

Lab no. 7

RECTIFIER AND INVERTER MODE

1. Introduction

The process through which the alternating voltage waveform (AC voltage) of the electrical power is converted into a direct (constant) voltage waveform (DC voltage) or into a pulsating waveform with a direct (DC) component is called **rectification**. The electronic equipment that makes this conversion in a static process is called **rectifier**.

It is very important to know the load type connected to the output of a rectifier. According to this aspect, a certain type of rectifier will be chosen, with a certain structure and with certain semiconductor power devices. From this point of view, the essential information refers to the *unidirectional* or to the *bidirectional* power exchange between the rectifier and the load. Starting from this classification criterion, it can be highlighted the next types of electrical loads:

- Passive loads – characterized exclusively by a positive power having the significance of a consumed power;
- Active loads – characterized by a positive power, but also by a negative power with the significance of a returned or a given power. This process is possible if the loads have their own energy source.

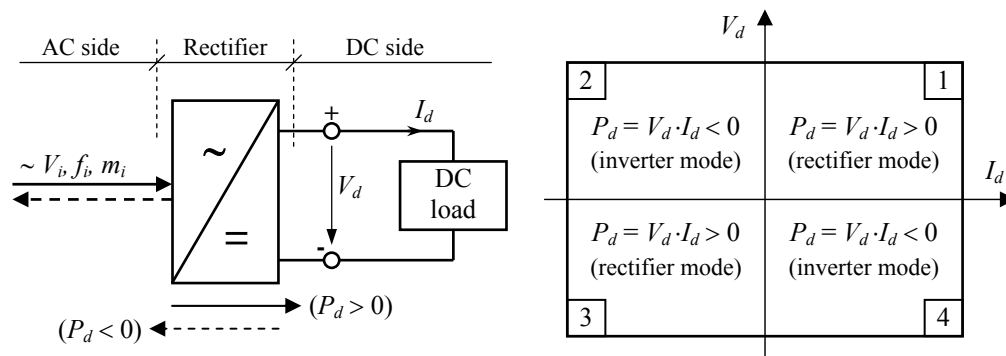


Fig.7.1 I_d - V_d electrical plane corresponding to the rectifier DC side and the P_d power flow directions.

In order to highlight the direction of the power flow between the rectifier and the load, one has to use the i - v axis system (*electrical plane*) of the variables from the rectifier output, the I_d direct current (DC) and the V_d direct voltage– Fig.7.1.

Because the V_d voltage and the I_d current are direct (constant) values we can refer to them as positive and negative values, so we can refer to the four quadrants of the electrical plane $I_d - V_d$ where we can define the DC electrical power from the converter's output: $P_d = V_d \cdot I_d$.

If the load connected to the converter output consumes power, the converter operates as an electrical source. According to the signs' convention, when the sources provide energy, fulfilling their role, they are characterized by a positive power. In Fig.7.1, for a positive power ($P_d > 0$) the converter makes an AC/DC conversion functioning in **rectifier mode**. This mode can be obtained in the 1st quadrant when the voltage V_d and the current I_d are positive, respectively in the 3rd quadrant when both variables are negative.

If the load connected to the converter output is an active one functioning in power generating mode (as a DC source) and the rectifier has the capacity of recovering this power by transferring it in the reverse direction, to the AC side, we can write: $P_d < 0$. Thus, the rectifier makes a DC/AC conversion, operating in **inverter mode**. This steady state can be obtained in the 2nd quadrant when the current direction is reversed ($I_d < 0$) or in the 4th quadrant when the V_d voltage polarity changes ($V_d < 0$).

For the DC side of a converter, the term that indicates the possibility of changing the current direction is called **bidirectionality**, and the term that indicates the possibility of changing the voltage polarity is called **reversibility**.

2. Rectifier and inverter mode of the line-frequency converters

Fig.7.2 shows the simplest structure of a phase-controlled rectifier which makes the AC/DC power conversion, the half-wave rectifier. The topology includes a thyristor T_h in a loop with an AC voltage source v_s and a DC load in two variants. In the first variant, Fig.7.2 (a), the load is purely resistive, formed only by the R resistance (case presented in Lab no.3 where it was described the thyristors phase-control technique). In the second variant, Fig.7.2 (b), the load is of a resistive-inductive type ($R-L$). These variants will be presented comparatively in order to highlight the operational differences and modes of the converter according to the power transfer direction.

a) First variant – purely resistive load (R)

Fig.7.2(c) shows the converter waveforms when the thyristor delay angle is $\alpha < 90^\circ$ and the load is purely resistive (R). We can see that, during the time interval when the T_h thyristor is off the current through it is zero and the v_d output voltage (the voltage drop on the resistance R) is also zero. During the thyristor's on-time interval, approximately the entire supply voltage will be found at converter's output, on the R resistance.

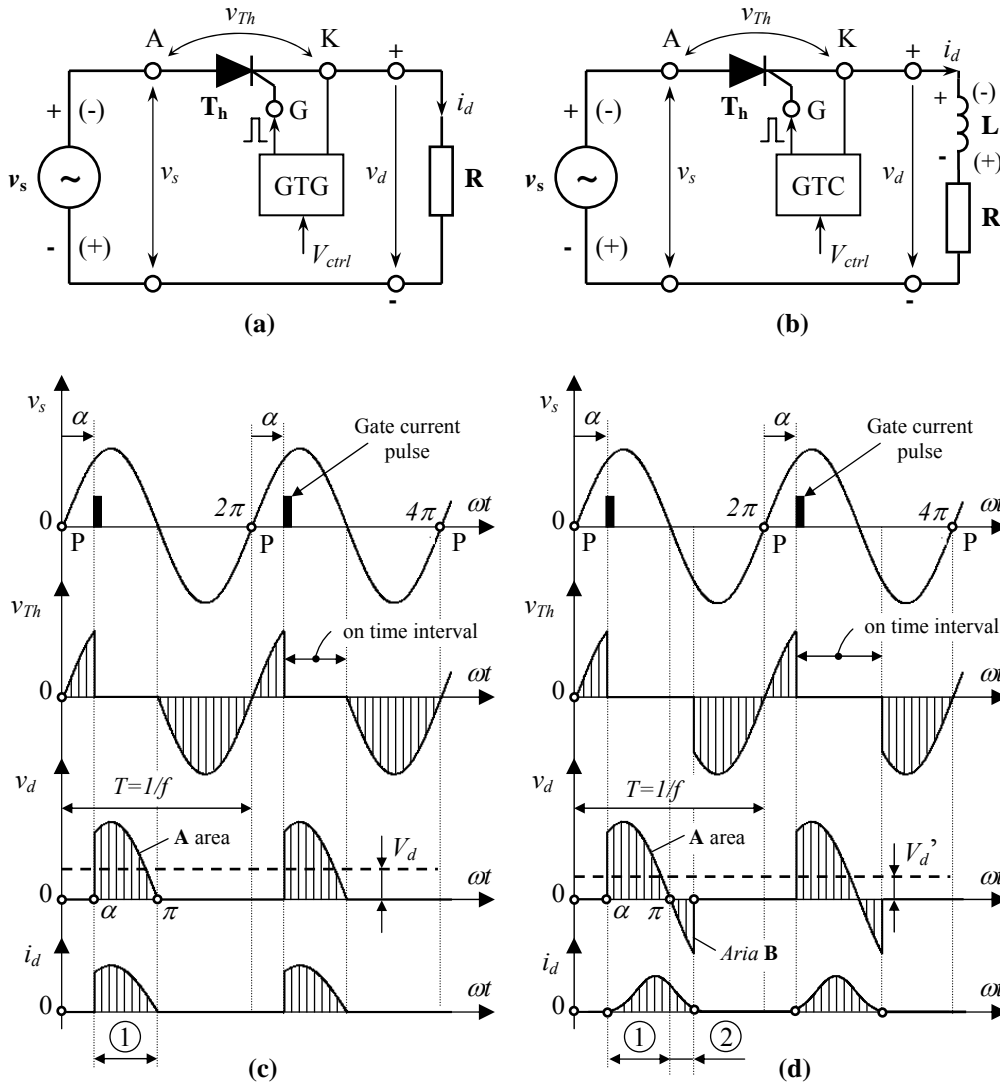


Fig.7.2 Instantaneous rectifier mode (1st time interval) and the instantaneous inverter mode (2nd time interval) at a half-wave rectifier.

Because of the purely resistive load, the waveform of the output current i_d is the same with the waveform of the output voltage v_d . When the supply voltage v_s passes through zero, towards negative half-wave, the i_d current becomes also zero. After this moment, the thyristor's turn-off conditions are complied, respectively the reverse bias for a minimum time interval (t_q blocking time – catalogue parameter) and zero value of the current through the device. Once the thyristor is turned off, it will take over the entire negative half-wave and a part of the positive half-wave until the gate current pulse appears in the next T period of the input AC voltage.

Notice that, on the load resistance we have only portions of the positive half-wave, shorter or wider depending on the value of the delay angle (see Fig.7.2.c). Thus, the output voltage v_d appears as positive pulses waveform, a periodical signal with the T_p time period, equal with the time period of the input AC voltage: $T_p=T=1/f$. Because these pulses are not alternative, the output voltage v_d contains a DC component $V_{d\alpha}$ whose value can be calculated with the average value equation applied to a periodical signal (see the Lab no.3):

$$V_{d\alpha} = \frac{1}{T} \int_0^T v_d(t) \cdot dt = \frac{\mathbf{A\ area}}{T} = \frac{\sqrt{2}V_s}{2\pi} \cdot (1 - \cos\alpha) \geq 0 \quad \text{for } 0 \leq \alpha \leq \pi \quad (7.1)$$

Fig.7.2.(c) shows that, during the time interval given in radians $[\alpha, \pi]$, the voltage $v_d(t)$, as well as the current $i_d(t) = v_d(t) / R$, have positive values. Consequently, the **instantaneous electrical power** in the DC side of the rectifier is positive during this time interval:

$$p_d(t) = v_d(t) \cdot i_d(t) > 0 \quad (7.2)$$

This positive value is equivalent to the load's power consumption at any moment inside the interval: $\alpha \leq \omega t \leq \pi$. It can be said that, during this interval, the phase-controlled rectifier operates only in **instantaneous rectifier mode** because the instantaneous electric power flows all the time from the AC side to the DC side.

If the average load current is positive ($I_d > 0$) the **average value of the power** in the DC side:

$$P_d = \frac{1}{T} \cdot \int_0^T p_d(t) \cdot dt = V_{d\alpha} \cdot I_d > 0 \quad (7.3)$$

is also positive. Globally, the converter transfers electric power from the AC side to the DC side. Thus, the controlled rectifier operates in a **global rectifier mode** or simply in a **rectifier mode**.

b) Second variant – resistive-inductive load (R-L)

By adding an inductance to the load, as shown in Fig 7.2(b), the operating mode of the converter becomes more complex. The inductance will insert a filtering effect for the i_d current and therefore its waveform can't follow the voltage waveform (see Fig.7.2.d). The mathematical expression that describes the current time evolution can be determined by solving the first-order differential equation available after $\omega t = \alpha$ moment:

$$R \cdot i_d + L \cdot \frac{di_d}{dt} = v_s = \sqrt{2} \cdot V_s \cdot \sin \omega t \quad (7.4)$$

The solution of this equation, in which has been neglected the thyristor on-voltage ($v_{Th(on)} \approx 0$) is:

$$i_d(t) = K \cdot e^{-t/\tau} + \frac{\sqrt{2} \cdot V_s}{\sqrt{R^2 + (\omega L)^2}} \sin(\omega t - \varphi) \quad (7.5)$$

where:

- K is the integration constant that can be determined from the initial conditions: $\omega t = \alpha \Rightarrow i_d(t) = 0$
- $\tau = L/R$ is the time constant of the R - L load circuit;
- $\varphi = \arctg \frac{\omega L}{R}$ is the phase displacement introduced by the L inductance;

As results from the Fig.7.2 (d), the i_d current's flow will extend for a time interval after the moment when the voltage v_s passes through zero towards negative values. We can say that, a certain time interval, the thyristor conducts the current during the negative half wave. Consequently, a negative voltage occurs in the pulses' waveform of the output voltage v_d . Thus, the thyristor conduction time interval can be divided in two intervals:

$$(1) \left. \begin{array}{l} v_d(t) > 0 \\ i_d(t) > 0 \end{array} \right\} \Rightarrow p_d(t) = v_d(t) \cdot i_d(t) > 0, \text{ time interval in which the instantaneous}$$

power from the DC side is positive and the converter operates in **instantaneous rectifier mode**, transferring electric energy from the AC source to the DC load. This energy is consumed by the R resistance (being converted into heat) and by the L inductance that stores the energy in its electromagnetic field.

$$(2) \left. \begin{array}{l} v_d(t) < 0 \\ i_d(t) > 0 \end{array} \right\} \Rightarrow p_d(t) = v_d(t) \cdot i_d(t) < 0, \text{ time interval in which the instantaneous}$$

power from the DC side is negative and the phase-controlled rectifier operates in **instantaneous inverter mode**, transferring electric energy from the DC load back to the AC source.

In fact, the power that flows inversely through the converter in the instantaneous inverter mode is given by the inductance, the only one capable to store energy in the load circuit. This energy begins to be provided by the inductance when its voltage $v_L(t) = L \cdot \frac{di_d(t)}{dt}$ changes the polarity (in Fig.7.2.b the polarity from the

brackets) or more precisely when the current slope becomes negative ($\frac{di_d(t)}{dt} < 0$).

The inductance itself becomes a source when tries, with the help of the self-induced voltage polarity, to stop the i_d current decrease. The value of self-induced voltage is always imposed by the v_s supply voltage value and by the i_d current value through the

voltage drop across the R resistance, so that it is respected at all times Kirchhoff's law written for the converter loop shown in Fig.7.2 (b):

$$v_s(t) = v_R(t) + v_L(t) = R \cdot i_d(t) + v_L(t) \Rightarrow v_L(t) = v_s(t) - R \cdot i_d(t) \quad (7.6)$$

Until $\omega t = \pi$ the energy provided by the inductance is taken only by the load resistance. After this moment, when the supply AC voltage becomes negative ($v_s < 0$), the instantaneous power of the AC source becomes also negative ($p_s(t) = v_s(t) \cdot i_d(t) < 0$), which signifies an energy received by the source from the inductance or from the DC side of the converter.

It should be noted that the negative pulses from the v_d voltage waveform are generated effectively by the inductance and induced only by the v_s voltage of the AC source. The thyristor cannot propagate from the anode to the cathode a negative potential. During the negative pulses, through the thyristor a positive current ($i_d > 0$) continues to flow because the device is forward biased by the v_L voltage. This voltage creates, on the loop, a slightly positive sum: $v_{th} = v_s(t) + v_R(t) + v_L(t) > 0$ necessary for maintaining the thyristor in on-state until the inductance finishes all the energy from its field. When this energy is ended, the i_d current becomes zero. Therefore, the self-induced voltage v_L becomes also zero, immediately causing a reverse bias of the thyristor by the v_s supply voltage. In this way there are accomplished the conditions of the thyristor *natural turn-off*.

In the case of an R - L load, the average value $V'_{d\alpha}$ of the output voltage is smaller than in the case of the resistive load, because the integral from the (7.1) equation is equivalent to an algebraic sum of two areas: **A area** + **B area**, in which the **B area** is negative:

$$V'_{d\alpha} = \frac{1}{T} \int_0^T v_d(t) \cdot dt = \frac{1}{T} (\mathbf{A\ area} + \mathbf{B\ area}) < V_{d\alpha} = \frac{1}{T} \cdot \mathbf{A\ area} \quad (7.7)$$

The conduction time interval of the thyristor during the negative half-wave depends on the energy quantity accumulated in the inductance field. In turn, this energy depends on the average value of the load current I_d . It can be said that the magnitude of the **B area** depends on the load value and consequently the average output voltage depends, besides the α delay angle, on the load current:

$$V'_{d\alpha} = f(\alpha, I_d) \quad (7.8)$$

We can consider that the converter is *uncontrollable* when the value of the output voltage cannot be exclusively imposed by the control parameter (α delay angle) and this voltage depends also on a random variable such as the load current. Generally, it is the case of all converters which have the output current (load current)

interrupted during certain time intervals. We say that these converters operate in the **discontinuous current mode**.

If the conduction time interval of the thyristor on the negative half-waves becomes greater than the conduction time interval on the positive half-waves ($|B \text{ area}| > A \text{ area}$) the average output voltage becomes negative: $V'_{d\alpha} < 0$. In this situation the average power at the rectifier's output becomes also negative ($P_d = V'_{d\alpha} \cdot I_d < 0$), which is equivalent with a global power exchange from the DC side to the AC side. Thus, the phase-controlled rectifier operates in a **global inverter mode** or simply in an **inverter mode**.

The global inverter mode can be obtained in practice only with the help of the natural commutation phase-controlled rectifiers with two or more pulses (M2, B2, M3, B6 etc.). The half-wave rectifier, described above, doesn't operate on the principle of natural current commutation from a circuit path to another circuit path, because its power structure doesn't contain more paths in parallel configuration with rectifying semiconductor devices.

Noted that, the line-frequency rectifiers, phase-controlled (with thyristors) and with two or more pulses (single phase, three-phase rectifiers, etc.) **can operate in the inverter mode if certain conditions are met**:

- ✓ The converter delay angle α is in the range of $[90^\circ \div \alpha_{\text{inv(max)}} < 180^\circ]$.
- ✓ The DC load must contain its own energy source (active load) with its own DC voltage connected in a way so that its polarity helps to flow the I_d current in a positive direction (the only possible conditioned by the presence of the thyristors) a time interval during the negative half-waves greater than the time interval during the positive half-wave of the supply AC voltage.

3. Laboratory application

For the experimental study of the aspects described in the previous section, the setup with the block diagram shown in Fig.7.3 and the image shown in Fig.7.4 may be performed in the laboratory. The setup includes:

- a line-frequency transformer (TR) that supplies the half-wave rectifier with a low AC voltage ($24V_{ac}$);
- a thyristor mounted on a radiator on which are mounted also four connectors, (banana socket) two for the thyristor power terminals (anode, cathode) and the other two for the control terminals (gate, cathode);
- a thyristor gate trigger circuit (GTC) achieved with the help of the UAA145 phase control integrated circuit (trigger circuit described in Lab no.3);
- an autotransformer (ATR) that implements the variable inductance L ;
- a rheostat that implements the variable resistance R .

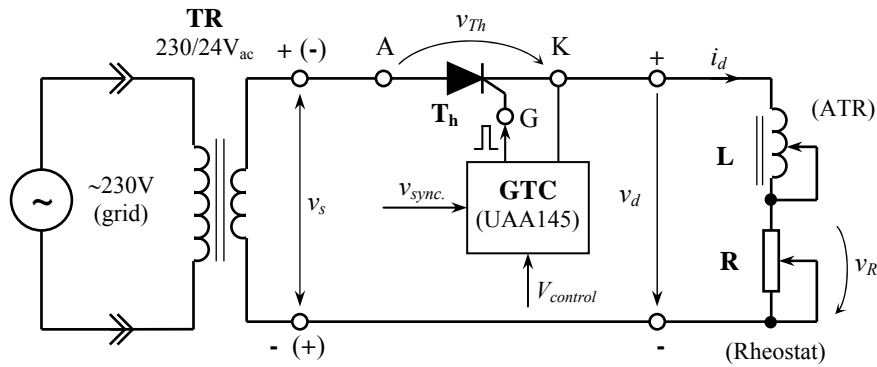


Fig.7.3 Application block diagram for studying the rectifier and inverter mode.

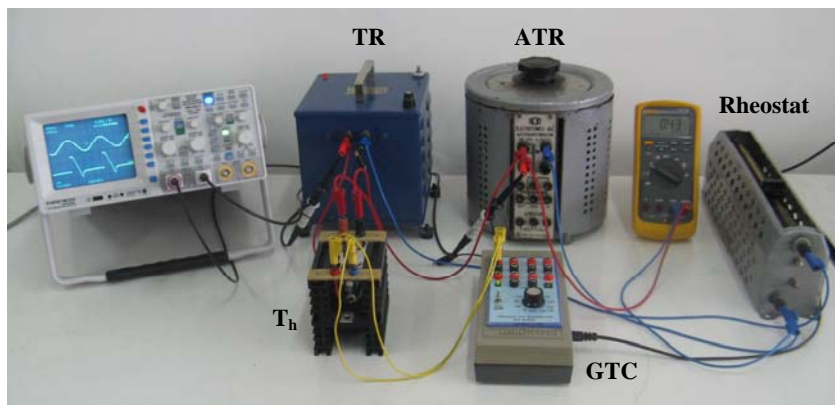


Fig.7.4 Image of the laboratory application.

For testing, there will be used a two spots oscilloscope to display the v_{Th} , v_d and i_d (v_R) waveforms which should be as in Fig7.2(c) and Fig7.2(d). To observe the circuit's behavior in the case of the purely resistive load, the cursor of the autotransformer will be placed in the zero position.

4. Objectives and procedures

1. It will be studied the theoretical aspects regarding the power exchange between the rectifier and the load and the correspondence between the energy flow directions and the quadrants of the electrical plane $I_d - V_d$;
2. It will be analyzed the exact meanings of the following terms regarding the rectifiers operation: *rectifier and inverter mode, reversibility, bidirectionality*;

3. It will be established the difference between the *instantaneous rectifier or inverter mode* and the same modes in terms of the average values – (*global rectifier or inverter mode*);
4. It will be analysed the conditions in which the inverter mode can be obtained by the line-frequency phase-controlled rectifiers (with thyristors);
5. The laboratory setup from Fig.7.3 will be performed and it will be checked the proper operation in the resistive load variants by observing simultaneously the voltages v_{Th} and v_d when the delay angle is adjusted. For this, the oscilloscope's ground for both channels will be connected to the thyristor's cathode, the channel 1 to the negative DC bus of the rectifier and the channel 2 to the thyristor's anode (the channel 1st signal will be shifted with 180° electrical degrees);
6. The delay angle will be set at a value close to that in Fig.7.2 and it will be shown the appearance of the instantaneous inverter mode by gradually increasing the L inductance (moving the ATR cursor);
7. It will be experimentally demonstrated that the thyristor conduction extension on the negative half-wave (extension of the 2nd time interval) depends on both the value of the L inductance and the value of the R resistance (value of the load current i_d), which suggests that the energy accumulated by the inductance ($W_L = L \cdot i_d^2 / 2$) is the cause for the appearance of the instantaneous inverter mode;
8. It will be displayed the waveform of the v_d output voltage simultaneously with the i_d current waveform by connecting the oscilloscope's ground to the negative rectifier DC bus, the channel 1 to the upper terminal of the L inductance and the channel 2 to the upper terminal of the R resistance. In this way, the correspondence between the three signals v_{Th} , v_d and i_d is done as shown in Fig.7.2;
9. The filtering effect of the i_d current will be observed with the increase of the L inductance and with the conduction extension on the negative half-wave;
10. It will be observed that, after the thyristor turn-on moment, the increasing slope of the current (di_d/dt) depends on the inductance value. Thus, it is obtained a connection between the inductance value from the rectifier's output and the duration (width) of the gate current pulse. The control pulse must be maintained until the value of the anode current through the thyristor reaches the holding value (I_H – catalogue parameter);

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