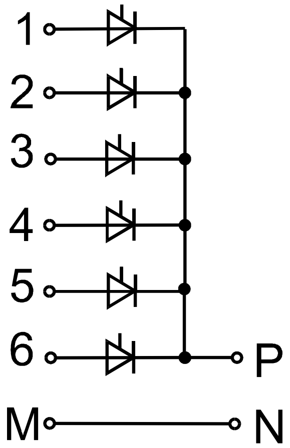
<tr><td>p = 6</td><td>B6 
</td><td>M6 
</td></tr>
</table>

Table 1 Line-frequency bridge and center tap converter

In this experiment, the operation principles of a controlled B2-converter in rectifier and inverter mode are investigated.

2 Characteristics of Thyristors

Fig. 1 shows a real (a) and an ideal (b) characteristic of a thyristor also called Silicon Controlled Rectifier (SCR). Operating states of a thyristor can be defined as follows:

- Forward blocking state
- Reverse blocking state
- Conduction state

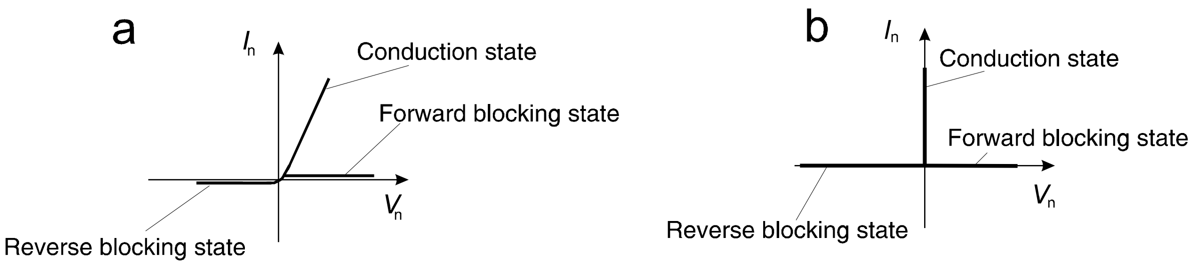


Fig. 1 Thyristor characteristics (a: real, b: ideal)

In the simplified circuit analysis, it is sufficient to apply the ideal characteristics (Fig. 1b). The idealized characteristic is based on following two assumptions:

- When the device is in blocking state, the device leakage current is zero.
- When the device is in conduction-state, the device forward voltage is zero.

3 Simplified Analysis of B2-Converter

Fig. 2 illustrates a fundamental B2-converter with terms of voltage, current and devices.

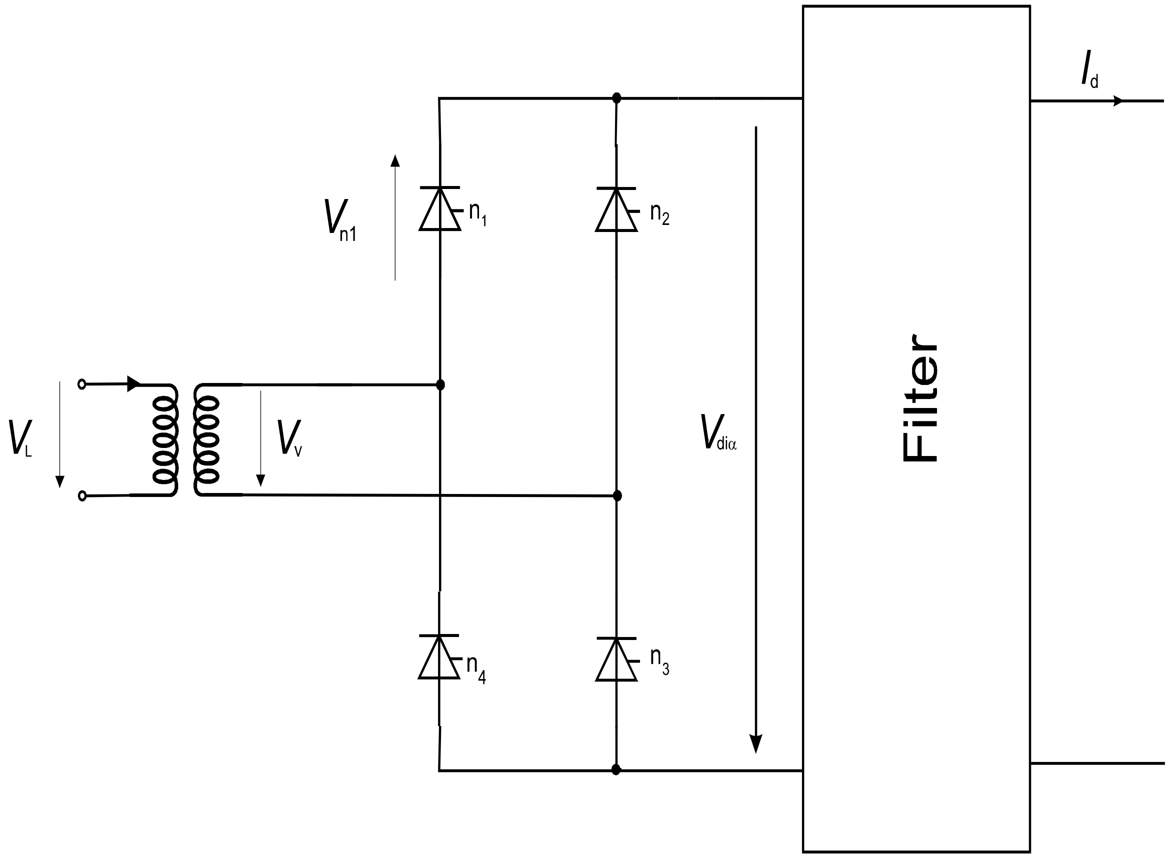


Fig. 2 Fundamental B2-converter

The magnetizing current, the flux leakage and losses of the transformer are neglected in this analysis. The ac grid is assumed to behave as an ideal sinusoidal voltage source (Fig. 3). All the devices are fired at the same firing angle a. This means that n_1 and n_3 conduct in the first half cycle and n_2 and n_4 conduct simultaneously in the second half cycle. Fig. 4 shows the current- and voltage curves in the operation with a pure resistive load without a filter. The current I_d and the internal rectified dc voltage V_{dia} are proportional to each other and pulsate at twice the line frequency between their peak values and zero.

The current I_d consists of a dc and an ac component:

$$I_d = \bar{I}_d + I_{d\sim}$$

Since the converter is utilized to supply dc voltage, the ac component of the current must be reduced ($I_{d\sim}$ ® 0) for most applications. This is realized by applying an additional filter in the circuit.

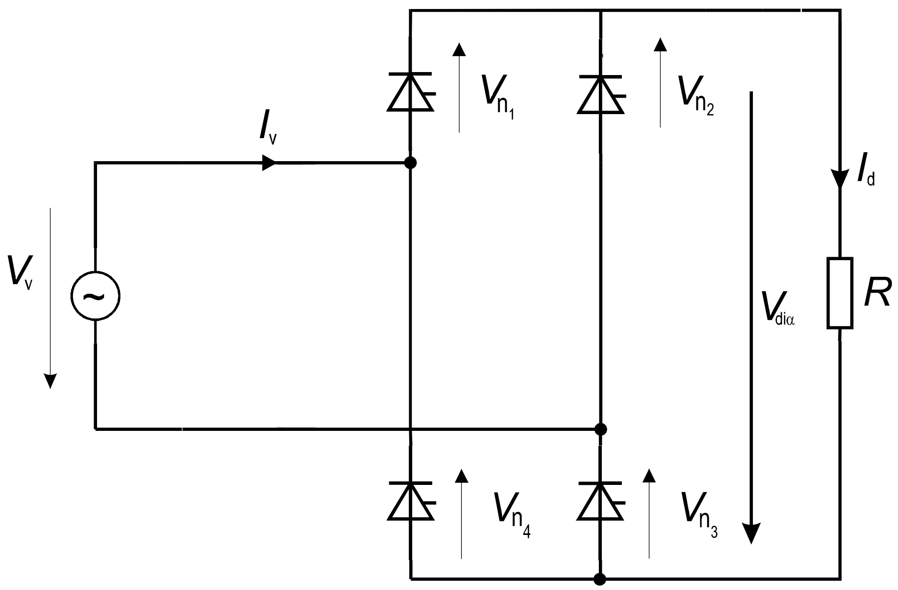


Fig. 3 B2-converter with a resistive load

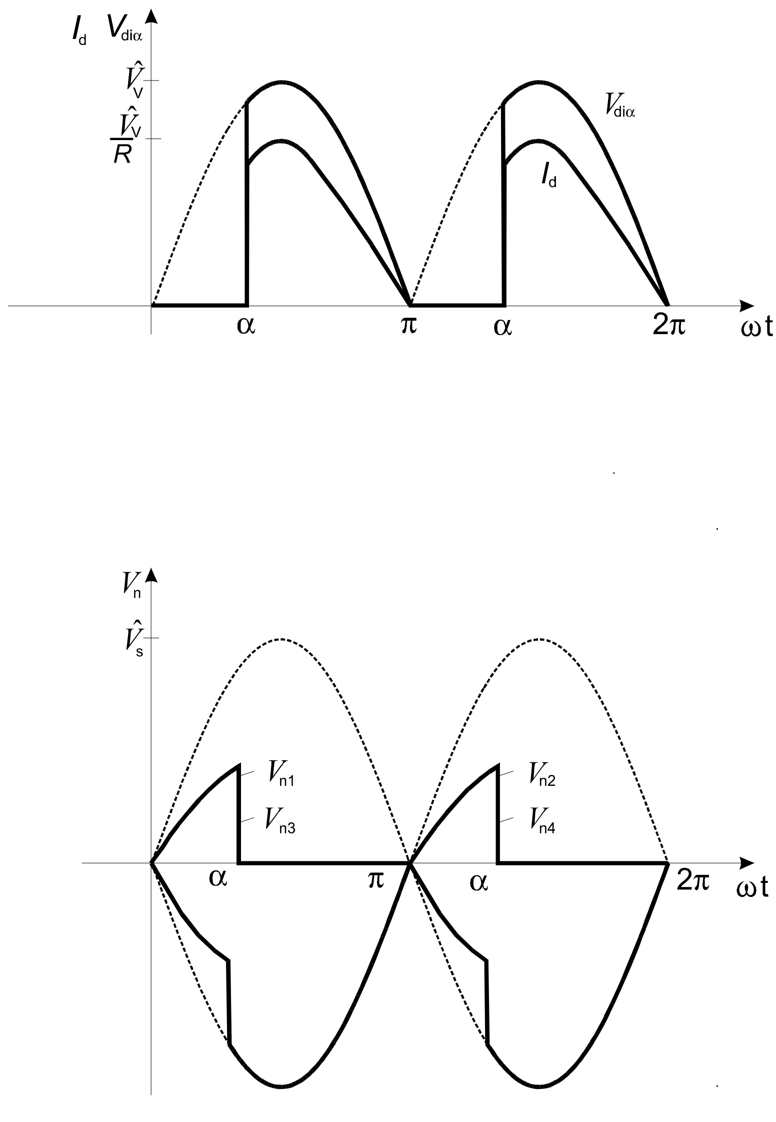


Fig. 4 Voltage and current curves of the load and thyristors

3.1 Inductive Filtering

In higher power applications, an inductive filter is preferred. It is achieved by inserting a filter inductor between the converter and the dc load. At first, the filter is assumed to be ideal (see further). Additionally, all losses and all inductances except the filter inductance L_d are neglected.

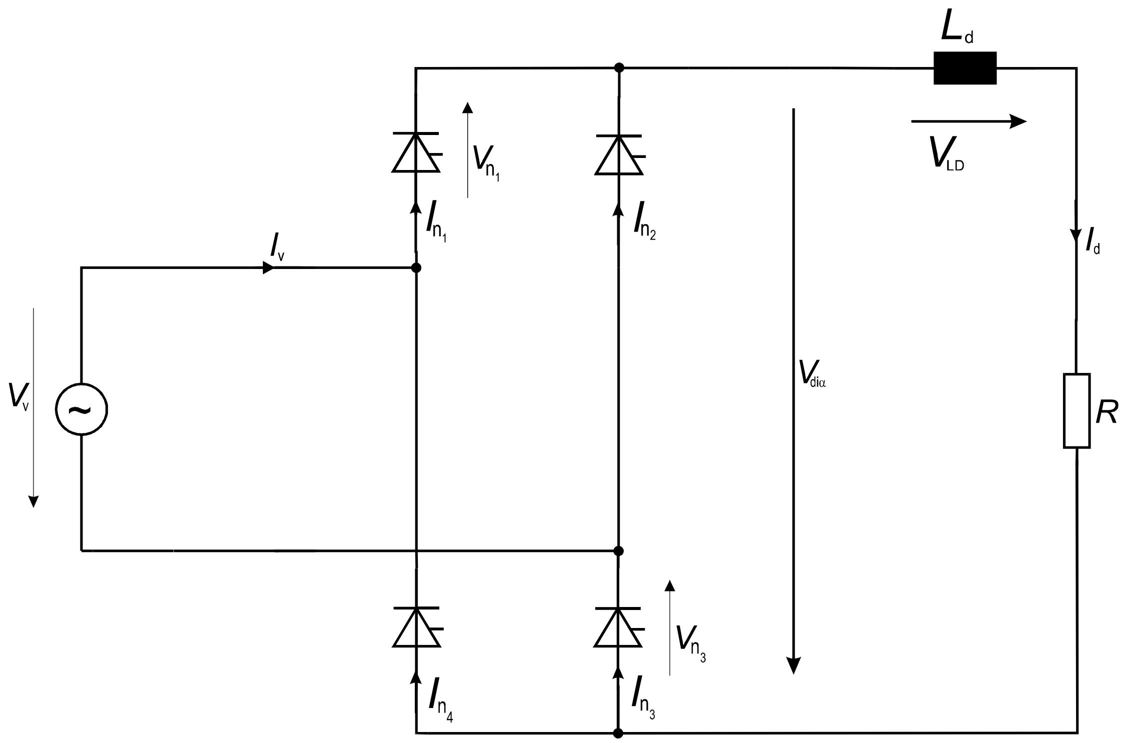


Fig. 5 B2-converter with inductive filter and resistive load

3.1.1 Ideal Filter (L_d ® ¥)

For the ideal filter, the value of the inductance L_d is assumed to be very large so that the current I_d can be considered constant.

Fig. 6 illustrates typical voltage and current waveforms. The rectified voltage V_{dia} consists of a dc and an ac component. The ac component appears at L_d and the dc component at R ($\overline{V}_{dia} = R\, I_d$).

In the interval 0 < ? t < *a*, the thyristors n_2 and n_4 conduct and the thyristors n_1 and n_3 are supplied with a positive voltage (blocking voltage). At the instant *? t* = *a*, the thyristors n_1 and n_3 are fired. In the same time, two short circuit paths (commutating circuit paths with the short-circuit currents I_k) are formed (n_1, n_2, V_v and n_3, n_4, V_v Fig. 7). This leads to the consequence in which the current in n_2 and n_4 decreases while the current in n_1 and n_3 increases. Since the commutating circuit path does not contain any resistance or reactance, the commutation is carried out very quickly, i.e. at the instant at which n_1 and n_3 are fired, the SCRs n_2 and n_4 turn off.

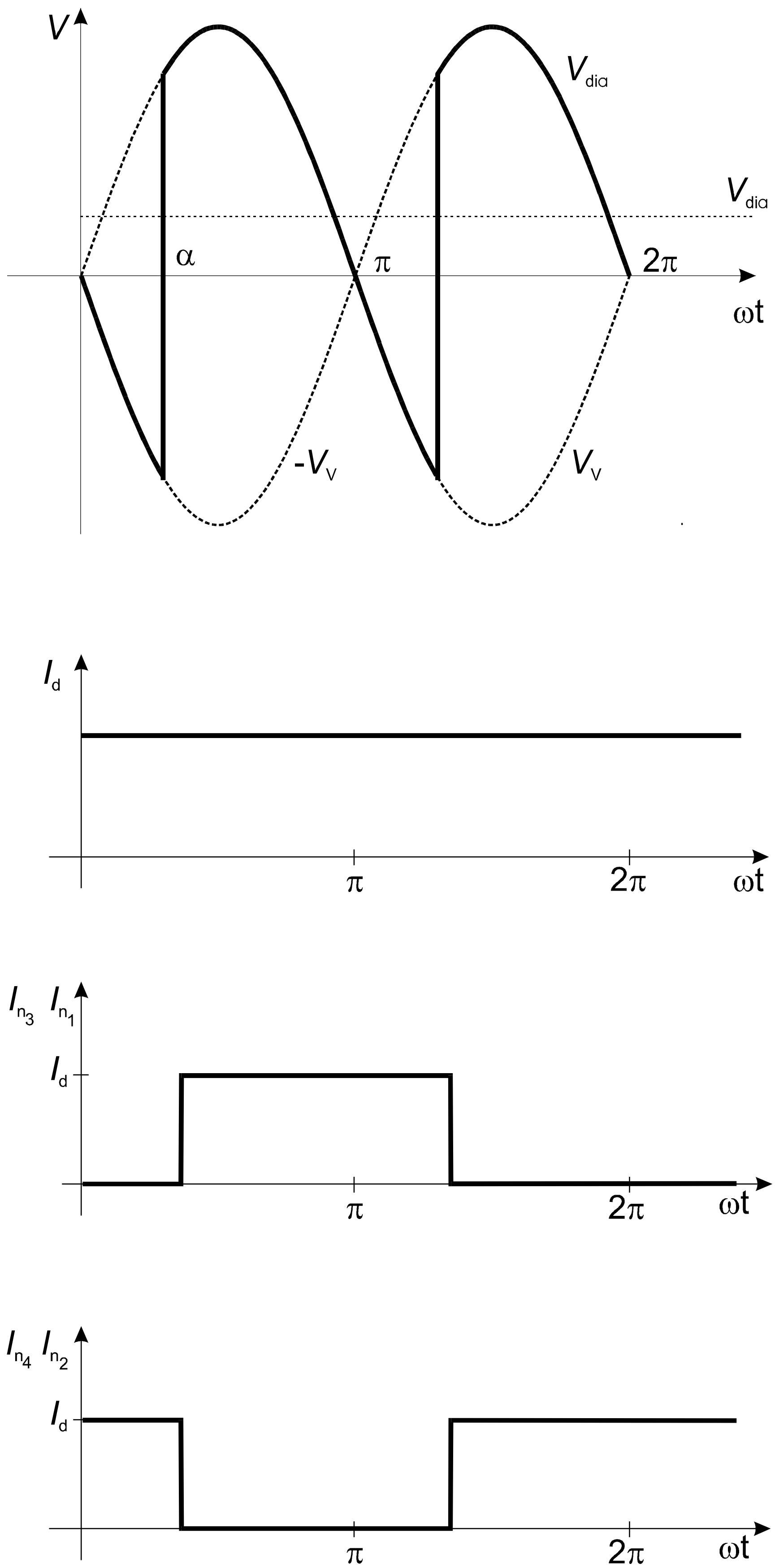


Fig. 6 Voltage and current curves of B2-converter with ideal inductive filter

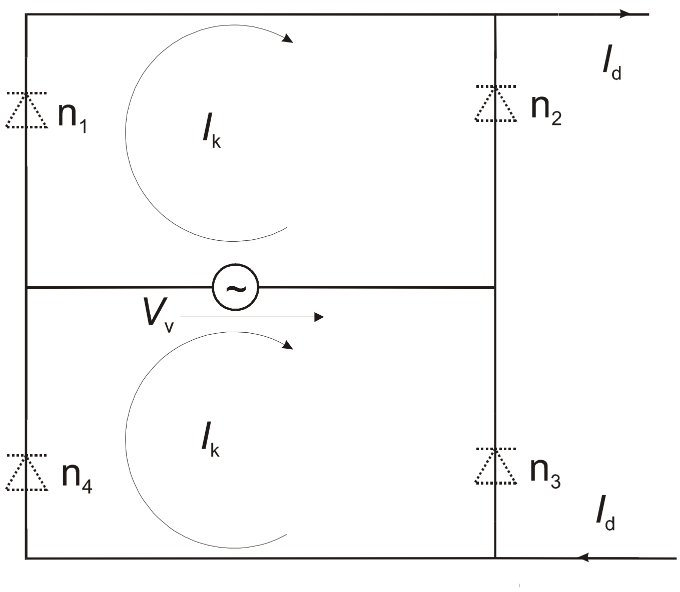


Fig. 7 Commutating circuit paths of B2-converter

The average value of the dc voltage $\overline{V}_{\mathrm{di}\alpha}$ (dc component), which depends on the firing angle α, can be derived as follows

$$\overline{V}_{\mathrm{di}\alpha} = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} \hat{V}_{\mathrm{V}} \cdot \sin \omega t \cdot \mathrm{d}\omega t = \frac{1}{\pi} \cdot \hat{V}_{\mathrm{V}} \cdot (-\cos \omega t)\Big|_{\alpha}^{\pi+\alpha}$$

$$= \frac{2}{\pi} \cdot \sqrt{2} \cdot \tilde{V}_{\mathrm{V}} \cdot \cos \alpha = \overline{V}_{\mathrm{di0}} \cdot \cos \alpha$$

with $$\overline{V}_{\mathrm{di0}} = \frac{2}{\pi} \cdot \sqrt{2} \cdot \tilde{V}_{\mathrm{V}} .$$

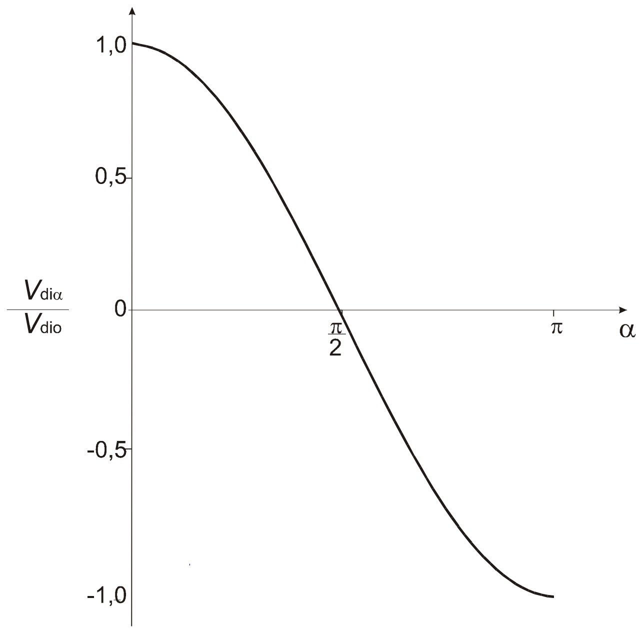


Fig. 8 Control characteristic of a B2-converter with ideal filter inductor

Fig. 8 illustrates the control characteristic of the B2-converter. This characteristic describes the ratio of the output voltage $\overline{V}_{\mathrm{dia}}$ and the maximum output voltage $\overline{V}_{\mathrm{di0}}$ as a function of the firing angle a.

Using the configuration with the resistive load in Fig. 5, the converter cannot operate in steady state with a firing angle a > p/2. If the converter operates with a firing angle a > p/2, the output voltage $\overline{V}_{\mathrm{di}a}$ should become negative corresponding to the characteristic in Fig. 8 and the power would be fed back to the ac grid. This operation is, however, not possible, since the resistive load cannot deliver any power. If a dc voltage source $V_{\mathrm{dc}} = \overline{V}_{\mathrm{dia}}$ (Fig. 9) is applied as the load, the power can flow now from the dc side to the ac side. This operation is called inverter mode, which is the second part of the characteristic in Fig. 8. Fig. 10 shows the corresponding voltage- and current-time curves (L_{d} ® ¥). In the ac side, the reversal of the energy flow can be recognized. The fundamental component ${}^1I_{\mathrm{V}}$ of the current I_{V} lags the alternating voltage with an angle greater than 90º. i.e.,

$$\tilde{V}_{\mathrm{V}} \cdot {}^1\tilde{I}_{\mathrm{V}} \cdot \cos j_1 < 0$$

and the ac grid is absorbing power.

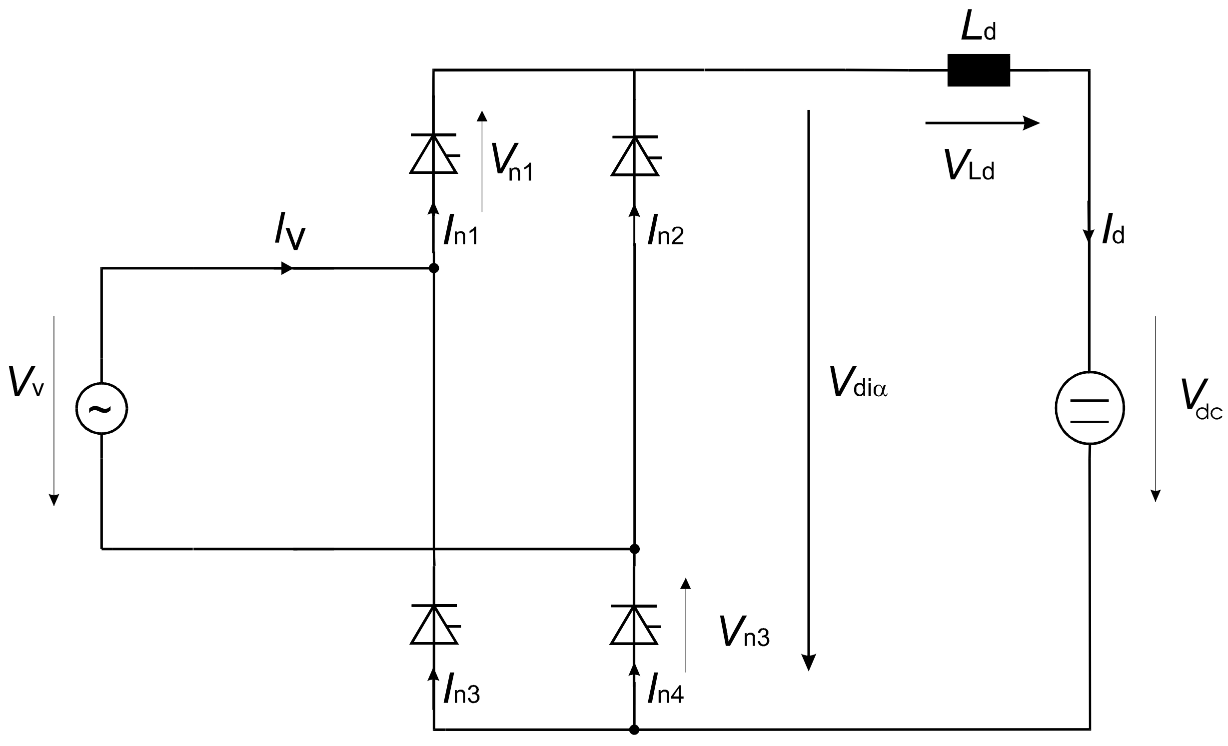


Fig. 9 B2-converter with inductive filter and dc voltage source as load

The shaded voltage area in Fig. 10 is the integral of the inductor voltage over one period of time. Since the average voltage across the inductance is always zero in steady-state operation, the positive voltage area $(V_{\mathrm{dia}} > \overline{V}_{\mathrm{dia}})$ must be equal to the negative voltage area $(V_{\mathrm{dia}} < \overline{V}_{\mathrm{dia}})$ and

$$\overline{V}_{\mathrm{dia}} = V_{\mathrm{dc}}$$

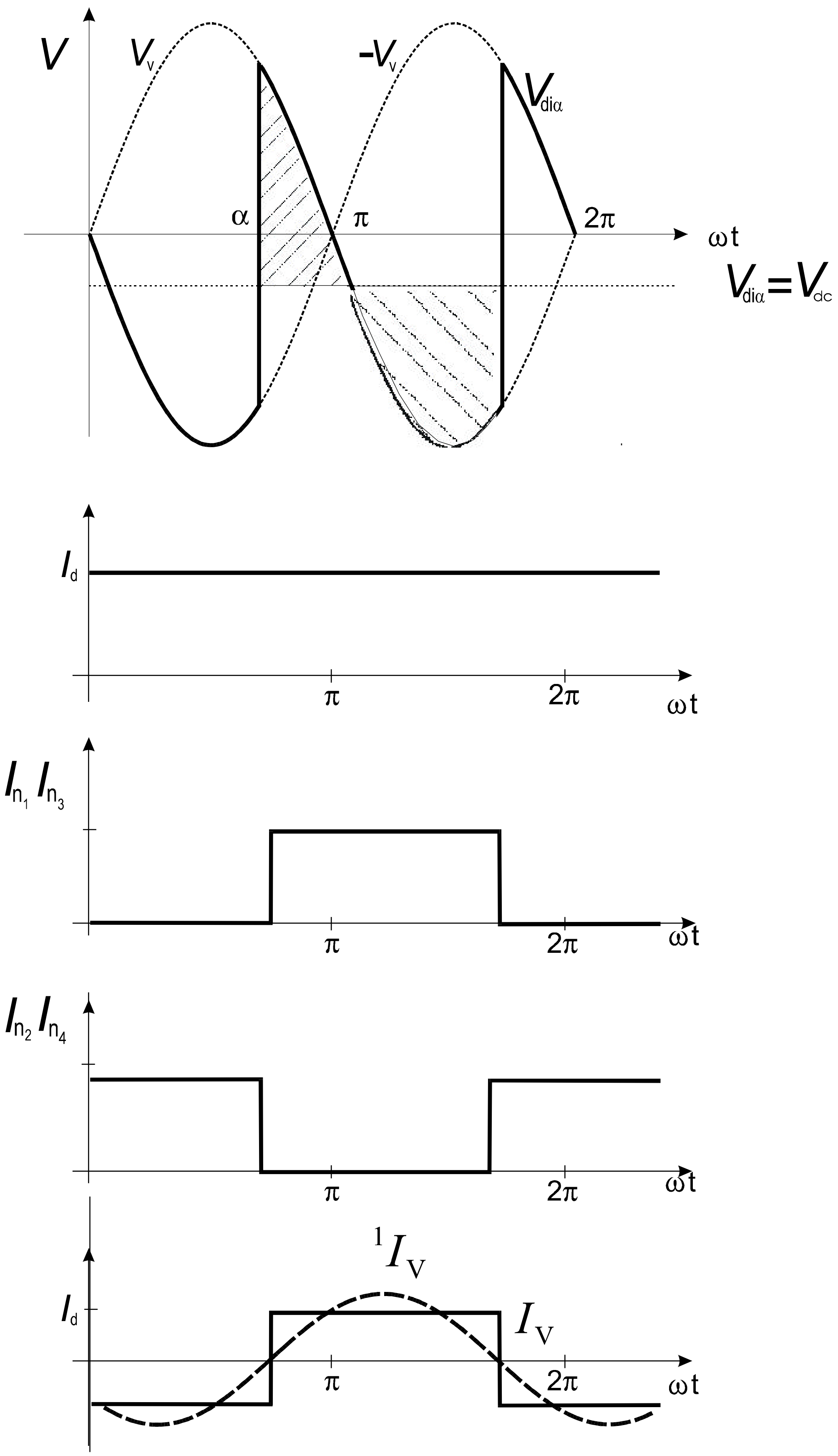


Fig. 10 Voltage and current curves of the B2-converter in Fig. 9 in inverter mode with L_d ® ¥, a. = 2p/3 and V_{dc} < 0

If it is assumed that the value of V_{dc} remains unchanged (as shown in Fig. 10) but the firing angle *a* is reduced, then the positive voltage area increases and the negative area decreases. As a result, the current in the inductance increases continuously until it becomes a short-circuit. Therefore, the firing angle *a*, which determines the value of V_{dia}, must be adjusted corresponding to V_{dc} to maintain a steady state operation (with limited current).

In practice, the possible maximum firing angle *a* is also determined by the **recovery time t_q**. The recovery time is a characteristic of thyristors. It is the time used by the thyristor to recover from the turn-on state after the thyristor current becomes zero until the thyristor completely turns off. During the recovery time, forward blocking mode is not allowed. This recovery time depends on the current flowing in the thyristor prior to turn off, the blocking voltage, the temperature and the design parameters of the thyristors (see data sheets). The **hold-off time t_c** is the time interval in which, after the zero-crossing of the current no blocking voltage is applied across the thyristor. This hold-off time is determined by the converter. One must guarantee that t_c ³ t_q.

If the hold-off time is less than the recovery time, the thyristors cannot recover and therefore latch i.e. continue to conduct the current. Moreover, the thyristors, which are just turned on, cannot take over the current from the previous thyristors. As a result, a commutation failure occurs leading to a sudden high positive rectified voltage at the output potentially causing a high short-circuit current.

3.1.2 Real Filter (L_d finite)

A infinite inductive filter is technically not possible to realize and a very large inductive filter is usually expensive due to difficulties in production. Therefore, in reality, the dc output voltage of the converter contains more or less ac components by using a finite inductive filter. As long as the current I_d does not become zero, the converter operates in a **continuous conduction mode**. If the average value of the load current I_d becomes small, the instantaneous value of I_d will reach zero (due to the unipolar characteristic of the thyristor which prevents current reversal) and remains at zero for a while before it rises again. This operation is called **discontinuous conduction mode**.

3.1.2.1 Continuous Conduction mode

For the analysis of this operation the circuit in Fig. 5 is used. However a finite value of L_d is applied instead of the infinite L_d.

During one period of the dc side (= one half period of the ac side), one pair of thyristors, e.g. n_1 and n_3 conducts. In this operation, the instantaneous current is not anymore constant due to the finite inductive filter and it can be calculated using the mesh-equation:

$$v_{\mathrm{dia}}(t) = v_{\mathrm{V}}(t) = Ri_{\mathrm{d}}(t) + L_{\mathrm{d}} \frac{\mathrm{d}i_{\mathrm{d}}(t)}{\mathrm{d}t}$$

The result is qualitatively illustrated in Fig. 11.

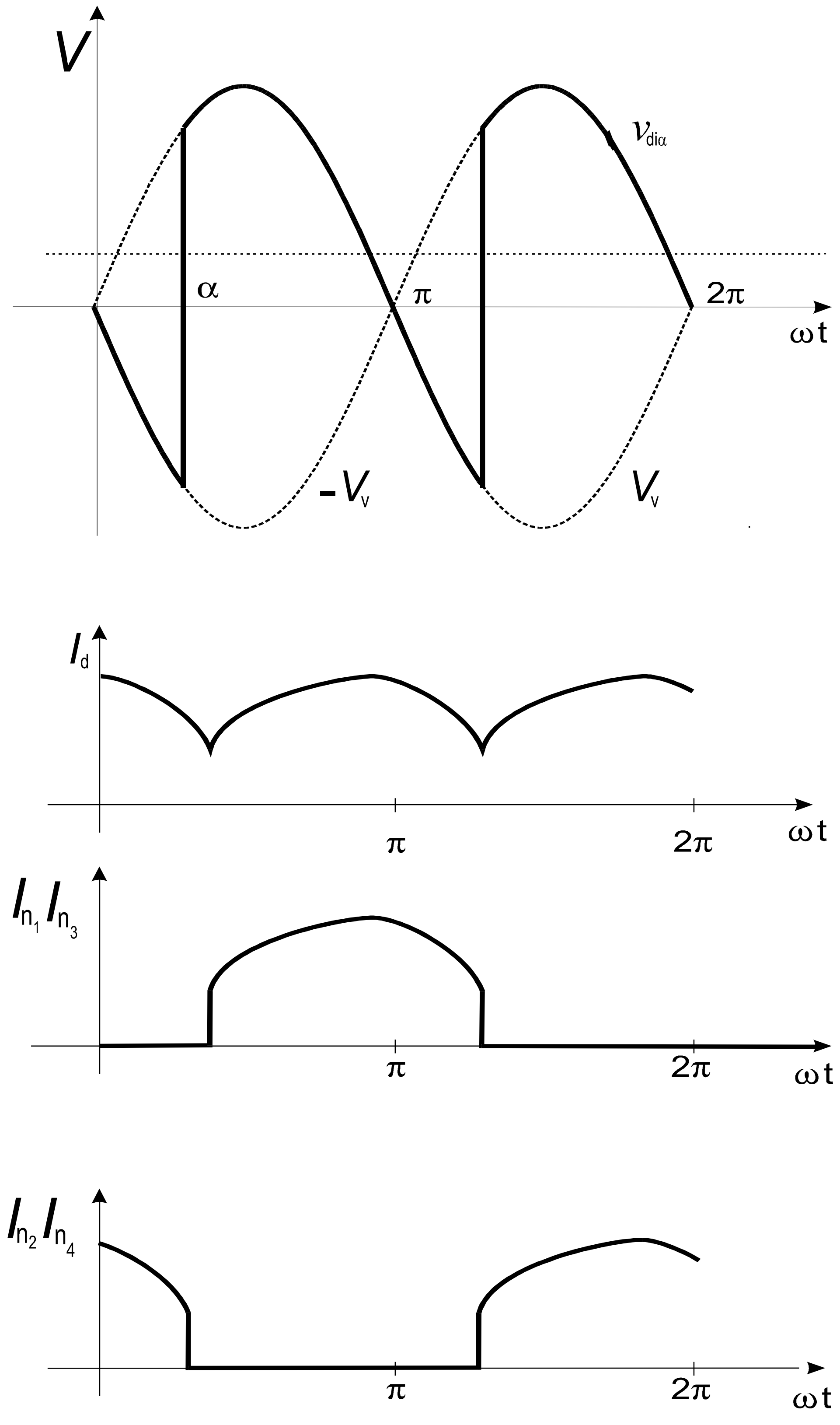


Fig. 11 Voltage and current curves of a B2-converter with a finite inductive filter

The average current $\bar{I}_\mathrm{d}$ can be determined by integrating the above mesh-equation during the conduction period of the thyristors n_1 und n_3 ($\alpha \le \omega t \le \pi+\alpha$):

$$\int_{\alpha}^{\pi+\alpha} v_\mathrm{dia} \cdot \mathrm{d}\omega t = \int_{\alpha}^{\pi+\alpha} v_\mathrm{V} \cdot \mathrm{d}\omega t = R \int_{\alpha}^{\pi+\alpha} i_\mathrm{d} \cdot \mathrm{d}\omega t + \omega \cdot L_\mathrm{d} \int_{\alpha}^{\pi+\alpha} \frac{\mathrm{d}i_\mathrm{d}}{\mathrm{d}\omega t}\, \mathrm{d}\omega t\,.$$

Considering that

$$\bar{I}_\mathrm{d} = \frac{1}{\pi} \int_{\alpha}^{\pi+\alpha} i_\mathrm{d} \cdot \mathrm{d}\omega t$$

and

$$\int_{\alpha}^{\pi+\alpha} \frac{\mathrm{d}i_d}{\mathrm{d}\omega t} \cdot \mathrm{d}\omega t = i_\mathrm{d}(\pi+\alpha) - i_\mathrm{d}(\alpha)$$

the following equation is obtained:

$$\int_{\alpha}^{\pi+\alpha} v_\mathrm{V}\,\mathrm{d}\omega t = \pi R \bar{I}_\mathrm{d} + \omega L_d\,[\, i_\mathrm{d}(\pi+\alpha) - i_\mathrm{d}(\alpha)\,]$$

Since the current I_d repeats periodically for every angle p, the following condition can be applied:

$$i_\mathrm{d}(\pi+\alpha) = i_\mathrm{d}(\alpha).$$

Therefore, the above equation is simplified as follows:

$$R\bar{I}_\mathrm{d} = \frac{1}{\pi} \int_{\alpha}^{\pi+\alpha} v_\mathrm{V} \cdot \mathrm{d}\omega t.$$

The right-hand side expression of the above equation is already calculated in section 3.1.1 as the average value of the rectified voltage. As a result:

$$\bar{V}_\mathrm{dia} = R\bar{I}_\mathrm{d}.$$

3.1.2.2 Discontinuous Operation

In discontinuous operation, the current I_d reaches zero value, before the other device turns on. For the converter with a dc voltage source in Fig. 9, the voltage and current-characteristics in discontinuous operation are shown in Fig.12.

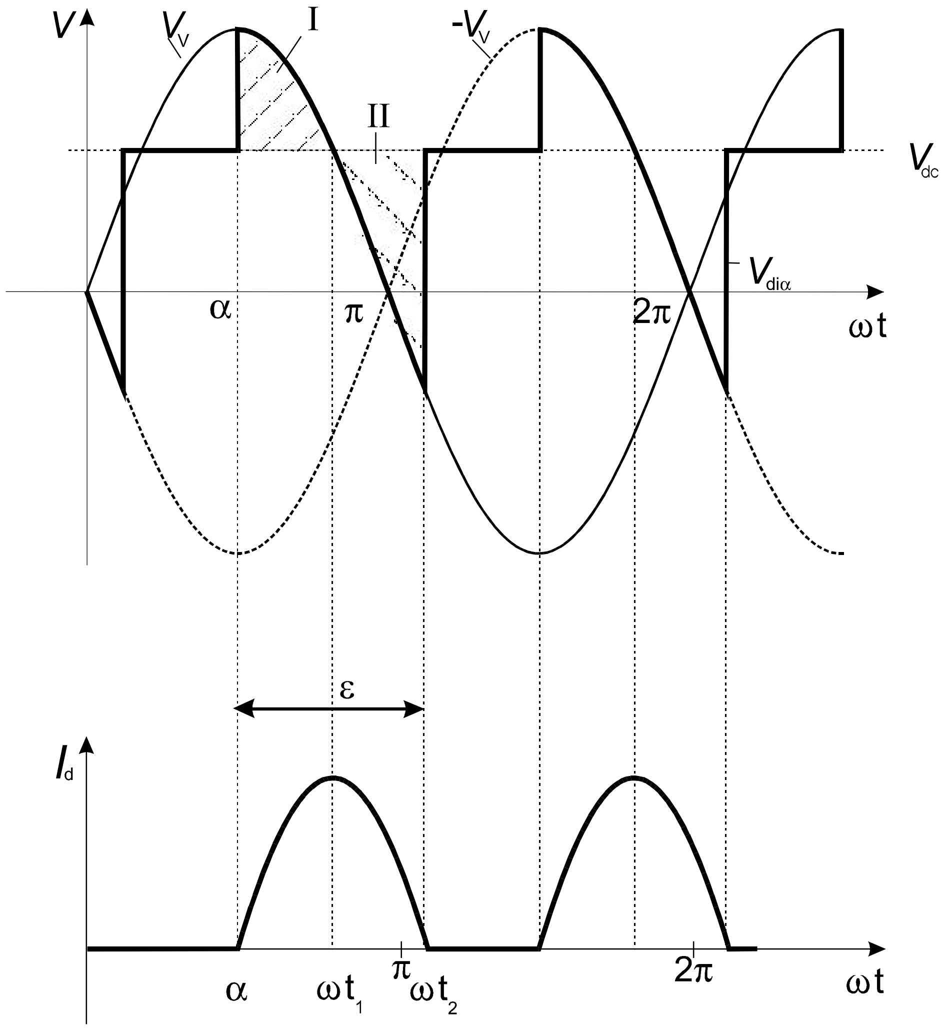


Fig. 12 Voltage and current curves for B2-converter in discontinuous operation

At an angle *a*, the electric valves n_1 and n_3 are fired. In the interval a = ? t = ? t_1, V_v is greater than V_{dc} and the inductance L_d is supplied by a positive voltage so that the current I_d increases and magnetizes the inductance L_d. Here the voltage area I is obtained. In the interval (? t_1=? t=? t_2), the voltage across the inductance L_d becomes negative. The current I_d decreases and starts demagnetizing L_d. Here the voltage area II is obtained. The current I_d becomes zero at ? t = ? t_2, when the inductance L_d is completely demagnetized. At this time, the voltage area II is equal to the voltage area I.

The angle between *a* and ? t_2 is called conduction angle *e*. It depends on the firing angle *a* and the ratio $V_{dc} / \hat{V}_V$.

In a two-pulse rectifier, the discontinuous operation occurs if *e* = *p*. The conduction angle *e* = *p* is given as a boundary condition for discontinuous operation.

If a resistance is applied as load or inserted in series with a dc voltage source, then the discontinuous operation is also possible. The conduction angle depends on *a*, R/wL_d and $V_{dc} / \hat{V}_V$.

When the device current is zero, the voltage V_{dc} has an influence on the device voltage and the device can be fired only in forward blocking state. This means that at the time, at which the device is fired, the voltage V_v must be larger than V_{dc}. A minimum firing angle a_{min}, which can be applied, is determined by:

$$a_{\min} = \arcsin\left(\frac{V_{dc}}{\hat{V}_V}\right)$$

3.2 Capacitive Filtering

In low power applications, a capacitive filter is usually applied. A capacitive filter can be achieved by connecting a filter capacitor C parallel to the resistive load R (Fig. 13). Similarly to the analysis carried out before, losses and inductance are neglected in order to simplify the analysis. In the following investigation of capacitive filtering, diodes are applied as the electric valves instead of thyristors, because the capacitive filter is mainly utilized together with diode-rectifiers.

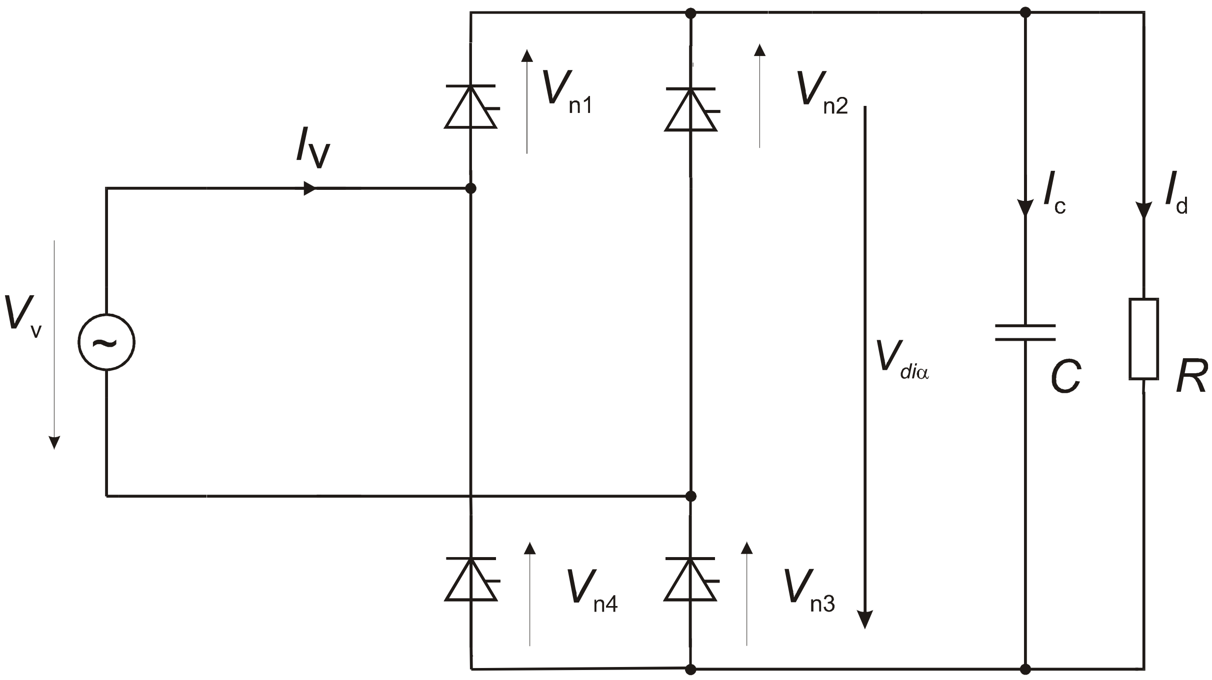


Fig. 13 B2-converter with capacitive filter

Similarly to inductive filtering in discontinuous operation, the devices n_1 and n_3 can turn on only when v_v reaches v_{dia}. Therefore, a firing delay angle ? can be defined as shown in (Fig. 14). During the conduction period (? = ? t = ?+e), the device currents I_{n1} and I_{n3} are equal to I_V and consist of the current of the filter capacitor I_C and the load current I_R:

$$i_V = C \cdot \frac{dv_V}{dt} + \frac{1}{R} v_V = V_V \cdot (wC \cdot \cos wt + \frac{1}{R} \sin wt).$$

The currents are qualitatively represented in Fig. 14. They start with large values, increase to a maximum and become zero (? t_1 = e + ?) before the other device pair is turned on. During the time in which no devices are conducting, v_{dia} decreases exponentially.

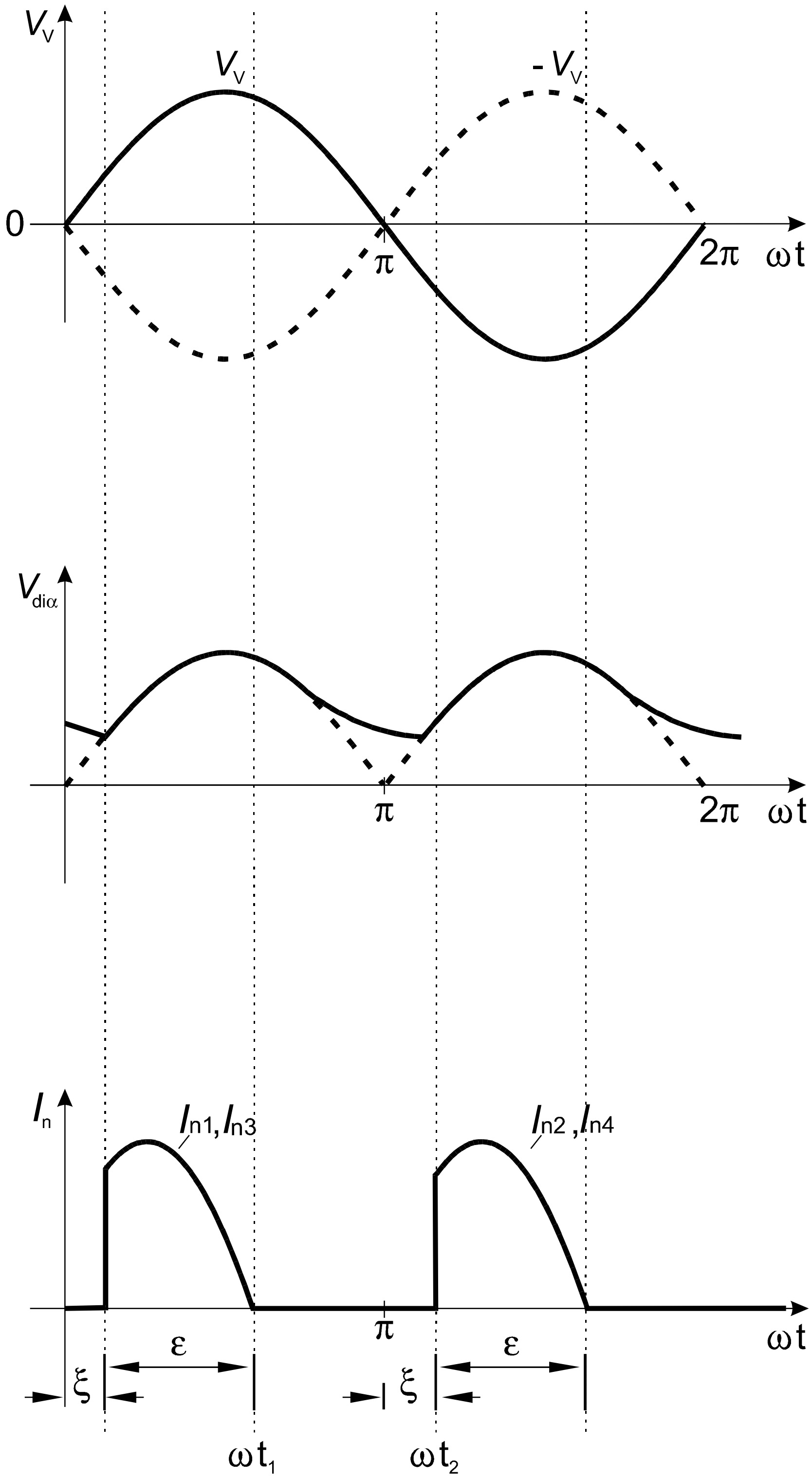


Fig. 14 Voltages and currents for a capacitive filter

The load current is continuous. However the device currents flow only during a limited time period ($e < p$), they are characterized by short time pulses with high amplitude.

3.3 Device losses

If the semiconductor devices are analyzed including their non-ideal characteristics, the device losses must be taken into account. In converters operating in a 50 or 60Hz grid, the dissipated heat of semiconductor devices is mainly caused by the conduction losses. Approximating the actual characteristic of semiconductor devices by the function $v_n = V_0 + R_d i_n$, the forward conduction power loss of the device can be obtained by the following equation:

$$p_V(t) = V_o i_n + R_d i_n^2(t)$$

The average value for the time period T can be calculated by:

$$\bar{P}_V = \frac{1}{T}\int_o^T p_V \mathrm{d}t = V_0 \frac{1}{T}\int_o^T i_n \mathrm{d}t + R_d \frac{1}{T}\int_o^T i_n^2 \, dt$$
$$= V_o \bar{I}_n + R_d \tilde{I}_n^2 = V_o \bar{I}_n + R\bar{I}_n^2 (\tilde{I}_n / \bar{I}_n)^2.$$

The average value of the conduction power losses depends on the rms value of the device current i_n at a given average device current. With non-uniform currents, e.g. pulses, the losses are considerably high due to the large ratio of $\tilde{I}_n / \bar{I}_n$.

Comparing the time characteristics of both the inductive and capacitive filtering, we can notice that in capacitive filtering, the device current has a higher amplitude and a small conduction angle. This leads to high losses in the device due to a large value of $\tilde{I}_n / \bar{I}_n$. In contrast to capacitive filtering, an inductive filter the device current with a lower amplitude and a longer conduction angle. Therefore, the rms value of the current is lower and the device is consequently stressed by less power losses. This is the main reason why in high power applications inductive filtering is preferred.

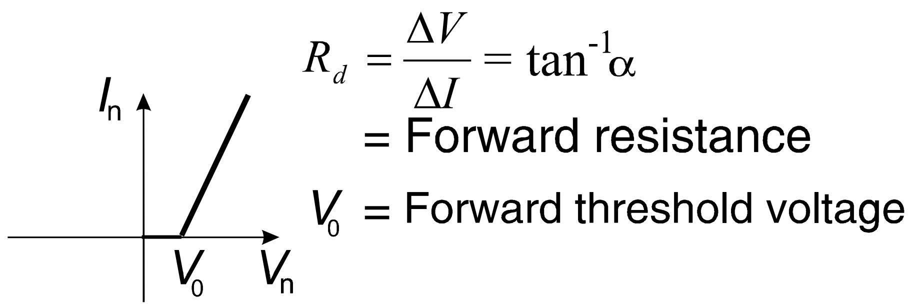


Fig. 15 Approximate real characteristic of a semiconductor device

These results can be in generally applied to topologies with more pulse numbers as well.

For the calculation of the device losses, the current i_n which is obtained by neglecting the device losses is applied to the equation $V_0 + R_d i_n$. It is assumed that the small forward voltage drop and the small reverse current have no significant influence on the current waveforms of the converter.

3.4 Effect on the ac grid

The ac grid is stressed by apparent power caused by the converters. The apparent power in the sinusoidal ac voltage system is proportional to the rms value of the ac current. The ac grid supplying the converter is less stressed, if the value of $\tilde{I}_n / \bar{I}_n$ becomes smaller. Consequently, the inductive filtering is also more favorable than the capacitive filtering.

3.5 Relationship of the rectified voltage and the load current

The calculation of the average value of the rectified voltage $\overline{V}_{\mathrm{dia}}$ for inductive filtering in a continuous operation (Section 3.1.2.1) concludes that the $\overline{V}_{\mathrm{dia}}$ does not depend on the average load current $\bar{I}_{\mathrm{d}}$. However, in reality, there are unavoidable losses in the converter circuit. Due to these losses, the rectified voltage $\overline{V}_{\mathrm{dia}}$ decreases while $\bar{I}_{\mathrm{d}}$ increases. Additionally, the threshold forward voltages cause a decrease in voltage which does not depend on current. In the multi-pulse converters, the inductance of the commutation circuit path decelerates the spontaneous current change from one device to the next one and therefore the commutation time is extended leading to a commutation overlap (see course notes). As a consequence, the voltage decreases with increasing current.

Also in capacitive filtering, a voltage decrease occurs at increasing load current, which is not discussed in detail here.

If the current $\bar{I}_{\mathrm{d}}$ by the inductive filtering becomes small so that discontinuous operation is reached, the voltage $\overline{V}_{\mathrm{dia}}$ increases whenever the current $\bar{I}_{\mathrm{d}}$ decreases, well above the values which are shown in Fig. 8 (see Fig.12).

4 Literature

[1] Mohan Ned, Undeland, Robbins, "Power Electronics- Converters, Application and Design", John Wiley & Son, 3rd Edition (2003).

[2] B.M. Bird, K.G. King, D.A.G. Pedder, "An Introduction to Power Electronics", John Wiley & Son, 2nd Edition (1993).

[3] F. Csaki, I. Hermann, P.Magyar, "Power Electronics - Problem Manual", Akademiai Kiado, Budapest, 2nd Edition (1979)

[4] DIN V 41761

[5] R.W. De Doncker, "Power Electronics Lecture Companion", Institute of Power Electronics and Electrical Drives, RWTH Aachen.

5 Experimental Procedure

In this experiment, the behavior of the B2-converter in rectifier and inverter operation mode is investigated.

The laboratory report consists of a question part and a measurement protocol. Both parts must be worked out during the experiment.

Caution: As soon as more than one signals (voltage or current curves) have to be displayed on the oscilloscope at the same time, it should be carefully noted if the grounds of both measuring channels are connected to the same potential point.

5.1 Rectifier Operation Mode

5.1.1 *R*-*L*-Load (Fig. 5)

Adjust the load resistance so that at minimum firing angle a current of $\bar{I}_d = 8A$ flows. Then adjust the firing angle to a = 70º.

1.Observe the dc voltage $v_{di\alpha}$ waveform and plot it in Fig. 16. Next display the thyristor voltage V_{n3}, together with the supply voltage V_v and plot the thyristor voltages also in Fig. 16

2. Observe and draw the curves of the thyristor currents i_{n3} and i_{n4} as well as the current i_d for one cycle. Use the template of Fig. 16.

3. Measure and draw the characteristic of $\overline{V}_{dia} = f(a)$ for this load (R and L = constant). Use the template shown in Fig. 17.

5.1.2 *L*-V_{dc}-Load (Fig. 9)

Replace the load resistance with a 12V battery. Be careful about the polarity of the battery. The battery should be charged!

1. Adjust the firing angle a so that the battery is charged by $\bar{I}_d = 3A$. Discuss the characteristics $V_{di\alpha}$, I_d and V_n.

5.2 Inverter Operation Mode

Change the circuit so that the energy flows from the battery in to the grid and the output current becomes 2A ($\bar{I}_d = 2A$).

1. Measure the dc voltage $V_{di\alpha}$ and the thyristor voltage V_{n3} again and plot the waveforms of these quantities in Fig. 18.

2. Draw the waveforms of the thyristor currents I_{n1}/I_{n3} and I_{n2}/I_{n4} as well as the current I_d for one cycle. Use the same template of Fig. 18

6 Experiment Protocol

6.1 Questions

The following questions should be discussed and answered during the experiment.

1. What is meant pulsation ? of a converter?

2. Explain the difference between the static characteristics of an ideal and a real thyristor.

3. Explain why a transformer with a M2-circuit has a worse utilization of the secondary winding than a transformer with a B2-circuit.

4. Which conditions must be fulfilled, so that a thyristor can be turned on?

5. The recovery time and hold-off time are mentioned in the experiment. Which time is the property of which element? Explain the meaning of these times.

6. Derive the equations for the sum of the thyristor voltages V_{n1} and V_{n3} (Fig. 4) in the rectifier operation mode with finite filter and a resistive load. Describe the voltage in the continuous and discontinuous operation for one full cycle. **Hint:** Apply the mesh-current method and consider the thyristors as ideal ones.

7. What value of V_{dia} is obtained during the discontinuous operation by using inductive filter with a resistance or a voltage source as a load?

8. Explain 2 reasons why the capacitive filtering is applied only for low-power applications.

6.2 Measurement Protocol

The following graphs and diagrams are used to record the experimental results.

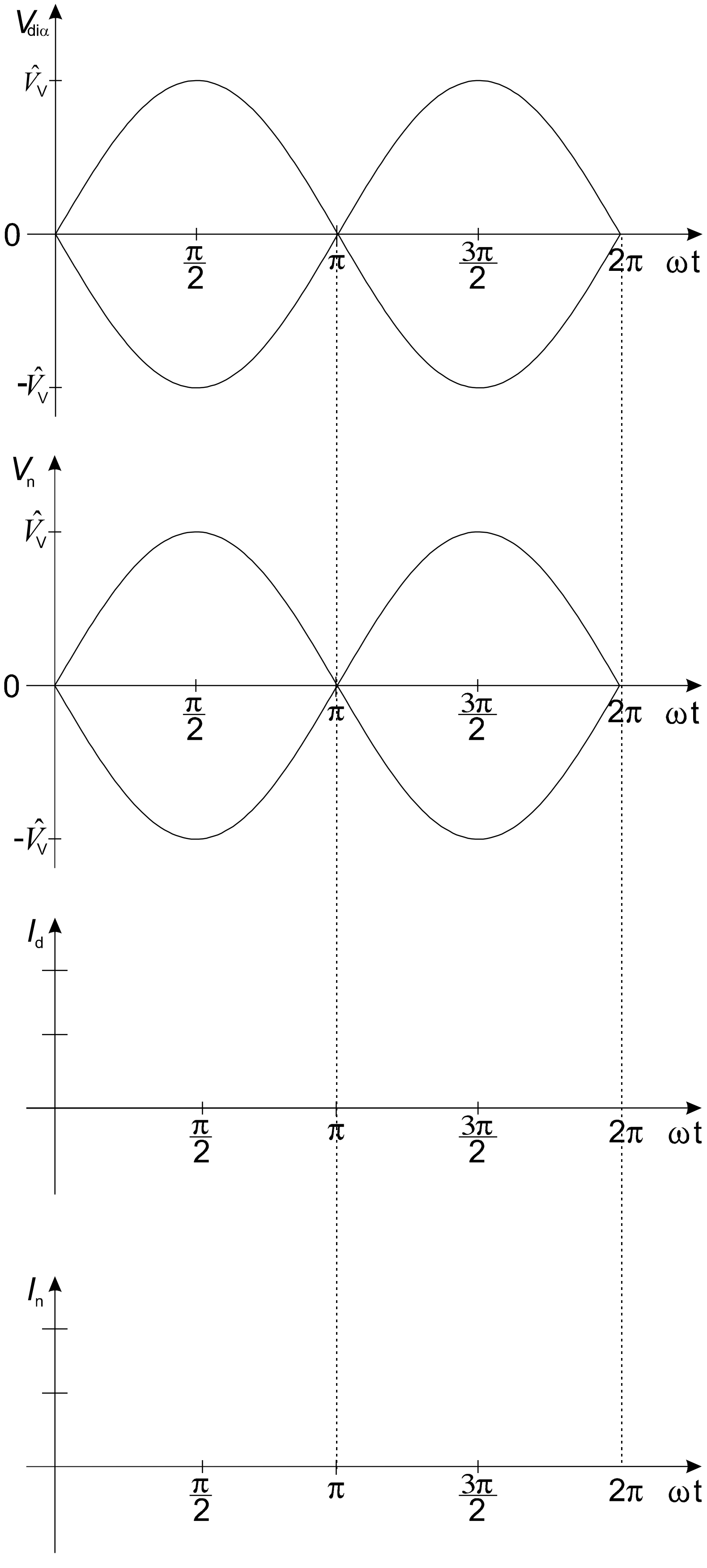
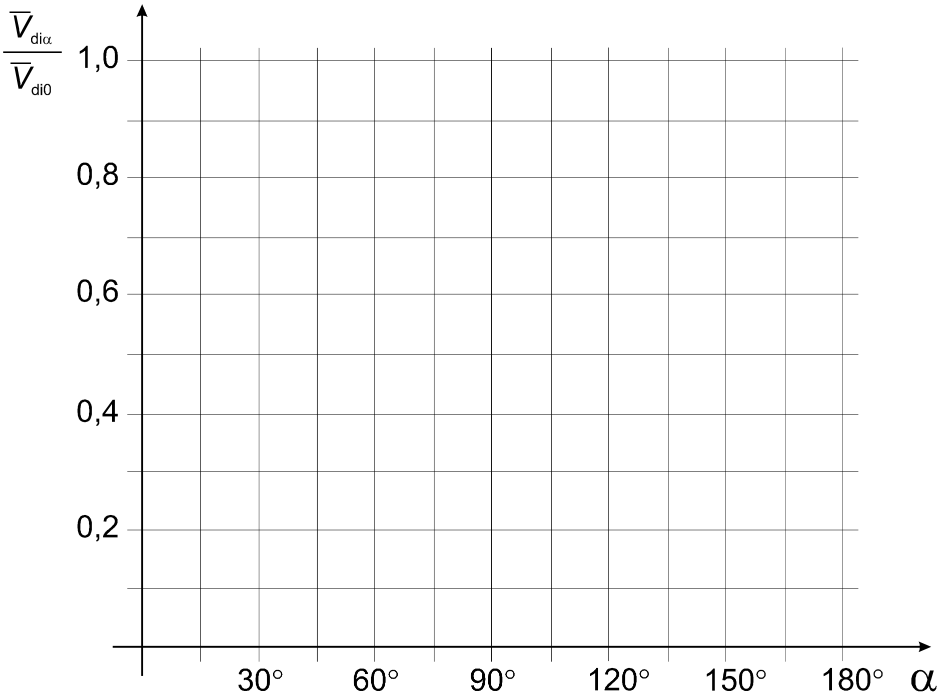


Fig. 16 Characteristics of *R*-*L*-Load for 5.1.1 (1 and 2),



α	15°	30°	45°	60°	75°	90°	105°	120°	135°	150°	165°	180°
$\overline{V}_{di\alpha}$ / V												
$\overline{V}_{di\alpha}$ / $\overline{V}_{di0}$												

Fig. 17 Transfer characteristics of *R*-*L*-Load for 5.1.1 (3)

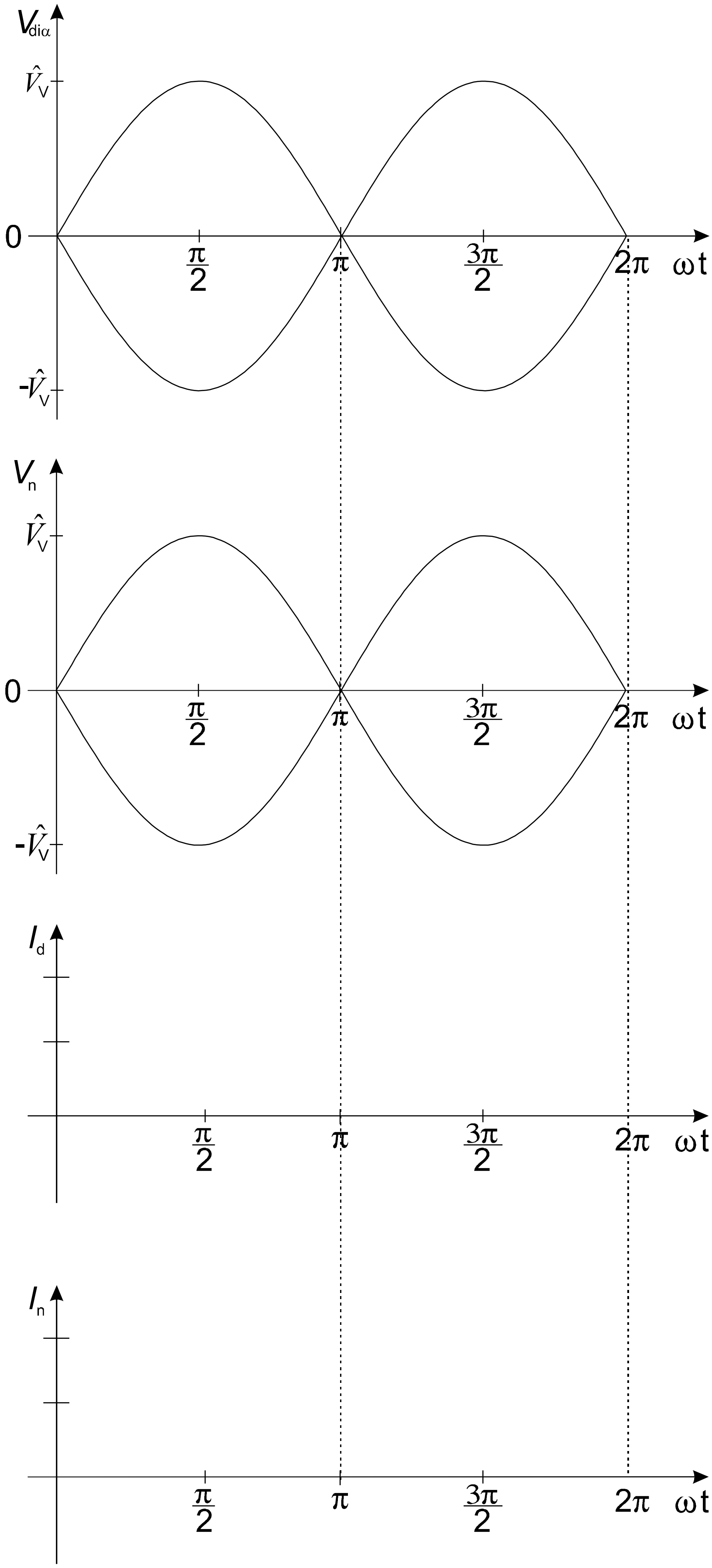


Fig. 18 Characteristics of L-V_{dc}-Load, Inverter Mode for 5.2