THREE-PHASE BRIDGE RECTIFIERS
(B6)

1. Introduction

Among all the line-frequency three-phase rectifiers (M3, M6, B6, ...) the most used is the six-pulses (full) bridge rectifier (B6). As shown in Fig.13.1, its topology consists of three legs with rectifying diodes (uncontrolled rectifiers), with thyristors (phase-controlled rectifiers) or with a diode and a thyristor (half-controlled rectifiers). In total, it results six rectifying semiconductor devices, three more than in the case of the three-phase midpoint rectifier (M3). An additional investment in power devices and in the control circuits is justified if we take into account the M3 rectifier disadvantages and the advantages of the full bridge rectifiers.

2. Three-phase bridge rectifier (B6) with current filter

In most applications the three-phase bridge rectifier is supplied directly from the utility power grid. If the level of the output DC voltage does not match with the level required by the DC load, a three-phase transformer will be used, denoted by TR in Fig.13.1. They are already known the DC loads which must be supplied with a well filtered DC current, such as the *R-L* passive loads (Fig.13.1.a) or the *R-L-E* active loads (e.g. DC motors → Fig.13.1.b). Even the frequency of the pulses from the waveform of the output DC voltage ($f_p = 6 \times f = 300$Hz) is three times higher than in the case of a single-phase bridge rectifier (B2), many times the DC load's own inductance is insufficient to filter enough the DC current and to avoid the discontinuous conduction mode of the rectifier operation. Consequently, an additional filter inductance L_f must be used. For simplicity, the supply AC voltages from the secondary transformer were labelled v_R, v_S, v_T, and for the thyristors it has chosen a numbering widely used in the literature that highlights the turn-on order during a complete cycle of operation.

a) <u>Analysis of the uncontrolled rectifier (with diodes)</u>

If in the three-phase topology of Fig.13.1 diodes are used instead of thyristors we obtain an uncontrolled rectifier with an output current filter. The operation of such a rectifier can also be obtained with the help of a phase-controlled rectifier with

<u>Authors</u>: M. Albu, R. Bojoi, M.P. Diaconescu

thyristors if we choose a delay (firing) angle $\alpha = 0^o$. In Fig.13.2 are presented the waveforms corresponding to this case.

The first diagram shows the v_R, v_S and v_T voltage waveforms, a three-phase AC system considered symmetrical and balanced, that supplies the bridge rectifier with the following natural commutation points:

–   **P_1, P_3, P_5** for the thyristors forward biased on positive half-wave $\rightarrow T_1,T_3,T_5$

–   **N_2, N_4, N_6** for the thyristors forward biased on negative half-wave $\rightarrow T_2,T_4,T_6$

These points are placed at the intersection of the phase voltages waveforms, as shown in Lab no.12, section 2, dedicated to the natural current commutating process.
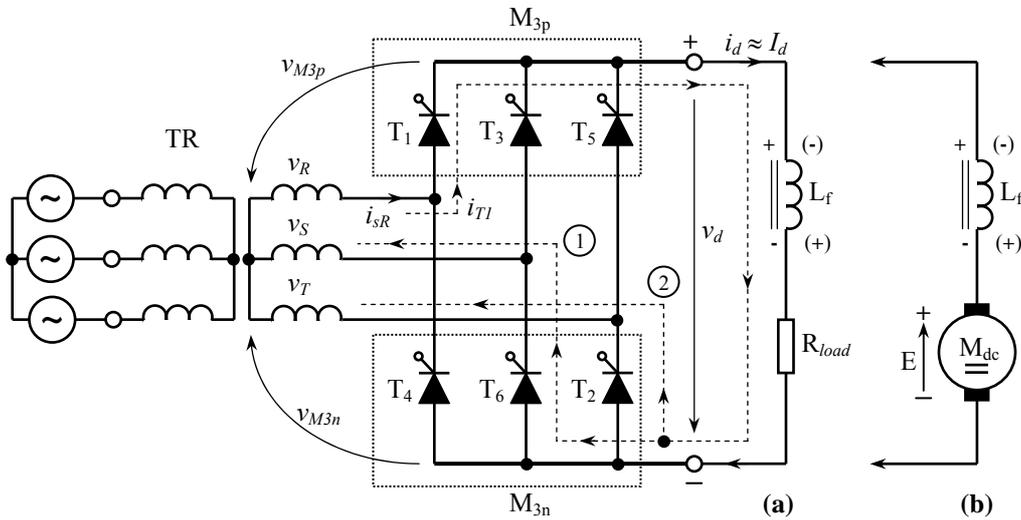
Fig.13.1 Three-phase bridge rectifier with: (a) R-L load; (b) R-L-E load.

In order to draw intuitively the waveform of the rectified output voltage, the B6 structure is considered as consisting of two midpoint structures M3: M_{3p} rectifier whose thyristors T_1, T_3, T_5 are forward biased during the positive half-waves and M_{3n} rectifier whose thyristors T_2, T_4, T_6 are forward biased during the negative half-waves. Thus, by applying the Kirchhoff law, it can be determined the v_d voltage with the help of equation:

$$v_d(t) = v_{M3p}(t) - v_{M3n}(t) \tag{13.1}$$

If we supposed that the reference potential is the neutral point potential of the three-phase voltage system (the midpoint potential of the transformer TR in Fig.13.1) for a delay angle $\alpha = 0^o$ (the gate trigger pulses are placed just in the position of the natural commutating points), result the v_{M3p}, v_{M3n} waveforms, as shown in Fig.13.2.
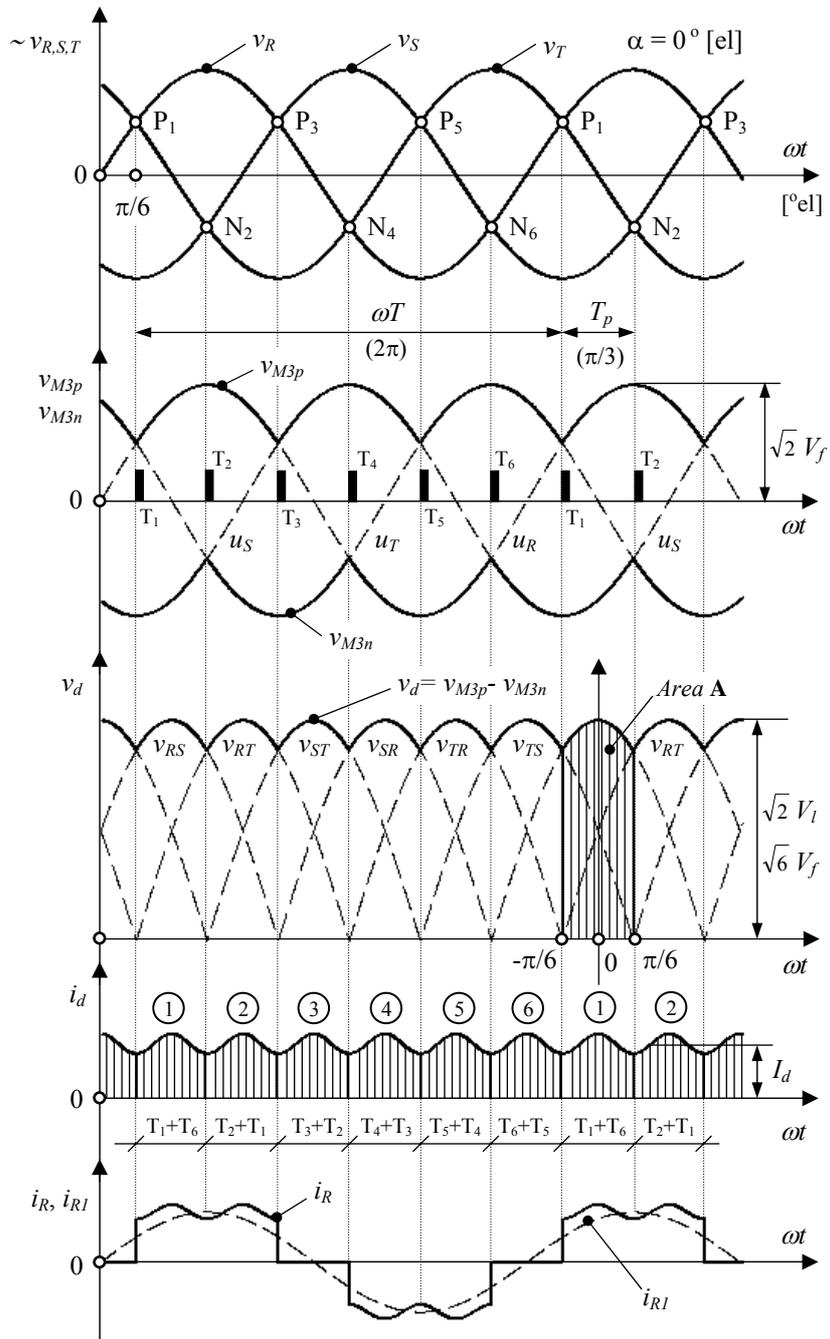
Fig. 13.2 Waveforms for a three-phase bridge rectifier (B6) achieved with diodes or thyristors whose delay angle is $\alpha=0^{\circ}$.

Authors: M. Albu, R. Bojoi, M.P. Diaconescu

In the continuous conduction mode of the three-phase bridge rectifier, it is always in conduction a device from M_{3p} structure with a device from M_{3n} structure. Thus, the waveform of the output voltage consists of *line-to-line voltages pulses* depending on the thyristors (diodes) conduction combination. As shown in Fig.13.2 each thyristor (diode) conducts the current an electrical angle of 120°. In the middle of each on-time interval an I_d current commutation appears, between two thyristors (diodes) from the opposite side of the bridge included in the other two legs which do not contain the devices in question. Thus, six pair combinations of on-state thyristors occur and therefore six pulses with six combinations of line-to-line voltages appear at the output of the rectifier in a time period of the input AC voltage. These six voltage combinations (v_{RS}, v_{RT}, v_{ST}, v_{SR}, v_{TR}, v_{TS}) are shown with dashed line in the third diagram of Fig.13.2. With solid line are figured only the output pulses corresponding to these voltage combinations, when the following pairs of thyristors are successively in on-state: (T_1, T_6), (T_2, T_1), (T_3, T_2), (T_4, T_3), (T_5, T_4), (T_6, T_5).

To calculate the DC output voltage provided by an uncontrolled rectifier with diodes or by a thyristors rectifier controlled with $\alpha = 0^o$ we applied the average formula during a T_p time interval ($\pi/3$ radians):

$$V_{d0} \overset{not}{=} \text{average value of } v_d(t) = \frac{1}{T_p} \int_0^{T_p} v_d(t) \cdot dt = \frac{1}{T_p} \cdot Area \text{ A} \qquad (13.2)$$

An easy way to calculate the $V_{d\alpha}$ expression is to place the time origin aligned to an output voltage pulse for which is applied the average value formula, in the middle position between two natural commutation points P and N, as shown in Fig.13.2. Consequently, the voltage $v_d(t)$ is described by the cosine function during a pulse time period $T_p = T/6 \rightarrow (2\pi/6 \text{ rad})$:

$$v_d(t) = \sqrt{2}V_l \cdot \cos \omega t = \sqrt{6}V_f \cdot \cos \omega t \quad \text{for} \quad \left(-\frac{\pi}{6} \le \omega t \le \frac{\pi}{6} \right) \qquad (13.3)$$

where V_f is the rms value of the phase voltage and $V_l = \sqrt{3} \cdot V_f$ is the rms value of the line-to-line (phase-to-phase) voltage. Therefore,

$$V_{d0} = \frac{1}{\pi/3} \int_{-\frac{\pi}{6}}^{\frac{\pi}{6}} v_d(\omega t) \cdot d(\omega t) = \frac{3}{\pi} \int_{-\frac{\pi}{6}}^{\frac{\pi}{6}} \sqrt{2}V_l \cos(\omega t) \cdot d(\omega t) =$$

$$= \frac{3\sqrt{2}V_l}{\pi} \left[\sin(\omega t) \right]_{-\frac{\pi}{6}}^{\frac{\pi}{6}} = \frac{3\sqrt{2}V_l}{\pi} \left[\sin \frac{\pi}{6} - \sin\left(-\frac{\pi}{6} \right) \right] = \qquad (13.4)$$

$$= \frac{3\sqrt{2}}{\pi} \cdot V_l = \frac{3\sqrt{6}}{\pi} \cdot V_f = 1{,}35 \cdot V_l \approx 2{,}34 \cdot V_f$$

If we compare the equation (13.4) with the same equation obtained for a single-phase bridge rectifier B2 ($V_{d0} \approx 0.9 \cdot V_f \rightarrow$ see Lab no.8) we see that the maximum DC voltage provided by a three-phase bridge rectifier is much higher than the maximum DC voltage provided by a single-phase bridge rectifier, for the same rms phase voltage V_f.

The filter inductance L_f necessary for a B6 rectifier may be much lower than the inductance used for a B2 rectifier to obtain the same ripple of the output current, due to the triple frequency of pulses from the output voltage waveform: $f_p = 6 \times f = 300$Hz, if $f = 50$Hz is the line frequency. However, even under these conditions the filter inductance cannot perfectly smooth the i_d current waveform, as shown in Fig.13.2. In this study we use only the average of the output current I_d.

In the same time if we look at the rectifier structure of Fig.13.1 and at the i_d diagram of Fig.13.2 we can understand how current commutation occurs from the T_1 branch to the T_6 branch, for example. Thus, in the middle of T_1 on-time interval, when T_2 receives the gate trigger pulse, the current switches from the path labelled with (1) to the path labelled with (2). The process is ongoing until all 6 cycles are completed, as shown in Fig.13.2. To obtain the equation (13.4) the commutation time intervals were neglected.

The last diagram from Fig.13.2 shows the waveform of the current absorbed by the rectifier from the AC source (power grid). It has been taken as an example the $i_R(t)$ current that flows through the R phase. It is noted that, this phase current is alternative, discontinuous and obvious non sinusoidal. During the time intervals in which:

- T_1 is on the phase current $i_R(t) = i_d(t) > 0$;
- T_4 is on the phase current $i_R(t) = -i_d(t) < 0$;

The half waves of the phase current i_R have rectangular shapes over which two pulses are added, more prominent as the output current i_d is poorly filtered. With this waveform it is evident that, besides the fundamental harmonic i_{R1}, the AC current contains many other harmonics.

Assuming that $i_d(t) \approx I_d = const.$ it can be calculated the rms value of the phase current I_f depending on the output DC current value. Thus, the rms current through phase R is:

$$I_f = I_R = \sqrt{\frac{1}{T} \int_0^T i_R^2(t) \cdot dt} = \sqrt{\frac{1}{2\pi} \left(\int_{\pi/6}^{5\pi/6} I_d^2 \cdot d(\omega t) + \int_{7\pi/6}^{11\pi/6} \left(-I_d\right)^2 \cdot d(\omega t) \right)} =$$
$$= I_d \sqrt{\frac{1}{2\pi} \cdot \left(\frac{4\pi}{6} + \frac{4\pi}{6} \right)} = I_d \sqrt{\frac{2}{3}}$$

(13.5)

Authors: M. Albu, R. Bojoi, M.P. Diaconescu

In steady-state operation of the three-phase rectifier, when the delay angle and the load current does not change, the consumption is symmetrical on the 3 phases and hence the rms values of the phase currents are equal:

$$I_f = I_R = I_S = I_T \qquad (13.6)$$

Disturbances introduced into the power grid

The waveform of the phase current $i_R(t)$ shown in Fig.13.2 highlights that the uncontrolled three-phase rectifier pollutes the utility power grid only with current harmonics. The fundamental harmonic $i_{R1}(t)$ of the $i_R(t)$ current is approximately in phase with the $v_R(t)$ voltage and therefore the reactive power tends to zero. The same observation is valid for the other two phases, S and T.

On the other hand, the commutation angle γ is higher when the natural commutation process begins immediately after the natural commutation point (see Lab no.12). There is a slow evolution of the commutation current i_k because the commutation voltage v_k is small. Consequently, the short circuit during the γ electrical angle extends, notching more the line-to-line voltage waveforms.

b) **Analysis of the phase-controlled rectifier (with thyristors)**

In Fig.13.3 are presented the waveforms corresponding to a three-phase bridge rectifier obtained with thyristors controlled with a delay (firing) angle $\alpha = 30^o$. Unlike Fig.13.2, in Fig.13.3 was added a new diagram with the gate trigger pulses for the all six thyristors: $T_1 \div T_6$. Each pulse is shifted by the α angle from the natural commutation points: P_1, N_2, P_3, N_4, P_5, N_6.

The operation of the B6 controlled structure in rectifier mode ($0^o < \alpha < 90^o$) is the same as described in the previous paragraph for $\alpha = 0^o$. There is always in conduction a thyristor from M_{3p} structure with one from M_{3n} structure (see Fig.13.1), so that the output voltage is:

$$v_d(t) = v_{M3p}(t) - v_{M3n}(t)$$

From the difference between the two waveforms v_{M3p} and v_{M3n} results the waveform of v_d which consist of six identical pulses in a time period T of the supply AC voltages. The six pulses are provided by the line-to-line voltages v_{RS}, v_{RT}, v_{ST}, v_{SR}, v_{TR} and v_{TS} during the time intervals when the following pairs of thyristors are successively in on-state: $(T_1\ T_6)$, $(T_2\ T_1)$, $(T_3\ T_2)$, $(T_4\ T_3)$, $(T_5\ T_4)$, $(T_6\ T_5)$. Each thyristor stays in on-state a time interval corresponding to an electrical angle of 120°. In the middle of each on-time interval a current commutation occurs between two thyristors from the opposite side of the bridge.
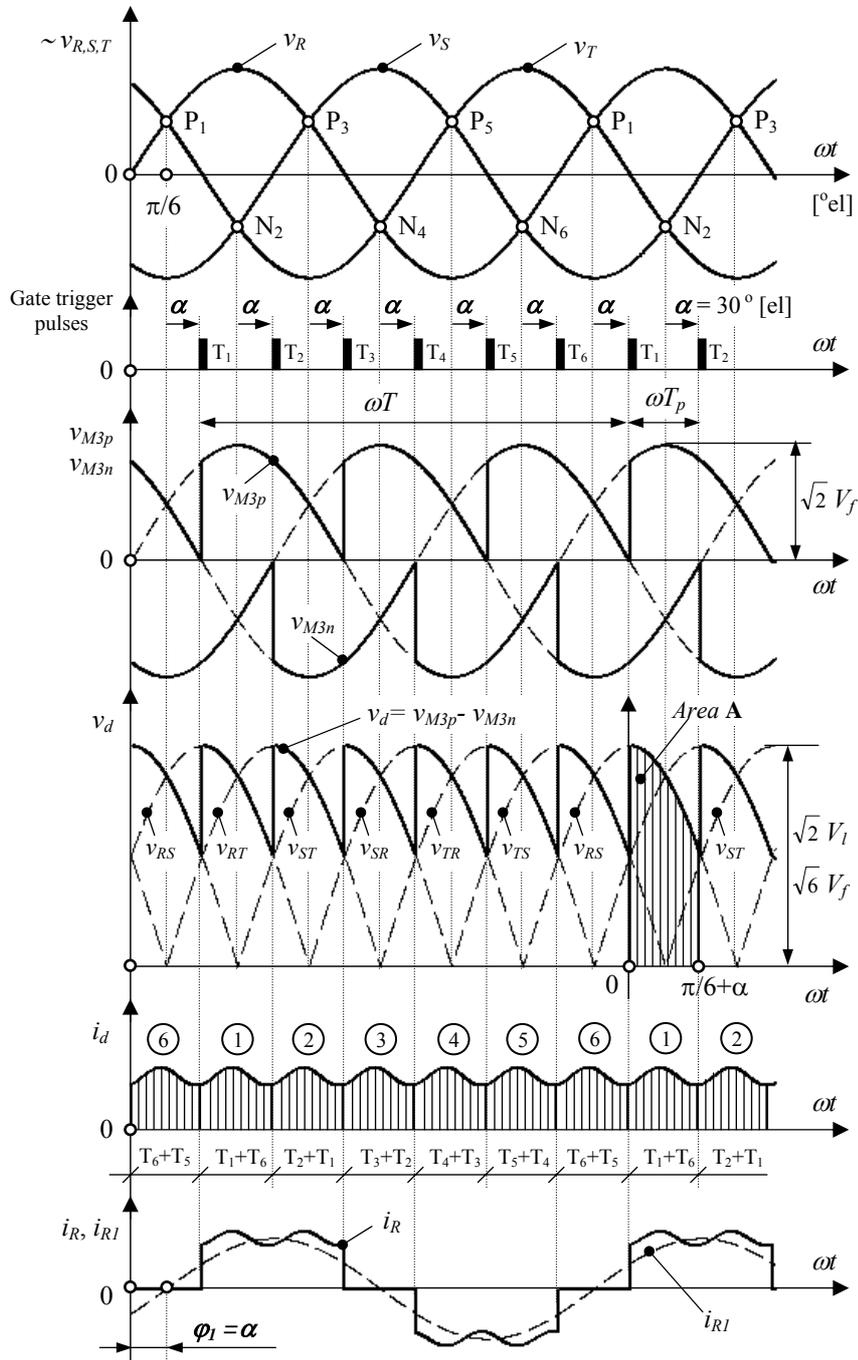
Fig. 13.3 Waveforms for a three-phase bridge rectifier (B6) achieved with thyristors whose delay angle is α=30°

Authors: M. Albu, R. Bojoi, M.P. Diaconescu

To calculate the DC voltage provided by a three-phase bridge rectifier with thyristors controlled with a certain α delay angle, we applied the average formula on a T_p interval ($\pi/3$ rad) from Fig.13.3:

$$V_{d\alpha} \overset{not}{=} \text{average value of } v_d(t) = \frac{1}{T_p} \int_0^{T_p} v_d(t) \cdot dt = \frac{1}{T_p} \cdot Area \text{ A} \qquad (13.7)$$

If we consider the time origin aligned to an output voltage pulse for which it is applied the average value formula, in the middle between two natural commutation points P and N, the average value $V_{d\alpha}$ becomes:

$$V_{d\alpha} = \frac{1}{\pi/3} \int_{-\frac{\pi}{6}+\alpha}^{\frac{\pi}{6}+\alpha} v_d(\omega t) \cdot d(\omega t) = \frac{3}{\pi} \int_{-\frac{\pi}{6}+\alpha}^{\frac{\pi}{6}+\alpha} \sqrt{2} V_l \cos(\omega t) \cdot d(\omega t) =$$

$$= \frac{3\sqrt{2} V_l}{\pi} \left[\sin(\omega t) \right]_{-\frac{\pi}{6}+\alpha}^{\frac{\pi}{6}+\alpha} = \frac{3\sqrt{2} V_l}{\pi} \left[\sin\left(\frac{\pi}{6}+\alpha\right) - \sin\left(-\frac{\pi}{3}+\alpha\right) \right] = \qquad (13.8)$$

$$= \frac{3\sqrt{2}}{\pi} \cdot V_l \cdot \cos\alpha = V_{d0} \cdot \cos\alpha$$

The equation (13.8) highlights the adjusting possibility of the output DC voltage exclusively through the α delay angle if the B6 phase-controlled rectifier operates in continuous conduction mode. The control characteristic $V_{d\alpha} = f(\alpha)$ shown in Fig.13.4 is the same with the control characteristic presented for the single-phase rectifier in Lab no.8. The nonlinearity of the rectifier transfer function can be maintained within acceptable limits if the delay angle values are limited in the range of: $30^\circ \leq \alpha \leq 150^\circ$.
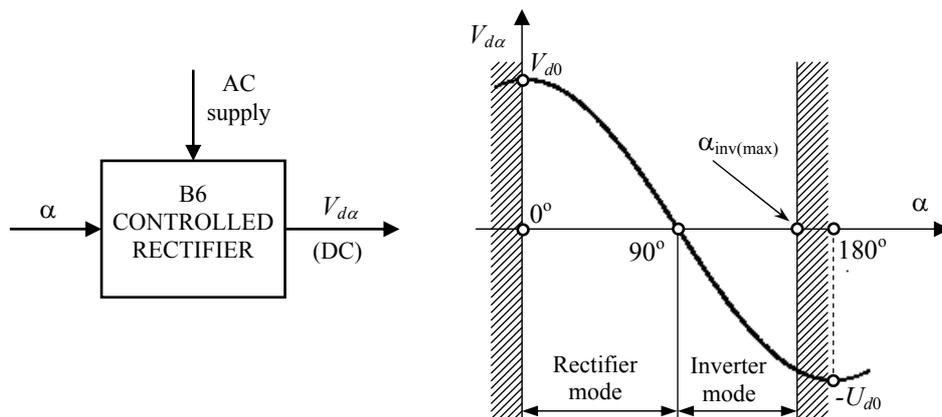
Fig. 13.4 Control characteristic of a phase-controlled three-phase bridge rectifier: $V_{d\alpha} = f(\alpha) = V_{d0} \cdot \cos\alpha$.

Analyzing the v_d voltage diagram shown in Fig.13.3, the equation (13.8) or the control characteristic shown in Fig.13.4 it is found that, once the delay angle leaves the $0°$ value and increases:

- The average voltage $V_{d\alpha}$ decreases progressively towards zero when the delay angle reaches the value $\alpha = 90°$. In range of $0°≤\alpha<90°$ the converter operates in rectifier mode ($U_{d\alpha} > 0$).

- For $90°<\alpha≤\alpha_{inv(max)}$ the converter can operate as an inverter ($U_{d\alpha} < 0 \rightarrow$ inverter mode) if the conditions described for the single-phase rectifier are fulfilled (see Lab no.8 and 9).

- The discontinuous conduction mode of operation can occur for an angle $\alpha>60°$ if the filter inductance is missing or is insufficient.

If we compare the v_d waveform shown in Fig.13.3 with the same waveform shown in Fig.13.2, it is evident that, the pulses' amplitude of the output voltage is greater for a controlled rectifier than for an uncontrolled B6 rectifier. Due to economic reasons the filter inductance L_f is sized so that the ripple of the i_d current to be kept below a certain value when the voltage pulses are maximal. This condition implies also a continuous conduction mode over a given DC load current I_d. Thus, in real applications the i_d current waveform has ripples, as shown in Fig.13.3. In the rectifier analysis we are working with the average value I_d of this output current.

Disturbances introduced into the power grid

The waveforms of the input AC phase-currents for a B6 controlled rectifier can be obtained graphically as it was explained in the case of a B6 uncontrolled rectifier. Also, for the phase-controlled rectifier is presented only the current waveform for the phase R, denoted by i_R in Fig.13.3. During the time intervals in which:

- T_1 is on the phase current $i_R(t) = i_d(t) > 0$;
- T_4 is on the phase current $i_R(t) = -i_d(t) < 0$;

According to the i_R diagram shown in Fig.13.3, if the B6 rectifier **is not** *supplied through a transformer with the primary windings connected in triangle*, the phase currents are alternative, discontinuous and the half waves have rectangular shape at which two pulses are added given by the i_d current ripples. Also, a phase displacement of the fundamental harmonic i_{R1} is observed versus the input AC voltage, considered sinusoidal, with the electrical angle $\varphi_1=\alpha$. Therefore it should be noted that, besides the harmonic pollution of the power grid due to the phase current waveform and besides the notches from the waveform of the grid voltages due to the natural commutation process, the phase-controlled B6 rectifiers absorb a **control reactive power** :

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$$Q = 3 \cdot V_f \cdot I_{f1} \cdot \sin \varphi_1 = 3 \cdot V_f \cdot I_{f1} \cdot \sin \alpha \qquad (13.9)$$

where I_{f1} is the rms value of the fundamental harmonic of the phase currents. As a warning, this value is different from the rms value $I_f = I_R = I_S = I_T$ of the entire phase current calculated with the help of equation (13.5).

Control practical aspects of the three phase bridge rectifiers

There are two important aspects that must be taken into consideration when the gate trigger circuit of a B6 thyristors rectifier is designed. The first one is related to *the rectifier starting and its maintaining in operation under discontinuous conduction mode* and the second is related *to the way in which the synchronization function of the gate trigger circuit is implemented.*

1) Rectifier starting

We can see in Fig.13.3 that the gate trigger pulses are generated successively depending on the order in which the thyristors must take the current conduction. Each thyristor turn-on determines the turn-off of another thyristor from the same side of the bridge due to the natural commutation process (described above or in Lab no.12). During the rectifier operation, all commutations occur when, in the opposite side of the bridge, a thyristor is in on-steady-state (at the middle of this on-time interval). It may be believed that the role of the gate trigger circuit is to generate successively these pulses at a certain control angle α for a normal operation mode of the rectifier.

The first problem appears when we want to start the converter, when we expect that a thyristor is already in on-state, but in fact it is not. For this reason the gate trigger circuit should generate two pulses simultaneously, electrically isolated: first trigger pulse for the thyristor that has to be in on-state and the second trigger pulse for the thyristor that must be turned on in that moment. For example, if we consider the instant when the thyristor T_1 must be turned on, when a gate trigger pulse is sent for it, another gate trigger pulse must be sent to the thyristor T_6 ($T_1 \rightarrow T_6$), see Fig.13.5. Further when T_2 will be turned-on, a trigger pulse should be sent also for the thyristor T_1. We can observe that the thyristor T_1 received two gate trigger pulses: the first when it must take the current conduction through the natural commutation process and the second trigger pulse, delayed by 60°, that helps starting and operating the B6 phase-controlled rectifier.

Consequently, the gate trigger circuits are made with a combinational structure that provides two gate pulses for each thyristor of a B6 rectifier, as follows: $T_1 \rightarrow T_6$; $T_2 \rightarrow T_1$; $T_3 \rightarrow T_2$; $T_4 \rightarrow T_3$; $T_5 \rightarrow T_4$; $T_6 \rightarrow T_5$. If only a single pair of thyristors (e.g. T_1 and T_6) was turned-on simultaneously, the rectifier would start, but it can't operate with all thyristor combinations in discontinuous conduction mode. In this mode both thyristors of the six pair combinations are turned off during the time period

T_p, before the appearance of the next gate trigger pulses. For this reason, to pass the rectifier through all six cycles of operation, it is necessary to use a control circuit which provides for each thyristor two trigger pulses delayed with 60°, as shown above.

In Fig.13.5 is shown, in a simplified form, the block diagram of the gate trigger circuit corresponding to the phase R. This circuit controls the first leg of the three-phase bridge rectifier, respectively the thyristors T_1 and T_4. It is noted that each pulse transformer is equipped with two secondary windings, the first winding for the thyristor that must be turned on at an instant and the second winding for the thyristor that must be in on-state at that instant. To receive trigger pulses from two directions an OR logic circuit with two diodes is used for each thyristor gate.
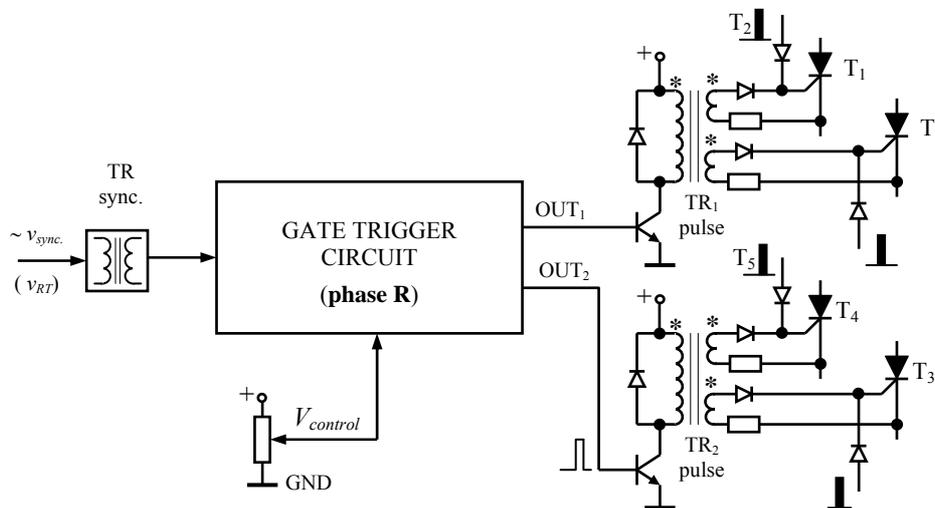
Fig. 13.5 Example of a gate trigger circuit for the first leg of the three-phase bridge rectifier (T_1, T_4).

2) Synchronization of the gate trigger circuit

For a proper control of the thyristors included in a three-phase structure, the synchronization function must be implemented in order to mark precisely the natural commutation points placed at the phase-voltage waveforms intersections. In practice, to achieve the gate trigger circuits, specialized integrated circuits are used, such as UAA145. These circuits can detect only the zero crossing of the synchronization voltage (v_{sync}). If for synchronization, the phase voltages (v_R, v_S, v_T) are used, the zero crossing occurs with 30° earlier from the natural commutation point (see the zero crossing of the v_R voltage and the position of the natural commutation point P_1 shown in Fig.13.3). A solution to this synchronization version would be to limit the control voltage ($V_{control}$) so that the gate trigger pulses can appear after a minimum delay of $30°$ from the zero crossing of the phase voltages. The solution limits the control range,

Authors: M. Albu, R. Bojoi, M.P. Diaconescu

restraining it to the maximum 150°el. To avoid all these difficulties, it is best to synchronize the trigger circuits according to the line-to-line voltages (v_{RT}, v_{SR}, v_{TS}) which crosses zero exactly in the points of natural commutation position. In Fig.13.5 the gate trigger circuit for the bridge leg connected to the phase R, is synchronized by the v_{RT} line-to-line voltage (see Fig.13.4) which passes through zero exactly at the natural commutation points P_1 and N_4, points corresponding to the T_1, T_4 thyristors.

3. Laboratory application

To achieve the laboratory setup of the three-phase bridge rectifier (B6), the same flexible laboratory installation described in the Lab no.12 it will be used. This installation is dedicated to the three-phase rectifiers study. For the present application, there will be made the connections on the panel in order to obtain the B6 thyristor structure, in a first experiment with resistive-inductive load *(R-L)*, as in Fig.13.1(a) and in the second experiment with an active *R-L-E* load (DC motor – M_{dc}), as in Fig.13.1(b). Fig.13.6 shows the laboratory application image in which a DC motor in series with a filter inductance L_f is used as B6 rectifier load.

In the case of *R-L* load, an autotransformer (ATR) will be used as filter inductance L_f, while for the load resistance a rheostat will be used. By changing the position of the ATR cursor it can be adjusted the inductance value and can be induced the discontinued conduction mode. At the limit, when the cursor is in zero position, the rectifier load can be considered purely resistive. On the other hand, by changing the rheostat cursor position we can change the resistance value and therefore the magnitude of the average output current.
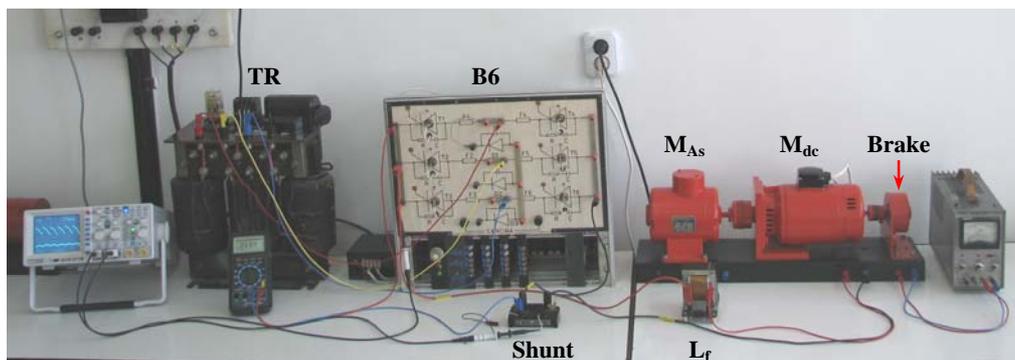
Fig.13.6 Image of the laboratory application.

In the active load variant, as a filter inductance we can use the same autotransformer or a fixed value inductance especially designed for laboratory experiments (see Fig.13.6). By using the autotransformer we can induce the discontinuous conduction mode of rectifier operation. The load current changing can

be obtained through an electromagnetic brake, mechanically coupled with the DC motor shaft. This brake is supplied by a laboratory DC source and through its voltage adjustment the brake torque can be modified and therefore the rectifier output current. To display the waveforms of currents i_d and i_R, shunts will be used. The circuit elements connections will be achieved through cables provided with banana plugs.

　　　To display simultaneously the v_d and i_d waveforms it will be used an oscilloscope with two spots and to measure the average value of output voltage $V_{d\alpha}$, a voltmeter will be used.

4. Procedures and objectives

1. It will be studied the theoretical aspects regarding the operation of the three phase bridge rectifiers with current filter: waveforms, equation of the average output voltage, control characteristic, disturbances introduced into the utility grid, control aspects, etc.

2. It will be performed with the help of the laboratory installation, the experimental setup with the block diagram shown in Fig.13.1(a) $\rightarrow$ three-phase thyristors bridge rectifier with R-L load;

3. It will be started the control block of the installation and it will be successively displayed using an oscilloscope, the synchronization voltage (v_{sync}) together with the zero pulses, saw-tooth signal and the gate trigger pulses from the front panel of each control module (corresponding to each leg of the three-bridge) made with the UAA145 integrated circuits;

4. From the front panel of distribution module it will be displayed the trigger pulses for each thyristor (before the pulse transformer) and it will be noticed that each power device is triggered with two successive current pulses shifted with 60°. This aspect can be observed also if we display the trigger pulses directly from the thyristors gate;

5. It will be supplied the power block of the installation (B6 thyristor structure) by pushing the START button and it will be displayed the waveforms of u_{M3p}, respectively u_{M3n} voltages provided by the two M3 structures included in the B6 topology (continuous conduction mode $\rightarrow$ high L_f);

6. It will be displayed the v_d and i_d waveforms for different control angles, in the rectifier mode. It will be observed that the voltage v_d waveform results from the difference of the v_{M3p} and v_{M3n} waveforms.

7. It will be measured, using the voltmeter, the average value $V_{d\alpha}$ in continuous conduction mode for different control angles;

8. It will be fixed a control angle over 60° and it will be decreased, progressively, the filter inductance modifying the position of the autotransformer cursor until

the discontinued conduction mode occurs and it will be observed the increase of the average output voltage as this mode is accentuated;

9. It will be displayed the v_d and i_d waveforms to the limit, when the inductance L_f is zero (the load is purely resistive) and it will be observed the discontinuous conduction mode occurring as soon as the delay angle $\alpha > 60^o$.

10. It will be performed with the help of the laboratory installation, the experimental setup with the block diagram shown in Fig.13.1(b) $\rightarrow$ phase-controlled three-phase bridge rectifier with *R-L-E* active load (DC motor M_{dc} – see image of Fig.13.6);

11. It will be highlighted the motor speed variation with the delay angle adjusting in the range of $(0^o \div 90^o)$ and in the presence of a low load torque imposed by the electromagnetic brake;

12. In the conditions of using a variable filter inductance (autotransformer) it will be induced the discontinued conduction mode of operation and it will be observed the changing of the voltage waveform v_d, the increasing of the output DC voltage and the motor speed increasing after this mode appears;

13. It will be set the value of the filter inductance at the limit of the discontinuous conduction mode and it will be seen the disappearance of this mode if the load torque is increased with the help of electromagnetic brake (the increase of the rectifier output current over a threshold corresponding to the L_f value);

14. The waveform of the input phase AC current will be displayed with the help of a shunt inserted on the R phase supply path. It will be discussed this waveform. The change of this waveform will be highlighted once the filter inductance decreases, both in continuous and also in discontinuous conduction mode.

15. The laboratory installation is provided with a recovery diode with its terminal connectors (bananas socket) placed on the front panel to be easily connected in antiparallel with the phase-controlled B6 rectifier. Thus, for *a B6 phase-controlled rectifier with recovery diode* it will be observed the v_d voltage waveform when the delay angle $\alpha>60^o$. Even through the load circuit the current is continuous (uninterrupted), the rectifier operates in discontinuous current conduction mode as in the case of a purely resistive load. It will be discussed this behaviour of the rectifier with recovery diode and where this configuration can be used.

References:

[1] Mohan N., Undeland T., Robbins W., *Power Electronics: Converters, Applications and Design*, Third Edition, Published by John Willey &Sons Inc., USA, 2003.
[2] Erickson R., Maksimovic D, *Fundamentals of Power Electronics*, University of Colorado, Boulder, Colorado, Published by Kluwer Academic Publishers, USA, 2001.

[3] Albu M., *Electronică de putere* - vol I: *Noţiuni introductive, dispozitive, conversia statică alternativ-continuu a energiei electrice*, Casa de Editură "Venus" Iaşi, 2007.

[4] Albu M., Diaconescu M., Bojoi R**.**, *Comanda semiconductoarelor de putere, convertoare statice cu comutaţie naturală*, Casa de Editură "Venus", Iaşi, 2008.

[5] Diaconescu M.P., Graur I.,: *Convertoare statice – baze teoretice, elemente de proiectare, aplicaţii*, Ed. „Gh. Asachi", Iaşi, 1996.

[6] Ionescu Fl., Floricău D., Niţu S., Six J.P, Delarue Ph., Boguş C.: *Electronică de putere - convertoare statice*, Ed. Tehnică, Bucureşti, 1998.

[7] Kelemen A., Imecs M., *Electronică de putere*, Ed. Didactică şi Pedagogică, Bucureşti, 1983.

Authors: M. Albu, R. Bojoi, M.P. Diaconescu