Lab no. 12

THREE-PHASE MIDPOINT RECTIFIERS WITH CURRENT FILTERS

1. Introduction

Midpoint rectifiers (**M**) are usually supplied through a centre-tapped transformer. In the case of the three-phase midpoint rectifier (M3), the transformer may be missing, if there is an access to the neutral point of the power grid. Many times, the presence of the transformer is justified by the necessity to optimize the magnitude of the rectifier output voltage to the level demanded by the load. However, the presence of the transformer is expensive, because each secondary winding supplies the rectifier during only a single half-cycle of the input AC voltage. Consequently, for a given load power, the transformer must be oversized.

The advantages of the midpoint rectifiers consist in the small number of semiconductor devices used by the power structure and also in the simplicity of the control circuit (gate trigger circuit). On the other hand, compared with the three-phase bridge rectifier (B6) the pulses frequency of the output voltage is half of the pulse frequency of the output voltage provided by a three-phase bridge rectifier. Therefore, the current and voltage filters used by the three-phase midpoint rectifiers must be higher. In addition, the maximum value of the DC voltage provided by a M3 rectifier is half of the maximum value provided by the B6 rectifier and to the M3 rectifier the discontinuous conduction mode may be appear at a lower delay (firing) angle. If one takes into account all these disadvantages and the tendency in the modern power electronics to eliminate and reduce, as much as possible, the inductances and the capacities of the power electronic systems by adopting silicon alternatives, it is easily explained why the midpoint rectifiers are rarely used. Their analysis is justified by didactic reasons because they are simpler and the bridge structure is achieved through a combination of two midpoint structures.

In applications whose power exceeding 1kW, three-phase rectifiers are recommended. Compared with a single-phase rectifier, a three-phase rectifier has the following advantages:

- ✓ loading symmetrical the three-phase power grid (utility grid);
- ✓ the pulse frequency from the output voltage waveform is higher, which allows the filters size reduction;

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- ✓ for the same input AC voltage, the maximum output DC voltage is higher in case of three-phase rectifiers;
- ✓ discontinuous conduction mode may occur over a delay angle of 30^0 to the M3 phase-controlled rectifier and over a delay angle of 60^0 to the B6 phase-controlled rectifier (at the single-phase rectifiers discontinuous conduction mode can occur as soon as the delay angle leaving 0^o value).

2. Three-phase midpoint rectifiers (M3)

A three-phase midpoint topology (M3) is shown in Fig.12.1. This includes a three-phase line-frequency transformer (TR) whose secondary windings, in star connection, supply a power structure with three diodes (uncontrolled rectifier) or with three thyristors (phase-controlled rectifiers). The DC load of the rectifier is connected between the positive bus (cathode terminals connected together) and the common point (midpoint) of the secondary windings, as shown in the figure. For simplicity we will analyze the rectifier with a resistive-inductive *R-L* load (rectifier with current filter). The transformer TR is supplied with the three-phase voltages of the power grid: v_R, v_S, v_T.

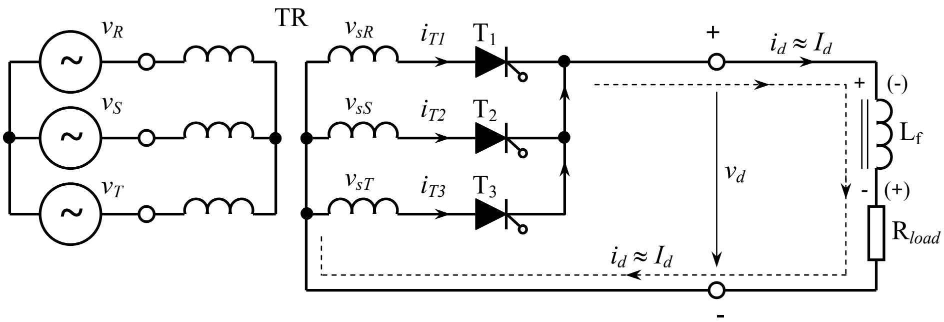


Fig. 12.1 Three-phase midpoint rectifier (M3) with current filters.

The filter inductance L_f included in the load circuit is considered sufficiently large to filter well the output DC current and to maintain the rectifier in a normal operation mode – continuous conduction mode. Consequently, one can approximate: $i_d(t) = I_d$ = constant. Based on the natural commutation process, this current is cyclically commutated between three paths corresponding to the T_1, T_2, T_3 thyristors.

a) <u>Natural commutation process in the case of a three-phase midpoint rectifier (M3)</u>

In power electronics the ***extended notion of the commutation (switching)*** *means the passing of the electric current from one circuit path (branch) to another circuit path (branch).*

Natural commutation implies the *natural* transfer of the current from one branch circuit to another branch under the "pressure" of a ***commutation voltage*** that appears after the semiconductor device found on the next branch is turned on. This current commutation is used in power structures made exclusively with power semiconductor devices without turn-off control (diodes, thyristor and triacs). These devices cannot stop, "at order" the current flow through a circuit branch. Thus, a current deviation technique is used with the help of a voltage that decreases the current through the first path and increases the current through the new, second, path. A cyclical commutation of the current between two or more circuit branches can occur if the commutation voltages are alternative. For this reason, the natural commutation technique can be used only in power structures supplied by the AC power sources.

The M3 three-phase midpoint rectifier is a suggestive power structure with the help of which can be explained in detail the natural commutation process. Thus, in Fig.12.1 the output DC current I_d, considered constant, is periodically commutated between the three T_1, T_2, T_3 branches with the time period $T_p= T=1/f,$ where f is the frequency of the input AC voltage .

In order to describe mathematically the successive steps which occur during the natural commutation we consider the initial situation in which the T_1 thyristor is on. Thus, the equivalent circuit which may describe the natural commutation of the I_d current from the (1) path that includes the T_1 thyristor to the (2) path that includes the T_2 thyristor is shown in Fig.12.2.

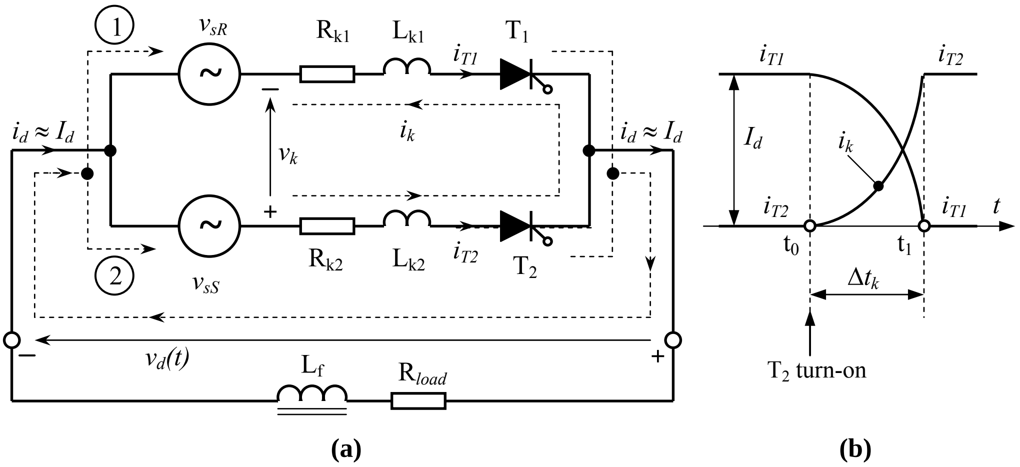


Fig. 12.2 (a) Equivalent circuit that illustrates the natural commutation process; (b) Currents evolution through circuit branches during the commutation time.

In the overall case, each branch involved in the current commutation process can be equivalent with a series circuit that includes an AC source, an R_k resistance, an L_k inductance and a thyristor whose turn-on moment starts the natural commutation process. For the midpoint three-phase structure shown in Fig.12.1, the input AC source consists of the three voltages induced in the TR secondary windings, v_{sR}, v_{sS} and v_{sT}. Due to these voltages the commutation voltage v_k appears whose polarity makes possible the current commutation. In Fig.12.2 was represented the polarity of v_k voltage that favours the I_d commutation from the (1) branch to (2) branch.

The L_k inductances from the branches are those who have the last impact on the natural commutation process. Due to their presence, the current cannot suddenly commutate from one branch to another branch. Thus, a commutation time interval appears in which I_d flows through the both branches ($I_d = i_{T1} + i_{T2}$) – see Fig.12.2. A suggestive explanation can be made if one takes into consideration the i_k commutation current imposed by the v_k commutation voltage. As shown in the figure, this voltage decreases the current from the (1) path and increases the current from the (2) path.

$$i_{T1}(t) = I_d - i_k(t); \qquad i_{T2}(t) = i_k(t) \tag{12.1}$$

To obtain the i_k current waveform and the value of the commutation time interval it will be written the voltage equation (Kirchhoff) in the loop formed by the two branches:

$$v_k = R_{k2} \cdot i_k + L_{k2} \cdot \frac{di_k}{dt} - R_{k1} \cdot (I_d - i_k) - L_{k1} \cdot \frac{d(I_d - i_k)}{dt} \tag{12.2}$$

where the v_k commutation voltage is given by difference of the two sine wave voltages from the branches:

$$v_k = v_{sS} - v_{sR} = \sqrt{2} \cdot (\sqrt{3} \cdot V_s) \cdot \sin(\omega t - 150^0) \tag{12.3}$$

With V_s is labelled the rms value of phase voltage from the transformer secondary windings. $\sqrt{3} \cdot V_s$ is the rms line-to-line voltage from the three-phase transformer secondary windings. For simplicity, the commutation voltage v_k is considered as a reference voltage:

$$v_k = V_{k(\max)} \sin \omega t \tag{12.4}$$

Taking into consideration that the derivative of the I_d current (constant) is zero, the equation (12.2) becomes:

$$\left(R_{k1} + R_{k2}\right) \cdot i_k + \left(L_{k1} + L_{k2}\right) \cdot \frac{di_k}{dt} = V_{k(\max)} \sin \omega t + R_{k1} \cdot I_d \tag{12.5}$$

It was obtained a first-order differential equation whose solution consists of three terms as follows:

1) First term (the transitory solution of the homogeneous differential equation):

$$i_{k1}(t) = K \cdot e^{-\tau \cdot t} \tag{12.6}$$

where K is the integration constant and $\tau = \dfrac{L_{k1} + L_{k2}}{R_{k1} + R_{k2}}$ is the time constant of the loop formed by the two branches.

2) The second term (the steady-state solution given by $V_{k(\max)} \sin \omega t$):

$$i_{k2}(t) = \frac{V_{k(\max)}}{Z_k} \cdot \sin(\omega t - \varphi_k) \tag{12.7}$$

where $Z_k = \sqrt{(R_{k1} + R_{k2})^2 + \omega^2 (L_{k1} + L_{k2})^2}$ is the whole impedance of the loop and $\varphi_k = \mathrm{arctg} \dfrac{\omega \cdot (L_{k1} + L_{k2})}{R_{k1} + R_{k2}}$ is the phase displacement between i_k and v_k.

3) The third term (the steady-state solution given by $R_{k1} \cdot I_d$):

$$i_{k3}(t) = \frac{R_{k1}}{R_{k1} + R_{k2}} \cdot I_d \tag{12.8}$$

Therefore, the whole solution of the differential equation (12.5) can be written as:

$$\begin{aligned} & i_k(t) = i_{k1}(t) + i_{k2}(t) + i_{k3}(t) = \\ & = K \cdot e^{-\tau \cdot t} + \frac{V_{k(\max)}}{Z_k} \cdot \sin(\omega t - \varphi_k) + \frac{R_{k1}}{R_{k1} + R_{k2}} \cdot I_d \end{aligned} \tag{12.9}$$

Assuming that $t_0 = \alpha/\omega$ is the moment when the natural commutation process start, when the T_2 thyristor is turned on (see Fig.12.2.b), the K integration constant can be calculated knowing that the commutation current i_k is zero in this moment:

$$i_k(t_0) = 0 \quad \Rightarrow \quad K = e^{\tau \cdot t_0} \left(-\frac{V_{k(\max)}}{Z_k} \cdot \sin(\omega t_0 - \varphi_k) - \frac{R_{k1}}{R_{k1} + R_{k2}} \cdot I_d \right) \tag{12.10}$$

After attributing the value for the constant K in the expression (12.9) we can calculate the commutation time interval considered complete when the thyristor T_2 branch takes the whole I_d current (t_1 time), described mathematically by the equality:

$$\begin{aligned} & i_k(t_1) = I_d \quad \Leftrightarrow \\ & \Leftrightarrow \quad K \cdot e^{-\tau \cdot t_1} + \frac{V_{k(\max)}}{Z_k} \cdot \sin(\omega t_1 - \varphi_k) = \frac{R_{k2}}{R_{k1} + R_{k2}} \cdot I_d \end{aligned} \tag{12.11}$$

Equation (12.11) can be solved by numerical methods to obtain the t_1 time value. Based of this, it can be calculated the value of the commutation time interval:

$$\Delta t_k = t_1 - t_0 = f(\alpha, I_d) \tag{12.12}$$

One can observe that the duration of the commutation process is influenced by the value of the control angle ($\alpha = \omega \cdot t_0$) and by the value of the load current I_d.

Corresponding to the commutation time interval, one can define an electric angle, parameter used in practice. This angle is called ***commutation angle*** or ***overlapping anodic angle***. The latter denomination is justified by the fact that during the current commutation process, the both thyristors or the both diodes are in on-state (conduction) which is equivalent with a superposition of the anode terminals (short circuit). In the literature we find various notations for the commutation angle ***u***, **μ**, γ etc. Whatever the notation, its value is given by the equation:

$$\gamma = \omega \cdot \Delta t_k \text{ [}^{\circ}\text{el. degree]} \tag{12.13}$$

Next, the commutation angle will be noted with γ (*gamma*). Because Δt_k depends on the load current and on the delay angle through the *K* constant, it is evident that the commutation angle value depends, also, on these variables $\gamma = f(\alpha, I_d)$. This aspect is very important, because the commutation angle modifies the average (DC) value of the voltage from the output of the line-commutated rectifiers.

If we analyze the equivalent circuit shown in Fig.12.2.(a) during commutation time interval and we apply the second Kirchhoff law, we can write the following equations:

For the first path: $$v_d(t) = v_{sR} + R_{k1} \cdot i_k + L_{k1}\frac{di_k}{dt} \tag{12.14}$$

For the second path: $$v_d(t) = v_{sS} - R_{k2} \cdot i_k - L_{k2}\frac{di_k}{dt} \tag{12.15}$$

Considering that the rectifier branches are symmetrically, we can write: $R_{k1}=R_{k2}$ and $L_{k1}=L_{k2}$. Under these conditions, if we sum the equation (12.14) with (12.15) we get:

$$2 \cdot v_d(t) = v_{sR}(t) + v_{sS}(\text{t}) \Rightarrow v_d(t) = \frac{v_{sR}(t) + v_{sS}(\text{t})}{2}, \quad t_0 \le t \le t_1 \tag{12.16}$$

The equation (12.16) emphasizes that ***during the commutation time interval*** Δt_k ***the voltage at the rectifier output is the mean of the AC voltages from the two branches which are in the natural commutation process.***

b) Analysis of three-phase midpoint rectifiers M3

The waveforms which highlight the operation of three-phase midpoint rectifiers taking into consideration the natural commutation process are presented in Fig.12.3. The natural commutation point for the T_2 thyristor is placed in the position in which the commutation voltage $u_k = u_{sS} - u_{sR}$ passes through zero and becomes positive. It can be noticed that, ***the natural commutation points for three-phase rectifiers are placed at the intersection of the phase voltages waveforms***. For the thyristors which operate during the positive half-waves, as in the case of M3 structure from Fig.12.1, these points are labeled P_1, P_2 and P_3 (see Fig.12.3). With a delay from them, with the same firing angle, are triggered the thyristors T_1, T_2, and T_3 (in the figure are shown the waveforms for $\alpha = 60^o$).

The Fig.12.3 shows the commutation current i_k, when the i_{T1} current decreases and the i_{T2}current increases during the γ commutation angle. After T/3 time interval (T=1/f is the time period of the input AC voltage) the next natural commutation of the I_d current occurs, from the T_2 thyristor branch to the T_3 thyristor branch, followed by the commutation to the T_1 thyristor branch, back again. Thus, each thyristor stay in conduction a T_p = T/3 time interval or a 2π/3 radians angle during the whole T time period.

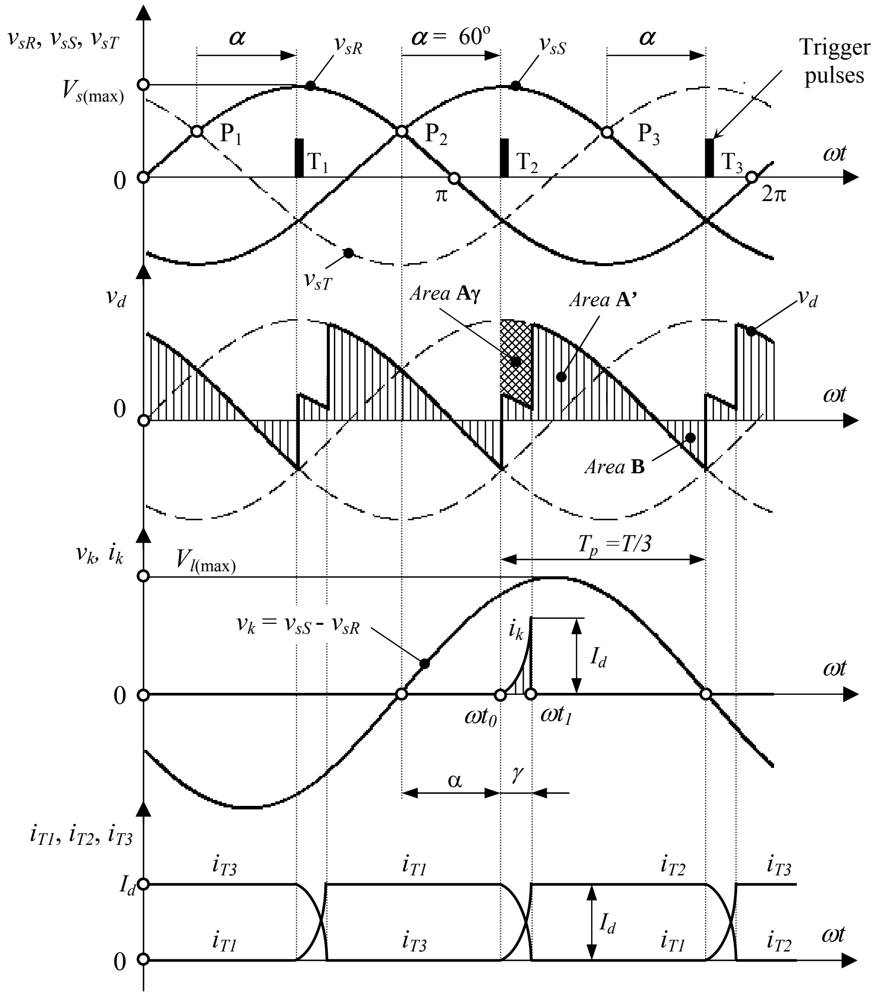


Fig. 12.3 Real waveforms which take into consideration the natural commutating process at the three-phase midpoint phase-controlled rectifier M3.

Analyzing the waveform of the output voltage we can observe that, during the γ commutation angle, the voltage $v_d(t)$ is equal with the mean value of the phase voltages from the commuting branches, according to the relation (12.16).

In ideal current commutation conditions ($\gamma = 0 \Rightarrow L_{k1} = L_{k2} = L_{k3} = 0$) and when the resistances of the commutation branches are neglected ($R_{k1} = R_{k2} = R_{k3} = 0$) the $v_d(t)$ output voltage waveform consists of successive pulses given by identical portions of the phase voltages v_{sR}, v_{sS}, v_{sT}, without Aγ areas, as shown in Fig.12.4. Thus, the output DC voltage can be calculated applying the average formula during a pulse time period T_p:

$$V_{d\alpha} \overset{not}{=} \text{average value of } v_d(t) = \frac{1}{T_p}\int_{t_0}^{t_0+T_p} v_d(t)\cdot dt = \frac{1}{2\pi/3}\left[Area\ \mathrm{A} + Area\ B\right] \qquad (12.17)$$

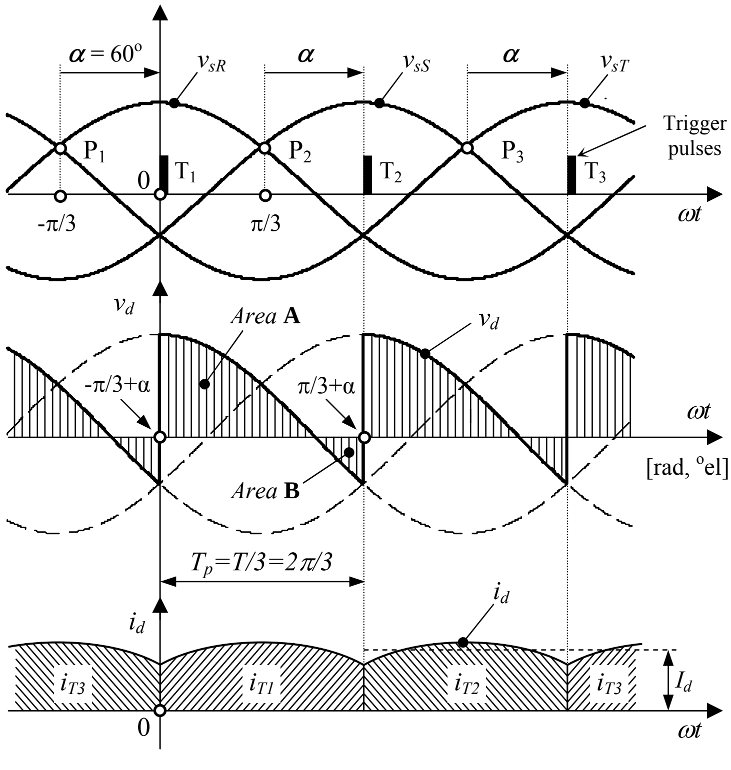


Fig.12.4 Waveforms in the case of an ideal current commutation for the midpoint three-phase controlled rectifier.

A fast method to calculate the $V_{d\alpha}$ expression is to place the time origin in front of an output voltage pulse for which is applied the average value formula, at midway location between two natural commutation points, as shown in Fig.12.4.

Consequently, in expression (12.17), $v_d(t)$ can be described with the cosine function during a pulse time period T_p (2π/3 rad). It follows:

$$V_{d\alpha} = \frac{1}{2\pi/3}\int_{-\frac{\pi}{3}+\alpha}^{\frac{\pi}{3}+\alpha}\sqrt{2}V_s\cos(\omega t)\cdot d(\omega t) = \frac{3\sqrt{2}V_s}{2\pi}\left[\sin(\omega t)\right]_{-\frac{\pi}{3}+\alpha}^{\frac{\pi}{3}+\alpha} =$$

$$= \frac{3\sqrt{2}V_s}{2\pi}\left[\sin\left(\frac{\pi}{3}+\alpha\right) - \sin\left(-\frac{\pi}{3}+\alpha\right)\right] = \frac{3\sqrt{6}\cdot V_s}{2\pi}\cdot\cos\alpha \qquad (12.18)$$

If we consider the control angle α = 0° the operation of the thyristor rectifier becomes similar with that of a diode rectifier and the average output voltage is:

$$V_{d0} = \frac{3\sqrt{6}\cdot V_s}{2\pi}\cdot\cos 0^0 = \frac{3\sqrt{6}\cdot V_s}{2\pi} \cong 1{,}17\cdot V_s \qquad (12.19)$$

Thus, in case of ideal current commutation (instantaneous), the average value of output voltage of the same controlled rectifier with a certain delay angle α can be written as:

$$V_{d\alpha} = V_{d0}\cdot\cos\alpha \qquad (12.20)$$

which is a known and valid equation, as was presented before in Lab no.8, *if the rectifier operates in continuous conduction mode and in ideal current commutation conditions.*

In case of real current commutation conditions it should be taken into consideration *Area* Aγ which is missing from *Area* A > 0. Corresponding to the missing area the average value of the output voltage decreases with:

$$\Delta V_{d\alpha} = \frac{1}{T_p}\cdot Area\ \mathrm{A}\gamma = \frac{1}{2\pi/3}\cdot Area\ \mathrm{A}\gamma \qquad (12.21)$$

The *Area* Aγ from Fig.12.3 can be calculated taking into consideration the output voltage decreases due to the natural commutation process:

$$Area\ \mathrm{A}\gamma = \int_{t_0}^{t_1}\frac{v_k(t)}{2}dt = \int_{t_0}^{t_1}\left(\mathrm{R_k}\cdot i_k + L_k\frac{di_k}{dt}\right)dt =$$

$$= \int_{\alpha}^{\alpha+\gamma}\left(\mathrm{R_k}\cdot i_k + L_k\frac{di_k}{dt}\right)d(\omega t) \qquad (12.22)$$

In the equation (12.22) the resistances and inductances were considered equals on the two commutation branches: $R_{k1} = R_{k2} = R_k$ and $L_{k1} = L_{k2} = L_k$. With this equation is quite difficult to calculate *Area* Aγ. For this reason is neglecting the resistances ($R_k \approx 0$) which are much lower than the inductive reactance ($R_k << \omega L_k$.). In this simplified conditions the equation (12.22) integral can be easily calculated:

$$Area\ A\gamma = \int_{\alpha}^{\alpha+\gamma} L_k \frac{di_k}{dt} d(\omega t) = \omega \cdot L_k \int_{0}^{Id} di_k = \omega \cdot L_k \cdot I_d \qquad (12.23)$$

Using the equation (12.21) it results the expression of the average output voltage if it is taken into consideration the real commutation process, but neglecting the voltage drops on the branches resistances:

$$V_{d\alpha}^{'} = V_{d0} \cdot \cos\alpha - \Delta V_{d\alpha} = V_{d0} \cdot \cos\alpha - \frac{\omega L_k I_d}{2\pi / 3} \qquad (12.24)$$

The equation (12.24) reveals that the DC voltage provided by a controlled rectifier do not depends only on the delay angle, even the converter operates in continuous conduction mode. The output DC voltage has small decreases once the load current I_d increases, as shown in Fig.12.5 where are presented the ***load characteristics*** whose slope is induced by the natural commutation process and by the internal impedances of the AC source.

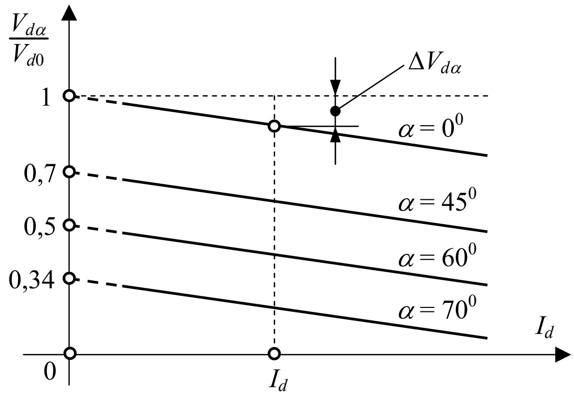


Fig. 12.5 Load characteristics of the phase-controlled rectifiers.

The voltage drop $\Delta U_{d\alpha}$ given by equation (12.24) is greater if we take into consideration the resistances from the commutation branches (R_k) and the internal impedances of the AC source (Z_s).

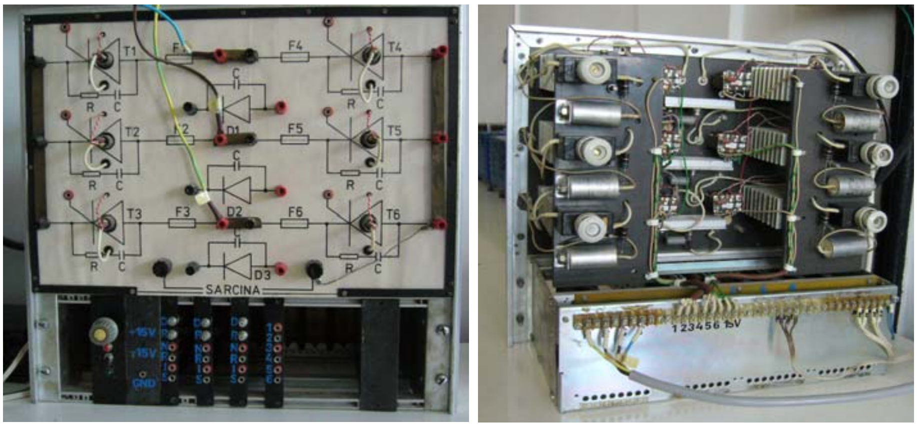
$$\Delta U_{d\alpha} = f(\omega L_k, R_k, Z_s, I_d) \qquad (12.25)$$

The load characteristics shown in Fig.12.5 are presented with dashed lines at small I_d currents, because no matter how large is the filter inductance, in the small currents range the rectifier operates in discontinuous conduction mode and the DC output voltage increases. These increases are not presented in the figure.

The $V_{d\alpha}$ dependence on the load current can be reduced if the rectifiers are supplied by transformers whose leakage inductances and winding resistances have low values. A further improvement can be obtained if the rectifier is supplied directly from the power grid, without transformer. In this variant, in the natural current commutation process are involved only the low values of the grid inductance and resistance.

3. Laboratory application

In order to achieve the laboratory setup with the three-phase midpoint controlled rectifier it will be used a flexible laboratory installation especially designed for the three-phase rectifiers study – see Fig.12.6.



(a) Front view **(b)** Rear view

Fig.12.6 Laboratory installation for three-phase rectifiers study.

The laboratory equipment contains two parts: the power part and the control part. The circuit elements included in the power part (thyristors, power diodes, heat sinks, R-C snubbers, fuses etc.) are mounted on the back of a panel, as shown in the Fig.12.5(b). On the front of this panel is plotted the circuit diagram with the available power semiconductor devices (thyristors, diodes) and are mounted standard connectors (banana sockets) for the devices terminals. Thus, with the help of especially bars and banana plug cables, we can modify the connections between terminals in order to obtain different topologies of the three-phase rectifiers: midpoint rectifier, full-controlled bridge rectifier, half-controlled bridge rectifier. The connectors on the front panel also make possible an easy access to various points in the power structure for measuring or for displaying the waveforms of certain variables (voltages, currents) including the trigger pulses from the thyristors gate terminals.

The control part has a modular structure with boards circuits (cards) mounted in a special drawer through guides and couples. It can be listed the following modules (from the left to the right in the front view of Fig.12.5.(a):

- ✓ the control module that includes a potentiometer for the α delay angle adjustment and the START/STOP buttons for the main contactor that supplies the power part;
- ✓ the DC source module that includes a regulated double DC source ($\pm 15V_{dc}$) for the control part supply;
- ✓ 3 modules with the gate trigger circuits for the thyristors of the three-phase bridge legs;
- ✓ the module that distributes the gate trigger pulses to the 6 thyristors;
- ✓ the module with 3 synchronization transformers for the gate trigger circuits.

The gate trigger circuits are achieved with the UAA145 integrated circuits in a improved scheme: with a constant current circuit in order to obtain a linear slop of the saw-tooth signal, with potentiometers mounted on the module front panels to adjust the width of the zero-crossing sync pulses and of the gate trigger pulses, etc. On the frontal panel of the modules are placed also connectors to measure and display the following signals: zero-crossing sync pulses, saw-tooth signals, gate trigger pulses and synchronization voltages. The last ones are obtained with the help of the synchronization transformers supplied with the line-to-line voltages because their zero-crossing marks the natural commutation points for the thyristors included in a three-phase rectifier. Each trigger circuit (module) provides gate trigger pulses, with the same delay angle value, for both, the upper and bottom thyristors of the bridge legs.

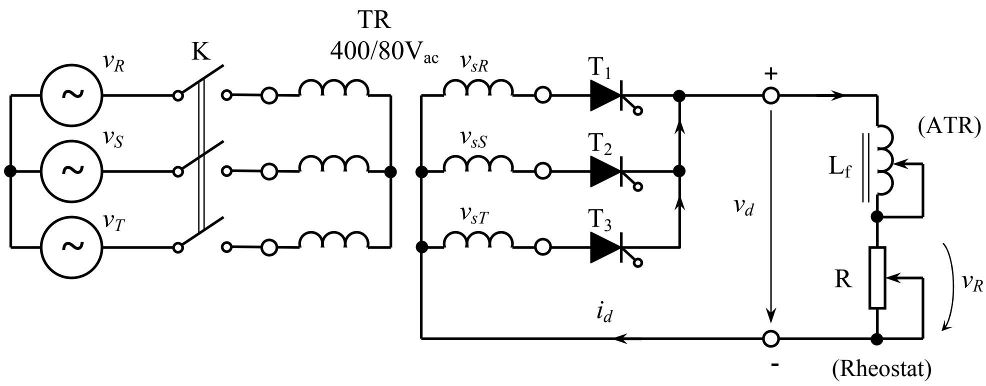


Fig.12.7 The laboratory setup for the three-phase midpoint rectifier study.

Because with the help of the laboratory setup we want to obtain also the three-phase full-bridge topology, the control part contains a module that distributes the gate trigger pulses to the 6 thyristors, module achieved with a logic circuit having the role of transmitting two trigger pulses, 60° shifted, for each thyristor gate. The second pulse is useful to start the three-phase bridge rectifier and to maintain the operation of this rectifier in discontinuous conduction mode (see Lab no.13).

The pulse transformers are placed in close proximity of each thyristor to avoid the possibility of inducing a false control signals. In the same purpose the connecting wires through which are transmitting the gate trigger pulses are twisted.

In order to obtain the experimental midpoint three-phase structure (Fig.12.7), it will be used from the laboratory installation, above described, only the thyristors which operate on the positive half-wave T_1, T_2 and T_3. Thus, their anode terminals will be connected, by means of the bananas plugs cables, to the secondary windings of the three-phase transformer TR. The resistive-inductive (*R-L*) load of the M3 phase-controlled rectifier will be connected between the positive DC bus (bar that connects the thyristors cathode terminals) and the midpoint of the TR secondary windings in star connection. As filter inductance it will be used an autotransformer (ATR) and as a load resistance a rheostat (R). In Fig.12.8 is shown the image of the laboratory setup.

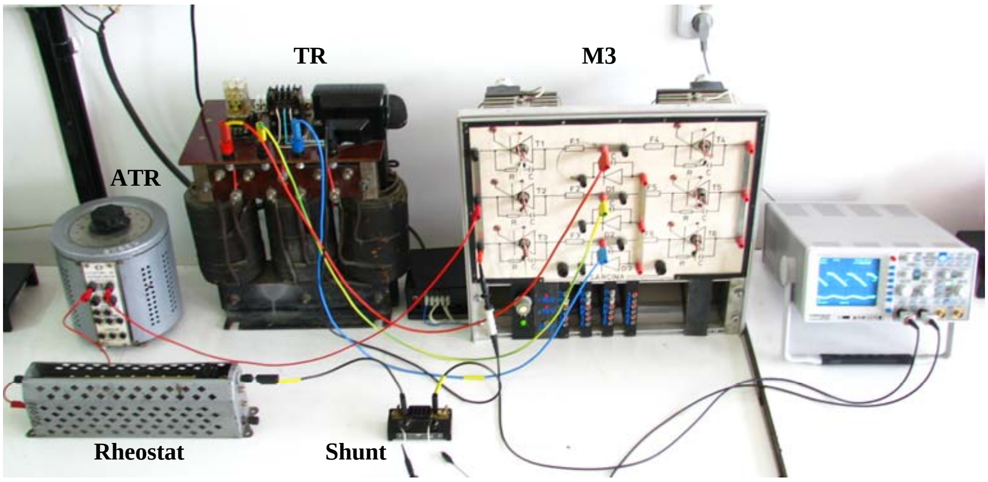


Fig.12.8 Image of the laboratory setup.

To simultaneously display the waveforms of the output voltage v_d and current i_d (v_R) it must be used a two spot oscilloscope and for measuring the average value of the output voltage $V_{d\alpha}$ it will be used a voltmeter. It can be displayed the waveforms corresponding to the M3 phase-controlled rectifier in case of a purely resistive load by moving the cursor of the autotransformer in the zero position.

4. Objectives and procedures

1. It will be analyzed the natural current commutation process at the three-phase midpoint rectifiers and how is affected the output voltage waveform during the commutation angle.

2. It will be studied the theoretical aspects regarding the operation of the three-phase midpoint rectifiers with current filters: waveforms, average voltage equation in case of ideal current commutation and in case of real current commutation, load characteristics, etc.
3. It will be performed the laboratory setup with the circuit diagram from Fig.12.7 and it will be started the operation of the converter in continuous conduction mode (high L_f) in order to view the waveforms v_d and i_d for various delay angles in rectifier mode ($\alpha<90^o$);
4. It will be measured the output DC (average) voltage $V_{d\alpha}$ for various delay angles with the help of the voltmeter in case of continuous conduction mode;
5. It will be fixed a delay angle higher than 30^o and it will be progressively decreased the inductance from the load circuit by acting on the autotransformer's cursor until the discontinuous conduction mode appear and it will be noticed the increasing of the average voltage as this mode emphasizes;
6. It will be displayed the waveforms v_d and i_d at the limit, when the inductance L_f is zero (the load is purely resistive) and it will be noticed that the discontinuous conduction mode appear after the delay angle increases beyond 30^o ($\alpha>30^o$).

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