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"KHARKIV POLYTECHNIC INSTITUTE"

**TEACHING AID**

for self-study

in the discipline "Power electronics and converter technology"  
for foreign students of electrical engineering specialties

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## INTRODUCTION

It is recommended to use those teaching aid when performing laboratory work on the discipline "Power electronics and converter technology" when studying the work of: smoothing filters in various schemes of uncontrolled rectifiers; controlled rectifiers with different types of load; pulse-width converters; autonomous current and voltage inverters on a virtual laboratory bench (VLB), which is a personal computer (PC) with the MatLab / Simulink software package installed on it.

*The purpose of virtual laboratory works* is to consolidate theoretical knowledge, through calculations, modeling and detailed study of electrical processes in various schemes of semiconductor converters in steady-state and transient operating modes.

The virtual laboratory bench allows you to study the parameters of circuits and their operation modes within a wide range.

### CHAPTER NO. 1

#### UNCONTROLLED RECTIFIER WITH SMOOTHING FILTERS

*The purpose of the work* is to study the operation principle and research various schemes of uncontrolled rectifiers with smoothing filters.

##### 1.1 Basic theoretical thesis

A *rectifier* is a converter of a supply network alternating voltage into a constant pulsing load voltage (with the possibility of regulation its average value or its absence). An *uncontrolled rectifier (UR)* cannot regulate the average value of the output voltage.

Rectifier's classification.

1. According to the supply network phases number:
  - a. single-phase rectifier;
  - b. three-phase rectifier.
2. Based on the number of output voltage pulses per cycle of the converter:
  - a. single-pulse rectifier;
  - b. two-pulse rectifier;
  - c. three-pulse rectifier;
  - d. six-pulse rectifier and so on.
3. Based on the rectifier circuit configuration:
  - a. midpoint type rectifier;
  - b. bridge type rectifier.

Single-phase rectifiers can be classified as either half-wave or full-wave circuits.

### 1.1.1 Single-phase half-wave uncontrolled rectifier

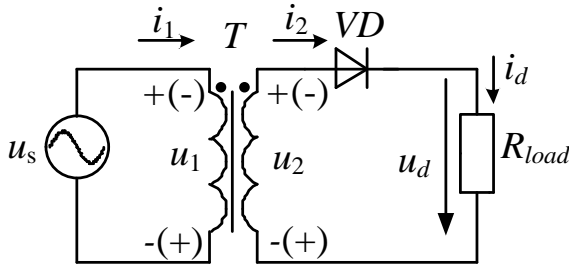


Figure 1.1 – Single-phase half-wave uncontrolled rectifier

A single-phase half-wave rectifier scheme and diagrams of the scheme's operation are shown in fig. 1.1. and fig. 1.2 respectively.

The scheme and diagrams uses the following designations for voltages and currents:

- $u_s$  – instantaneous mains voltage ( $u_s \approx u_1$ );
- $u_1, u_2$  – instantaneous voltages of the transformer primary and secondary windings;

primary windings;

- $i_1, i_2$  – instantaneous currents of the transformer primary and secondary windings;
- $i_{VD}$  – instantaneous diode current;
- $u_{VD}$  – instantaneous diode voltage;
- $u_d$  – instantaneous rectified voltage ( $u_d = u_{load}$ );
- $i_d$  – instantaneous rectified current ( $i_d = i_{load}$ ).

The analysis of the scheme operation is carried out without taking into account the voltage losses on the active resistance of the transformer windings and on the dynamic resistance of the open diode.

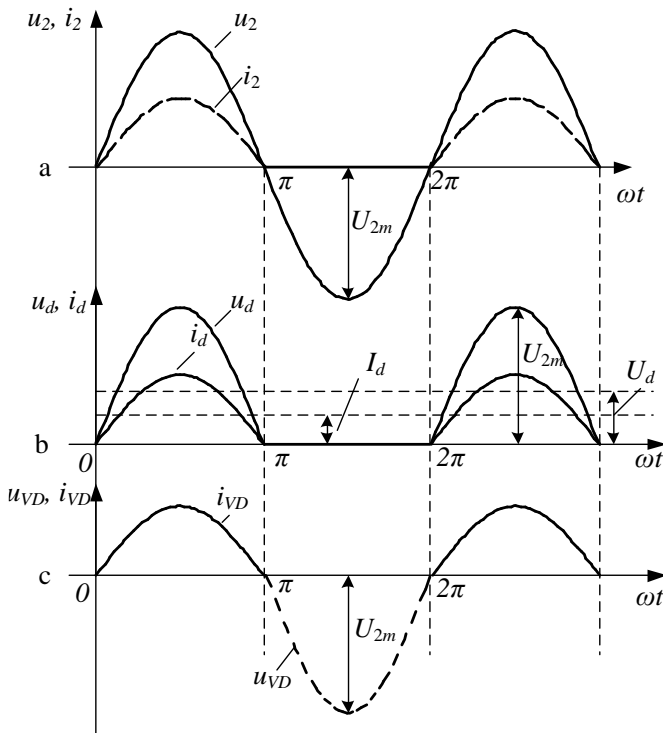


Figure 1.2 – Diagrams of Single-phase half-wave uncontrolled rectifier the operation

zero. In this case, the load voltage equal is zero and the open diode voltage repeats

Under the action of the alternating voltage  $u_2 = U_{2m} \sin \omega t$  of the secondary winding, the current in the load circuit  $i_{load} = i_d$  flows only in the positive half-cycle of the voltage  $u_2 > 0$ , when the diode anode has a positive potential relative to the cathode (the diode opening condition is satisfied). In this case, the load voltage  $u_{load} = u_d$  repeats the shape and magnitude of the secondary winding voltage  $u_2$  and the open diode voltage  $u_{VD}$  equal is zero (interval  $0 - \pi$ , fig. 1.2). In negative half-cycles of voltage  $u_2 < 0$ , when the anode potential becomes negative (the diode closing condition is satisfied), the current in the circuit equal is

the shape and magnitude of the secondary winding voltage (interval  $\pi - 2\pi$ , fig. 1.2).

During the period of the mains voltage on the load, one positive voltage wave is formed, which alternates with zero pauses, therefore such a rectifier circuit is called single-pulse and half-wave.

The *rectifier pulse rate* is the number of rectified voltage pulses per the period of the mains voltage.

Average rectified voltage:

$$U_d = \frac{1}{2\pi} \int_0^{2\pi} U_{2m} \sin \omega t d\omega t = \frac{U_{2m}}{\pi} = \frac{\sqrt{2} \cdot U_2}{\pi}, \quad (1.1)$$

where  $U_2$  is the rms voltage of the transformer secondary winding .

The maximum reverse voltage diode reaches the peak voltage of the secondary winding  $U_{2m}$ :

$$U_{VD \max} = U_{2m} = \sqrt{2} \cdot U_2 = \pi \cdot U_d. \quad (1.2)$$

Average rectified current (diode current):

$$I_d = I_{VD} = \frac{\sqrt{2} \cdot I_2}{\pi}, \quad (1.3)$$

where  $I_2$  – rms current of the transformer secondary winding.

The variable component of the rectified voltage and current for this circuit, as follows from the timing diagrams (fig. 1.2), is large, and the fundamental harmonic of the ripple has a frequency equal to the supply network frequency.

In the transformer core, due to the constant component of the secondary winding current, an additional constant magnetic flux is created, saturating the transformer core. This phenomenon is usually called forced magnetization of the transformer.

As a result of magnetization, the magnetizing current of the transformer increases several times compared to the current during normal operation (without magnetization). An increase in the magnetizing current requires an increase in the cross-section of the mains winding wire and the transformer size as a whole.

The main advantage of a single-pulse half-wave rectifier is the simplicity of the scheme.

Disadvantages: large size and weight of the transformer, significant reverse voltage diode, large ripple, presence of forced magnetization.

A single-pulse half-wave rectifier, due to the listed disadvantages, is used quite rarely, mainly in low-power devices.

### ***1.1.2 Single-phase full wave midpoint uncontrolled rectifier***

Figures 1.3 and 1.4 show a single-phase full wave midpoint uncontrolled rectifier scheme and it's currents and voltages timing diagrams, respectively.

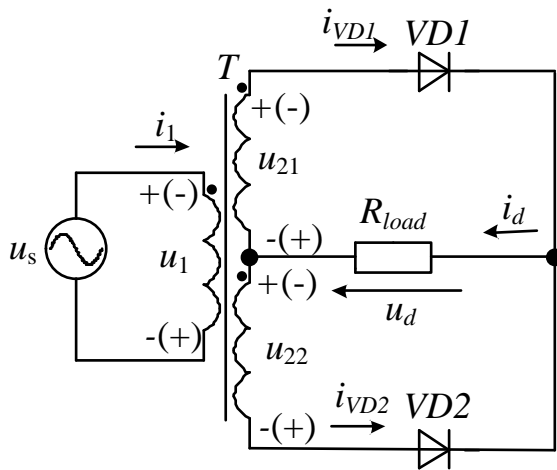


Figure 1.3 – Single-phase full-wave midpoint uncontrolled rectifier

The scheme and diagrams uses the following designations for voltages and currents:

- $u_s$  – instantaneous mains voltage ( $u_s \approx u_1$ );
- $u_1, u_{21}, u_{22}$  – instantaneous voltages of the transformer primary and two secondary windings;
- $i_1$  – instantaneous currents of the transformer primary windings;
- $i_{VD1}, i_{VD2}$  – instantaneous diodes currents;
- $u_{VD1}, u_{VD2}$  – instantaneous diodes voltages;

- $u_d$  – instantaneous rectified voltage ( $u_d = u_{load}$ );
- $i_d$  – instantaneous rectified current ( $i_d = i_{load}$ ).

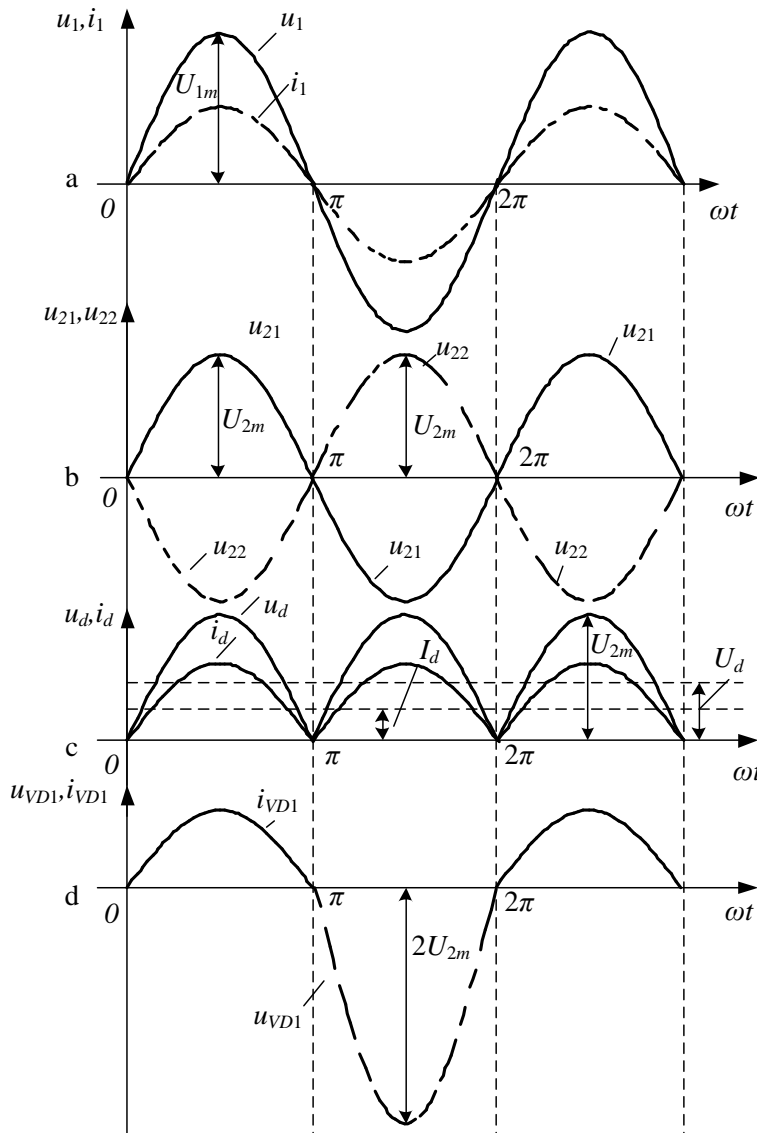


Figure 1.4 – Diagrams of Single-phase full-wave midpoint uncontrolled rectifier the operation

The analysis of the scheme operation is carried out without taking into account the voltage losses on the active resistance of the transformer windings and on the dynamic resistance of the open diode.

The single-phase full wave midpoint uncontrolled rectifier is consist of two single-pulse half-wave rectifier that works on one common load from two antiphrasis (relative to the load) AC voltage sources ( $u_{21}, u_{22}$ ). With an equal turns number of the two secondary windings of the transformer, the amplitudes  $U_{21m}, U_{22m}$  are equal to each other.

Diodes  $VD1$  and  $VD2$  pass current to the load alternately. During

the positive half-cycle of the mains voltage on the transformer secondary windings (polarity is indicated without brackets) (interval  $0 - \pi$ , fig. 1.4), the diode  $VD1$  is open and the current  $i_{VD1}$  passes through  $VD1$ , the load  $R_{load}$  and the half-winding of the transformer with voltage  $u_{21}$ . In the next half-cycle of the mains voltage (the polarity is indicated in brackets) (interval  $\pi - 2\pi$ , fig. 1.4), the  $VD2$  diode opens and the  $VD1$  diode closes. In this case, the current  $i_{VD2}$  flows through the diode  $VD2$ , the load  $R_{load}$  and the half-winding of the transformer with voltage  $u_{22}$ . Thus, the load current  $i_{load} = i_d$  flows in one direction during the mains voltage entire period. Rectified voltage  $u_d = u_{load}$  is a positive half-wave of voltages  $u_{21}$  and  $u_{22}$ . In this case, the current  $i_1$  of the transformer primary winding will be alternation (sinusoidal at active load).

During the period of the mains voltage on the load, two positive voltage wave is formed, therefore such a rectifier circuit is called full-wave.

Average rectified voltage:

$$U_d = \frac{1}{\pi} \int_0^{\pi} U_{2m} \sin \omega t d\omega t = \frac{2U_{2m}}{\pi} = \frac{2\sqrt{2} \cdot U_2}{\pi}, \quad (1.4)$$

where  $U_2$  is the rms voltage of the transformer secondary winding  $U_2 = U_{21} = U_{22}$ .

The maximum reverse voltage diode reaches the double peak voltage of the secondary winding  $U_{2m} = U_{21m} = U_{22m}$ :

$$U_{VD \max} = 2U_{2m} = 2\sqrt{2} \cdot U_2 = \pi \cdot U_d. \quad (1.5)$$

Average rectified current:

$$I_d = \sqrt{2} \cdot I_2. \quad (1.6)$$

Average diode current:

$$I_{VD} = \frac{I_d}{2}. \quad (1.7)$$

This rectifier circuit has only two diodes, but diode reverse voltage is equal to the sum  $U_{21m} + U_{22m}$ , the maximum value of which is equal to the reverse voltage amplitude and is 2 times higher than the rectified voltage amplitude. Also this rectifier circuit has 2 times less ripple compared to half-wave rectifier circuit, but more complex transformer design.

It is used in single-phase networks with a load voltage of up to 12 V.

### ***1.1.3 Single-phase full wave bridge uncontrolled rectifier***

The most widely used is a single-phase full wave bridge rectifier scheme. Figures 1.5 and 1.6 show a single-phase full wave bridge uncontrolled rectifier scheme and it's currents and voltages timing diagrams, respectively.

The scheme and diagrams uses the following designations for voltages and currents:

- $u_s$  – instantaneous mains voltage ( $u_s \approx u_1$ );

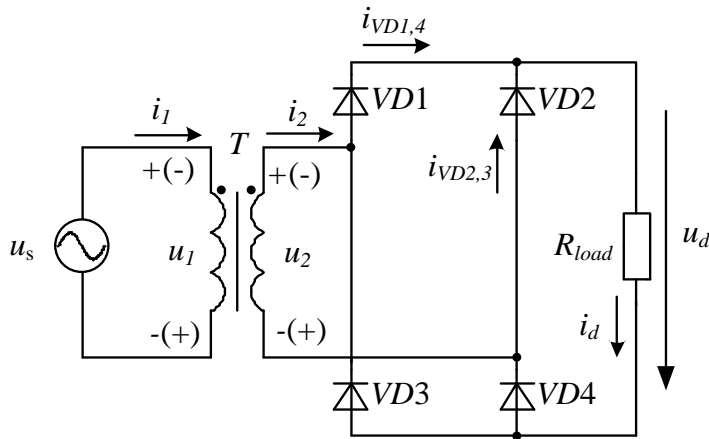


Figure 1.5 – Single-phase full-wave bridge uncontrolled rectifier

-  $i_d$  – instantaneous rectified current ( $i_d = i_{load}$ ).

The analysis of the scheme operation is carried out without taking into account the voltage losses on the active resistance of the transformer windings and on the dynamic resistance of the open diode.

The diodes form a bridge, in one diagonal of which the transformer secondary winding is included, and in the other - the load resistor  $R_{load}$ . Each pair of diodes works in turn. With a positive half-wave of voltage  $u_2 > 0$  (interval  $0 - \pi$ , fig. 1.6), diodes  $VD1$  and  $VD4$  are open (diodes  $VD2$  and  $VD3$  are close). In this case, the current in the load flows along the circuit through the transformer secondary winding, diode  $VD1$ , load resistor  $R_{load}$  and diode  $VD4$ .

In the next half-cycle  $u_2 < 0$  (interval  $\pi - 2\pi$ , fig. 1.6), diodes  $VD2$  and  $VD3$  are open (diodes  $VD1$  and  $VD4$  are close). The current passes through the diode  $VD2$ , the load  $R_{load}$  and the diode  $VD3$ . Therefore, in the load circuit, the current  $i_d$  flows in one direction throughout the entire period.

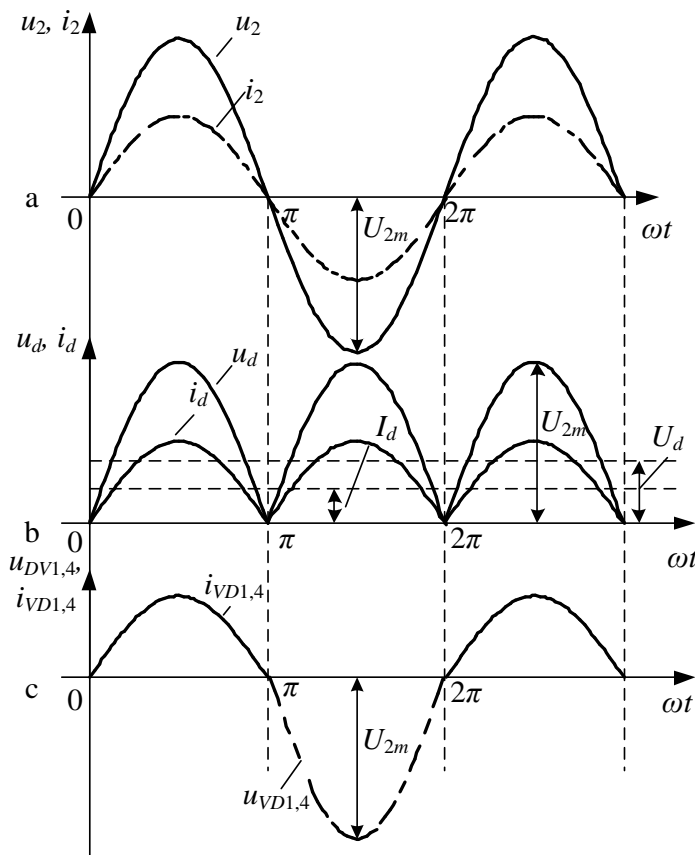


Figure 1.6 – Diagrams of Single-phase full-wave bridge uncontrolled rectifier the operation

-  $u_1, u_2$  – instantaneous voltages of the transformer primary and secondary windings;

-  $i_1, i_2$  – instantaneous currents of the transformer primary and secondary windings;

-  $i_{VD1,4}, i_{VD2,3}$  – instantaneous diodes currents;

-  $u_{VD}$  – instantaneous diode voltage;

-  $u_d$  – instantaneous rectified voltage ( $u_d = u_{load}$ );

such a rectifier circuit is called full-wave.

Average rectified voltage:

$$U_d = \frac{1}{\pi} \int_0^{\pi} U_{2m} \sin \omega t d\omega t = \frac{2U_{2m}}{\pi} = \frac{2\sqrt{2} \cdot U_2}{\pi}. \quad (1.8)$$

The maximum reverse voltage diode reaches the peak voltage of the secondary winding  $U_{2m}$ :

$$U_{VD \max} = U_{2m} = \sqrt{2} \cdot U_2 = \frac{\pi}{2} \cdot U_d. \quad (1.9)$$

Average rectified current:

$$I_d = I_2. \quad (1.10)$$

Average diode current:

$$I_{VD} = \frac{I_d}{2}. \quad (1.11)$$

Comparing the two full-wave rectifier schemes, the following conclusions can be drawn:

- with the same values of load current and voltage, the typical power, and, consequently, the transformer dimensions for the midpoint type scheme is larger than for the bridge type scheme. This is due to two secondary windings that pass current for half a period each;

- the diode reverse voltage in the bridge type scheme at the same rectified voltage is two times less than in the midpoint type scheme;

- the bridge type scheme requires twice as many diodes.

It is used in single-phase networks with a load voltage of more than 12 V.

#### **1.1.4 Smoothing filters**

Smoothing filters are designed to reduce the ripple of the rectified voltage and current. It consists of reactive elements ( $L$  or  $C$ ), which are connect between the rectifier output and the load. The operation principle of smoothing filters is based on the ability of reactive elements to accumulate energy when a power source is connected to them and to give it to the load when the power supply from the source decreases (or stops). This ensures a uniform supply of energy to the load.

The main parameter characterizing the efficiency of the smoothing filter is the *smoothing coefficient* equal to the ratio of the ripple coefficients at the input  $K_{r in}$  and output  $K_{r out}$  of the filter:

$$K_{sm} = \frac{K_{r in}}{K_{r out}} = \frac{U_{m(k) in}}{U_{m(k) out}} \cdot \frac{U_{d out}}{U_{d in}}, \quad (1.12)$$

if we neglect the losses in the filter, we can consider:

$$K_{sm} = \frac{K_{r in}}{K_{r out}} = \frac{U_{m(k) in}}{U_{m(k) out}} \quad (1.13)$$

The *ripple coefficient* is equal to the ratio of the fundamental harmonic amplitude of the rectified voltage  $U_{m(k)}$  to its average value  $U_d$  :

$$K_r = \frac{U_{m(k)}}{U_d} = \frac{1}{k^2 - 1} \cong \frac{1}{m^2 - 1}. \quad (1.14)$$

Assessment of the output voltage quality of an uncontrolled rectifier is usually carried out taking into account only the first harmonic, therefore we can taking  $k = m \cdot 1 = m$ , where  $m$  is the pulsation of the rectifier scheme.

Figure 1.7 shows the simplest smoothing filters connected between the rectifier and the load.

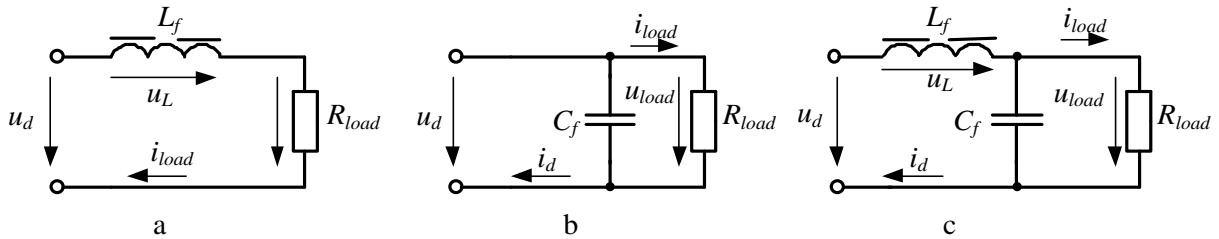


Figure 1.7 – Smoothing filters:  
a) inductive filter; b) capacitive filter; c) composite filter.

### 1.1.5 Inductive filter

In medium and high power rectifiers, an *inductive filter* is often used. It uses a choke  $L_f$ , which is connected in series with the load  $R_{load}$  (fig. 1.7, a). The choke most often has a ferromagnetic core with a non-magnetic gap.

According to Kirchhoff's law at any given time:

$$u_d = u_L + u_{load}, \quad (1.15)$$

where  $u_L = L_f \frac{di_{load}}{dt}$  – EMF-self-induction of the choke.

For the constant component of the load current  $u_L$  will be equal to zero, and for the variable component  $u_L$  will decrease or increase depending on the direction of the load current. In the interval of increasing load current, the choke  $L_f$  accumulates energy,  $u_L$  is directed opposite to  $u_d$ , reducing amplitude  $u_{load}$  and  $i_{load}$ , respectively. In the interval of decreasing the load current, the choke  $L_f$  gives off energy to the load,  $u_L$  unidirectionally with  $u_d$ , supporting  $u_{load}$  and  $i_{load}$ , respectively. The current in the load will change little. Thus, the shape of the load current curve will be smoothed and, as a consequence, the voltage curve across the active load will be smoothed. Since the change in the dynamics of the output voltage of the rectifier occurs an even number of times during the period of its operation, the inductive filter practically does not change (without taking into account the losses in the filter) the average value of the load voltage and does not affect the diode switching algo-

rithm in the circuit. Only the shape of the current consumed from the network will change. The shape of the network current formed from the sections of the load current in the conduction interval of the diodes will have a shape close to rectangular.

The inductance  $L_f$  is selected from the condition  $\omega_{(1)} \cdot L_f \gg R_{load}$ , where  $\omega_{(1)}$  is the angular frequency of the first harmonic of the ripple. When this condition is fulfilled, almost the entire AC component of the rectified voltage will drop across the inductor, and the DC component will be completely transferred to the load.

Amplitude of the  $k$ -th harmonic of the load current

$$I_{load \max(k)} = \frac{U_{\max(k) in}}{\sqrt{R_{load}^2 + (k\omega L_f)^2}}, \quad (1.16)$$

where  $U_{\max(k) in}$  – amplitude of the  $k$ -th harmonic of the filter input voltage.

Amplitude of the  $k$ -th harmonic of the load voltage

$$U_{load \max(k)} = U_{\max(k) out} = I_{load \max(k)} \cdot R_{load}. \quad (1.17)$$

Then the smoothing coefficient of the inductive filter without taking into account losses in it according to (1.13) is

$$K_{sm} = \frac{\sqrt{R_{load}^2 + (k\omega L_f)^2}}{R_{load}} \cong \frac{\sqrt{R_{load}^2 + (m\omega L_f)^2}}{R_{load}}. \quad (1.18)$$

Whence the filter inductance is

$$L_f = \frac{R_{load}}{k\omega} \sqrt{K_{sm}^2 - 1} \cong \frac{R_{load}}{m\omega} \sqrt{K_{sm}^2 - 1}. \quad (1.19)$$

Inductive filter is more efficient at high load currents (low  $R_{load}$ ).

### 1.1.6 Capacitive filter

In low-power rectifiers, the simplest capacitive filter is often used, which is a capacitor connected in parallel with the load. Such a filter for the rectifier represents a capacitive load, which noticeably changes the nature of the processes in the circuit. Consider the operation of the simplest single-phase half-wave rectifier with a capacitive filter. The scheme of this rectifier and the timing diagrams characterizing its operation are shown in figure 1.8.

In the time interval  $t_1 - t_2$  (fig. 1.8, b), the instantaneous voltage of the secondary winding of the transformer  $u_2$  is greater than the instantaneous load voltage  $u_{load}$ , the diode  $VD1$  is open and the capacitor  $C_f$  is charged from the source voltage. The sum of the load current and the capacitor charge current flows through the  $VD1$  diode, i.e.  $i_{VD} = i_C + i_{load}$ . In this case, a voltage drop occurs at the equivalent resistance of the charge circuit  $r_{ch}$  (diode and active resistance of the transformer windings)  $\Delta u = i_2 \cdot r_{ch}$ . Thus, the capacitor is charged along a curve that differs from the  $u_2$  shape by the amount of voltage drop in the charge circuit.

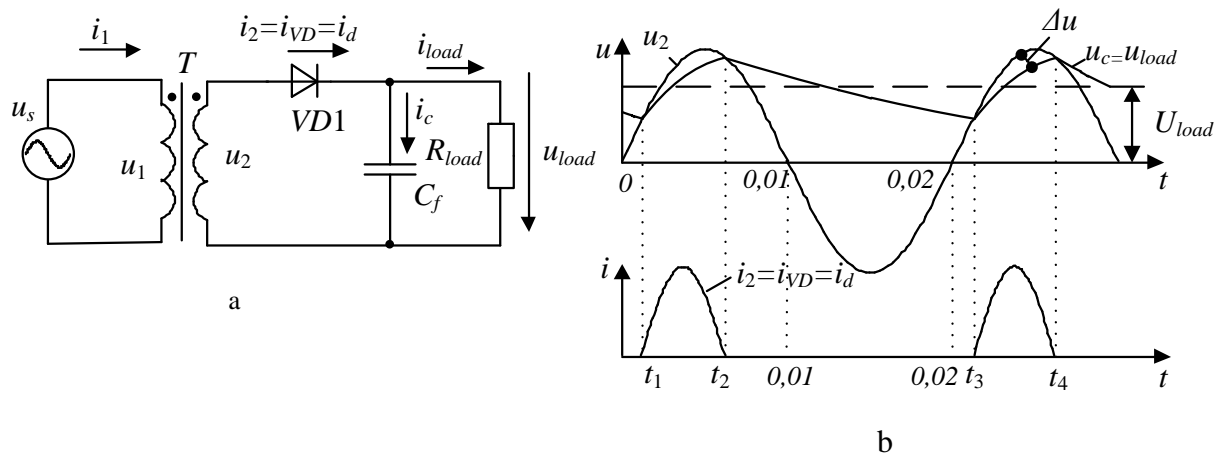


Figure 1.8. – Scheme of a single-phase half wave rectifier with a C-filter (a) and timing diagrams of rectifier voltages and currents (b)

At the moment of time  $t_2$ , the voltage of the secondary winding of the transformer  $u_2$ , changing according to the sinusoidal law, becomes equal, and at the next moment of time, it becomes lower than the voltage on the load and the capacitor connected in parallel with it  $u_{load} = u_C$ . Those potential of the anode of the diode  $VD1$ , determined by the voltage  $u_2$ , becomes less than the potential of its cathode, determined by the voltage  $u_C$ , and the diode  $VD1$  is closed. The load is disconnected from the supply voltage.

In the time interval  $t_2 - t_3$ , the capacitor is discharged to the load according to an exponential law with a time constant  $\tau = R_{load} \cdot C_f$ , maintaining a constant current in it (fig. 1.8, b).

At the moment  $t_3$ , the instantaneous value of the voltage of the secondary winding of the transformer  $u_2$  becomes equal and then greater than the voltage across the capacitor  $u_C$ . For the  $VD1$  diode, the open condition begins to be met and it opens, connecting the supply voltage to the load. In the time interval  $t_3 - t_4$ , the capacitor is charged. Then the process is repeated.

The instantaneous voltage across the load is determined by the capacitor charge and discharge curves, which depend on the shape of the power supply voltage and the time constants of the capacitor charge and discharge circuits (total active resistances in the charge and discharge circuits). The shape of the load current  $i_{load}$  curve follows the shape of the load voltage  $u_{load}$  curve. The shape of the diode current curve differs from the shape of the curve when operating on a purely resistive load: the current flow time decreases, and its amplitude increases due to the need to transfer the same energy to the load in a shorter time interval.

In a capacitive filter (fig. 1.7, b), it is necessary to fulfill the condition  $1 / \omega_{(1)} C_f \ll R_{load}$ . In this case, the variable component of the voltage will be closed through the capacitor  $C_f$ , and the constant component is supplied to the load.

From the above inequalities, it follows that the capacitive filter is more effective at low currents (large  $R_{load}$ ).

With accuracy sufficient for engineering calculations, the capacity of the C-filter can be determined by the expression

$$C_f = \frac{I_d \pi}{m \omega U_d K_{r out}}. \quad (1.20)$$

### 1.1.7 Composite filter

Inductive capacitive filters ( $L$ -shaped  $LC$  and  $U$ -shaped  $CLC$ ) are widely used at increased load currents, since the voltage drop across them can be made relatively small. The efficiency of such filters is quite high. The reaction of the switch to the composite filter is determined by the reactive element closest to it. The overall smoothing factor is equal to the product of the smoothing factors of each element included in the composite filter. The disadvantages of inductive-capacitive filters include: large dimensions and weight, an increased level of electromagnetic radiation from the filter elements, a relatively high cost and laboriousness of manufacture.

The most widely used  $L$ -shaped  $LC$  filter (fig. 1.7, c). For effective smoothing of pulsations with such a filter, the following conditions must be met:  $1 / \omega_{(1)} C_f \ll R_{load}$  and  $\omega_{(1)} L_f \gg R_{load}$ .

### 1.1.8 External characteristics of uncontrolled rectifiers

The external (load) characteristic of the rectifier is the dependence of the average rectified voltage load on the average load current.

At the output of the rectifier without a filter, the average no-load voltage ( $I_d = 0$ ) is

$$U_{d0} = \frac{1}{2\pi} \int_0^{2\pi} \sqrt{2} U_2 \sin \omega t dt = 0,45 U_2. \quad (1.21)$$

When current  $I_d$  flows through the diode  $VD1$  internal resistance  $r_g$  and the active resistance of the transformer windings  $r_{tr}$ , voltage drops occur, which lead to a decrease in the voltage  $U_d$ . In this case, the external characteristic of the rectifier without a filter is determined by the formula

$$U_d = U_{d0} - (r_g + r_{tr}) I_d, \quad (1.22)$$

where  $U_{d0}$  is the rectifier output voltage at  $I_d = 0$ .

Figure 1.9 shows the external characteristics of the rectifier  $U_d = f(I_d)$ .

Curve 1 shows the external characteristic without filter. By its slope, you can determine the internal resistance of the rectifier.

$$r_{in} = \Delta U_d / \Delta I_d \quad (1.23)$$

Curve 2 corresponds to a  $C$ -filter rectifier. When  $I_d = 0$ , the voltage  $U_{d0} = \sqrt{2} U_2$ , since in the absence of current  $I_d$ , the capacitor  $C_f$  is charged to the amplitude voltage of the secondary winding. With increasing current  $I_d$ , curve 2 falls off faster than curve 1, which is explained by a decrease in the time constant

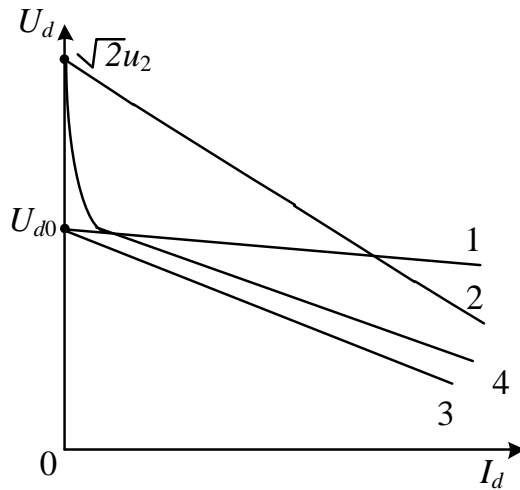


Figure 1.9 – External characteristics of the rectifier

filter with the load is connected in series, the presence of this component of the filter resistance is equivalent to an increase internal resistance of the rectifier. Therefore, the external characteristic of a rectifier with an inductive filter is represented by a straight line, but having a greater slope than the characteristic without a filter.

The external characteristic of the rectifier with an  $L$ -shaped  $LC$  filter (curve 4) has a significant difference from the characteristic with an inductive filter for idling. In this case, the capacitor is charged to the peak voltage of the transformer secondary winding.

## 1.2 Work order

### 1.2.1 Calculation of the uncontrolled rectifier scheme and smoothing filters

Calculate the uncontrolled rectifier scheme and smoothing filters according to the task variant given in appendix A.1. Select the main elements of the scheme. From the datasheets of the semiconductor diode and transformer take the characteristics necessary for modeling the scheme in the Matlab / Simulink package. All actions should be performed according to the calculation example below.

#### 1.2.1.1 The calculation example of the single-phase half-wave uncontrolled rectifier

The task for the calculation in accordance with appendix A.1 is given in table 1.1, and the scheme of a single-phase half-wave uncontrolled rectifier is shown in figure 1.1.

Let's calculate the scheme for an active load. From the formula for calculating the average rectified voltage (1.1), we determine the rms voltage of the transformer secondary winding:

$$U_2 = \frac{\pi \cdot U_d}{\sqrt{2}} = \frac{3,14 \cdot 12}{\sqrt{2}} = 26,66 \text{ V.}$$

$\tau = R_{load} \cdot C_f$ . This is usually considered a disadvantage, therefore, it is better to use a filter with a capacitive response with a constant or slightly changing resistance  $R_{load}$ .

Curve 3 in fig. 1.9 corresponds to the external characteristic of a rectifier working with an inductive filter. In addition to inductive resistance, a real filter also has an active resistance. Since the inductive

Table 1.1 – Task for the calculation of the single-phase half-wave uncontrolled rectifier

Source		Rectifier Scheme	Load		Filter	
$U_s$ , V	$f_s$ , Hz		$P_d$ , W	$U_d$ , V	$K_{r\ out}$ , %	$K_{sm}$
220	50	Single-phase Half wave	220	12	5	10

Losses on the diode are usually 1 – 2 V, the rms voltage of the transformer secondary winding taking into account the losses on the diode is 28,66 V.

The maximum reverse voltage of the diode reaches the peak voltage of the secondary winding  $U_{2m}$ , expression (1.2):

$$U_{VD\ max} = U_{2m} = \sqrt{2} \cdot U_2 = 28,66 \cdot \sqrt{2} = 40,5\text{ V.}$$

The safety factor of the reverse voltage is 1,5 – 2. The maximum reverse voltage diode taking into account the safety factor is 81,1 V.

The average rectified current (diode current) we determine from the formula (1.3):

$$I_d = I_{VD} = \frac{P_d}{U_d} = \frac{220}{12} = 18,3\text{ A.}$$

The safety factor of the average diode current is 1,5 - 2, account the safety factor average diode current equal is 36,7 A.

We are choosing a diode according to the maximum reverse voltage 81,1 V and average forward current 36,7 A. FERD40H100S diode have the maximum reverse voltage  $U_{RRM} = 100\text{ V}$  and the average forward current  $I_{F(AV)} = 40\text{ A}$  and it is suitable for us.

From the formula (1.3), we determine the rms current of the transformer secondary winding:

$$I_2 = \frac{\pi \cdot I_d}{\sqrt{2}} = \frac{3,14 \cdot 18,3}{\sqrt{2}} = 40,65\text{ A,}$$

then the power of the transformer can be determined by the expression:

$$P_{tr} \cong U_2 \cdot I_2 = 28,66 \cdot 40,65 = 1165\text{ W.}$$

Let's choose a transformer of the power 1165 W with a primary winding voltage 220 V and a secondary winding voltage 29 V. OCM1-1,6M transformer have the power 1600 W, the primary winding voltage 220 V and the secondary winding voltage 29 V. It is suitable for us.

The active load resistance can be determined by the expression:

$$R_{load} = \frac{P_d}{I_d^2} = \frac{220}{18,3^2} = 0,66\ \Omega.$$

Let's calculate the inductance and capacitance of the smoothing filter using expressions (1.19) and (1.20), respectively. To do this, we define the value of the cyclic frequency:

$$\omega = 2\pi f = 2 \cdot 3,14 \cdot 50 = 314,16 \text{ rad,}$$

then the smoothing filter capacity

$$C_f = \frac{I_d \cdot \pi}{m\omega U_d K_{rout}} = \frac{18,3 \cdot 3,14}{1 \cdot 314,16 \cdot 12 \cdot 0,05} = 0,305 \text{ F,}$$

and the smoothing filter inductance

$$L_f \cong \frac{R_{load}}{m\omega} \sqrt{K_{sm}^2 - 1} = \frac{0,66}{1 \cdot 314,16} \sqrt{10^2 - 1} = 0,021 \text{ H.}$$

After substitution of the calculated data into the model, it may be necessary to adjust the values of filter capacitance, filter inductance or load resistance, since the calculation is approximate.

Also to build a model you need to calculate peak sources voltage:

$$U_{s \text{ max}} = U_s \cdot \sqrt{2} = 220 \cdot \sqrt{2} = 311 \text{ V.}$$

In the window for setting the parameters of the semiconductor diode, you need:

- The dynamic resistance  $R_{on}(r_g)$ , which is determined from the diode datasheet. Its value can be determined from the table of the device characteristics or by the slope of the forward branch of the diode I - V characteristic. In the considering example  $r_g = 0,005 \Omega$ .

- The diode threshold voltage (forward voltage)  $V_f$ , which is also determined from the diode datasheet. Its value is most often indicated in the table of the device characteristics, if not, then it can also be determined from the direct branch of the diode I - V characteristic. In the considering example  $V_f = 0,705 \text{ V}$ .

- The snubber resistor and capacitance. We take their values equal to  $100 \Omega$  and  $0,2 \mu\text{F}$ , respectively.

In the window for setting the parameters of the transformer, you need:

- The winding resistances ( $R_1$  and  $R_2$ ), which can be determined from the following expression

$$R_1 = R_2 \cong \frac{1}{2}(1 - \eta) = \frac{1}{2}(1 - 0,95) = 0,025,$$

where  $\eta$  is a transformer efficiency, which can be determined from transformer datasheet. In the considering example  $\eta = 95 \%$ .

- The leakage inductances ( $L_1$  and  $L_2$ ), which can be determined from the following expression

$$L_1 = L_2 \cong \frac{1}{2} e_{sc} = \frac{1}{2} 0,035 = 0,0175,$$

where  $e_{sc}$  is a short-circuit voltage of the transformer, which can be determined from transformer datasheet. In the considering example  $e_{sc} = 3,5 \%$ .

- The magnetization resistance  $R_m$  and inductance  $L_m$  are taken equal to  $200$ , respectively.

### 1.2.1.2 The calculation example of the single-phase full wave midpoint uncontrolled rectifier

The task for the calculation in accordance with appendix A.1 is given in table 1.1, but for the scheme of the single-phase full-wave midpoint uncontrolled rectifier, which is shown in figure 1.3.

Let's calculate the scheme for an active load. From the formula for calculating the average rectified voltage (1.4), we determine the rms voltage of the transformer secondary winding:

$$U_{21} = U_{22} = \frac{\pi \cdot U_d}{2\sqrt{2}} = \frac{3,14 \cdot 12}{2\sqrt{2}} = 13,33 \text{ V.}$$

Losses on the diode are usually 1 – 2 V, the rms voltage of the transformer secondary winding taking into account the losses on the diode is 15,33 V.

The maximum reverse voltage of the diode reaches the double peak voltage of the transformer secondary winding  $U_{2m} = U_{21m} = U_{22m}$ , expression (1.5):

$$U_{VD \max} = 2U_{2m} = 2\sqrt{2} \cdot U_2 = 2 \cdot 15,33 \cdot \sqrt{2} = 43,4 \text{ V.}$$

The safety factor of the reverse voltage is 1,5 – 2. The maximum reverse voltage diode taking into account the safety factor is 86,8 V.

The average rectified current we determine by expression

$$I_d = \frac{P_d}{U_d},$$
$$I_d = \frac{220}{12} = 18,33 \text{ A,}$$

then the average diode current from the formula (1.7) equal is

$$I_{VD} = \frac{I_d}{2} = \frac{18,33}{2} = 9,15 \text{ A.}$$

The safety factor of the average diode current is 1,5 – 2, account the safety factor average diode current equal is 18,3 A.

We are choosing a diode according to the maximum reverse voltage 86,8 V and average forward current 18,3 A. STPS20S100C diode have the maximum reverse voltage  $U_{RRM} = 100 \text{ V}$  and the average forward current  $I_{F(AV)} = 20 \text{ A}$  and it is suitable for us.

From the formula (1.6), we determine the rms current of the transformer secondary winding:

$$I_2 = \frac{I_d}{\sqrt{2}} = \frac{18,3}{\sqrt{2}} = 13 \text{ A,}$$

then the power of the transformer can be determined by the expression:

$$P_{tr} \cong 2 \cdot U_2 \cdot I_2 = 2 \cdot 15,33 \cdot 13 = 400 \text{ W.}$$

Let's choose a transformer of the power 400 W with a primary winding voltage 220 V and a secondary winding voltage 14 V. OCM1-0,4 transformer have the power 400 W, the primary winding voltage 220 V and the secondary winding voltage 14 V. It is suitable for us.

The active load resistance is calculation like in the paragraph 1.2.1.1.

The inductance and capacitance of the smoothing filter we define like in the paragraph 1.2.1.1, only we need take pulsation  $m$  equal is two. Then the smoothing filter capacity and inductance equal are 0,15 F and 0,011 H, respectively, for the single-phase full wave midpoint scheme of the rectifier. After substitution of the calculated data into the model, it may be necessary to adjust the values of filter capacitance, filter inductance or load resistance, since the calculation is approximate.

Also to build a model you need to calculate peak source voltage, which equal is 311 V in our variant.

In the window for setting the parameters of the semiconductor diode, you need:

- The dynamic resistance  $R_{on}(r_g)$ , which is determined from the diode datasheet and in the considering example  $r_g = 0,009 \Omega$ .
- The diode threshold voltage (forward voltage)  $V_f$ , which is also determined from the diode datasheet and in the considering example  $V_f = 0,94 \text{ V}$ .
- The snubber resistor and capacitance we take equal are  $100 \Omega$  and  $0,2 \mu\text{F}$ , respectively.

In the window for setting the parameters of the transformer, you need the winding resistances

$$R_1 \cong \frac{1}{2}(1 - \eta) = \frac{1}{2}(1 - 0,93) = 0,035,$$

where  $\eta = 93 \%$  in the considering example.

$$R_2 = R_3 = \frac{R_1}{2} = \frac{0,035}{2} = 0,0175.$$

And leakage inductances

$$L_1 \cong \frac{1}{2}e_{sc} = \frac{1}{2}0,045 = 0,0225,$$

where  $e_{sc} = 4,5 \%$  in the considering example.

$$L_2 = L_3 = \frac{L_1}{2} = \frac{0,0225}{2} = 0,01125.$$

The magnetization resistance  $R_m$  and inductance  $L_m$  are taken equal to 200 like in the paragraph 1.2.1.1.

### *1.2.1.3 The calculation example of the single-phase full wave bridge uncontrolled rectifier*

The task for the calculation in accordance with appendix A.1 is given in table 1.1, but for the scheme of the single-phase full-wave bridge uncontrolled rectifier, which is shown in figure 1.5.

Let's calculate the scheme for an active load. From the formula for calculating the average rectified voltage (1.8), we determine the rms voltage of the transformer secondary winding:

$$U_2 = \frac{\pi \cdot U_d}{2\sqrt{2}} = \frac{3,14 \cdot 12}{2\sqrt{2}} = 13,33 \text{ V.}$$

Losses on the diode are usually 1 – 2 V, the rms voltage of the transformer secondary winding taking into account the losses on the diode is 15,33 V.

The maximum reverse voltage of the diode reaches the peak voltage of the secondary winding  $U_{2m}$ , expression (1.9):

$$U_{VD \max} = U_{2m} = \sqrt{2} \cdot U_2 = 15,33 \cdot \sqrt{2} = 21,7 \text{ V.}$$

The safety factor of the reverse voltage is 1,5 – 2. The maximum reverse voltage diode taking into account the safety factor is 43,4 V.

The average rectified current we determine like in the paragraph 1.2.1.2 and it equal is 18,33 A. Then the average diode current from the formula (1.11) equal is

$$I_{VD} = \frac{I_d}{2} = \frac{18,33}{2} = 9,15 \text{ A.}$$

The safety factor of the average diode current is 1,5 – 2, account the safety factor average diode current equal is 18,3 A.

We are choosing a diode according to the maximum reverse voltage 43,4 V and average forward current 18,3 A. VS-40CPQ050-N3 diode have the maximum reverse voltage  $U_{RRM} = 50 \text{ V}$  and the average forward current  $I_{F(AV)} = 20 \text{ A}$  and it is suitable for us.

From the formula (1.10), we determine the rms current of the transformer secondary winding:

$$I_2 = I_d = 18,3 \text{ A,}$$

then the power of the transformer can be determined by the expression:

$$P_{Tr} \cong U_2 \cdot I_2 = 15,33 \cdot 18,3 = 280,5 \text{ W.}$$

Let's choose a transformer of the power 400 W with a primary winding voltage 220 V and a secondary winding voltage 14 V. OCM1-0,4 transformer have the power 400 W, the primary winding voltage 220 V and the secondary winding voltage 14 V. It is suitable for us.

The active load resistance is calculation like in the paragraph 1.2.1.1.

The inductance and capacitance of the smoothing filter we define like in the paragraph 1.2.1.1, only we need take pulsation  $m$  equal is two. Then the smoothing filter capacity and inductance equal are 0,15 F and 0,011 H, respectively, for the single-phase full wave bridge scheme of the rectifier. After substitution of the calculated data into the model, it may be necessary to adjust the values of filter capacitance, filter inductance or load resistance, since the calculation is approximate.

Also to build a model you need to calculate peak source voltage, which equal is 311 V in our variant.

In the window for setting the parameters of the semiconductor diode, you need:

- The dynamic resistance  $R_{on}$  ( $r_g$ ), which is determined from the diode datasheet and in the considering example  $r_g = 0,01 \Omega$ .
- The diode threshold voltage (forward voltage)  $V_f$ , which is also determined from the diode datasheet and in the considering example  $V_f = 0,49 \text{ V}$ .
- The snubber resistor and capacitance we take equal are  $100 \Omega$  and  $0,2 \mu\text{F}$ , respectively.

In the window for setting the parameters of the transformer, you need the winding resistances ( $R_1$  and  $R_2$ ) and the leakage inductances ( $L_1$  and  $L_2$ ), which can be determined like in the paragraph 1.2.1.1 and them equal are 0,035 and 0,0225, respectively. The magnetization resistance  $R_m$  and inductance  $L_m$  are taken equal to 200 like in the paragraph 1.2.1.1.

### ***1.2.2 Simulation of the uncontrolled rectifier scheme without a filter and with various types of smoothing filters***

Simulation of the uncontrolled rectifier scheme is performed in the Matlab / Simulink package. Version 2016b is used in this teaching aid.

#### *1.2.2.1 Model building steps*

- Open a new Simulink model window, save it.
- From the Simulink library we take the “powergui” block and set parameters in its parameters window as shown in fig. 1.10. Simulation type: discrete and Sample time (s):  $0.2e-6$ .

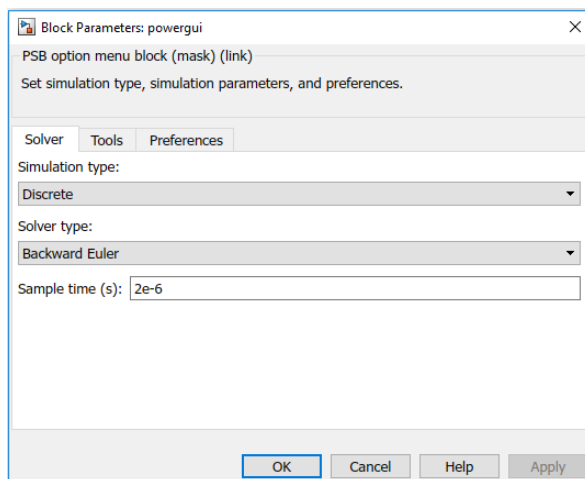


Figure 1.10. – Parameters window of the “powergui” block

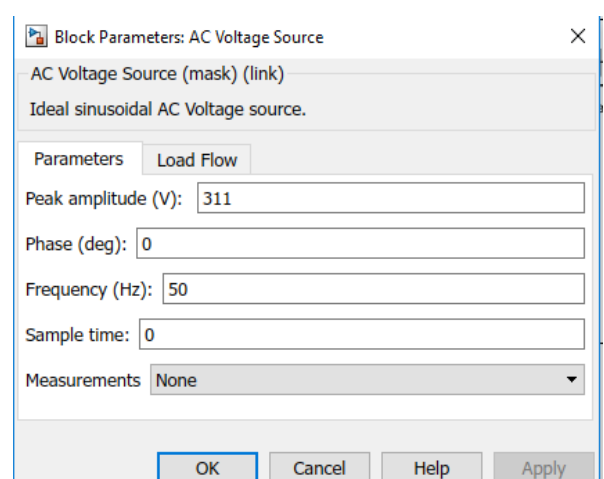


Figure 1.11. – Parameters window of the “AC Voltage Source” block

- From the Simulink library we take all the necessary blocks for modeling the scheme. It is “AC Voltage Source” (fig. 1.11), “Linear Transformer” (fig. 1.12),

“Diode” (fig. 1.13) and “Series RLC Branch” for modeling the load, capacitance and inductance of the output filter (fig. 1.14).

- We connect the blocks according to the scheme of our variant and in their parameters windows set the calculated parameters of the scheme elements (paragraph 1.2.1).

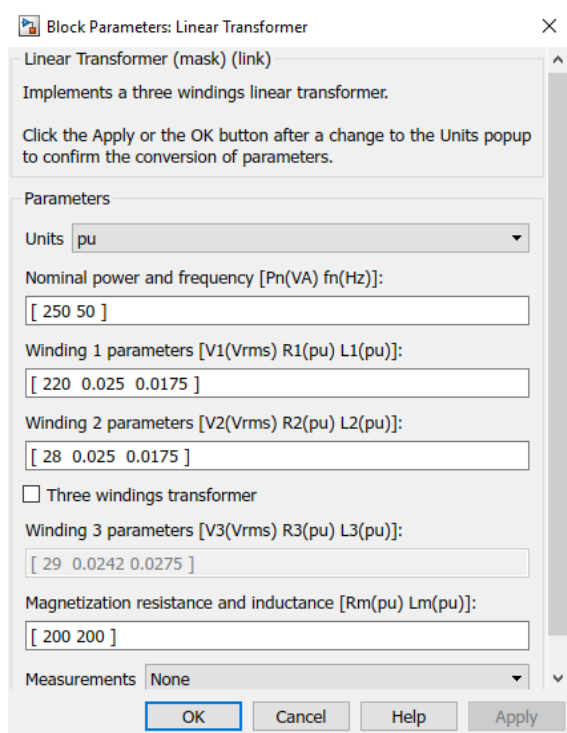


Figure 1.11. – Parameters window of the “Linear Transformer” block

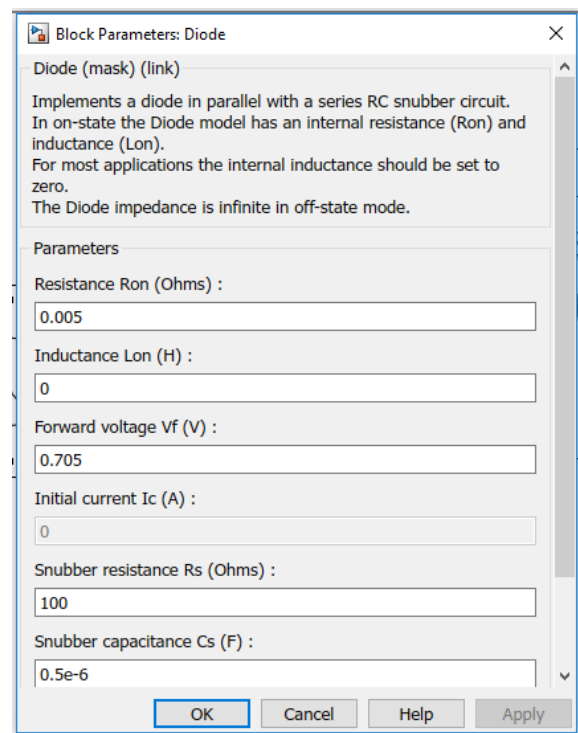


Figure 1.13. – Parameters window of the “Diode” block

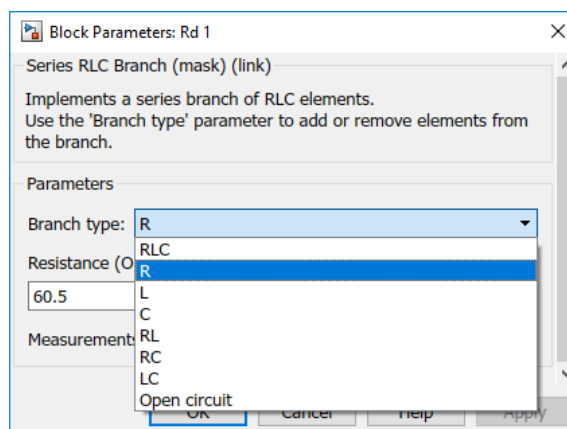


Figure 1.14. – Parameters window of the “Series RLC Branch” block

- From the library we take blocks for measuring voltage and current. We connect these blocks to a scheme for the sake of measuring the current and voltage of the network, current and voltage of the load and reverse voltage and forward current of the diode. "Voltage Measurement" block is connecting in parallel, and the "Current Measurement" block is connecting in series.

- From the library we take a "Scope" block for studying the shape of voltages and currents in the scheme. In the dialog window set the required

number of input ports (View / Layout and View / Configuration properties / Main) and sign the studied signals (View / Configuration properties / Display) (fig. 1.15 a,b,c). Connect the information ports of the "Voltage Measurement" and the "Current Measurement" blocks to the input ports of the "Scope" block.

- Start the simulation by clicking on the "Run" button. You need to evaluation of the correct scheme operation by the form of currents and voltages. If there is a strong discrepancy between the theoretical timing diagrams of currents and voltages with the simulation results, then check the calculations and the model scheme.

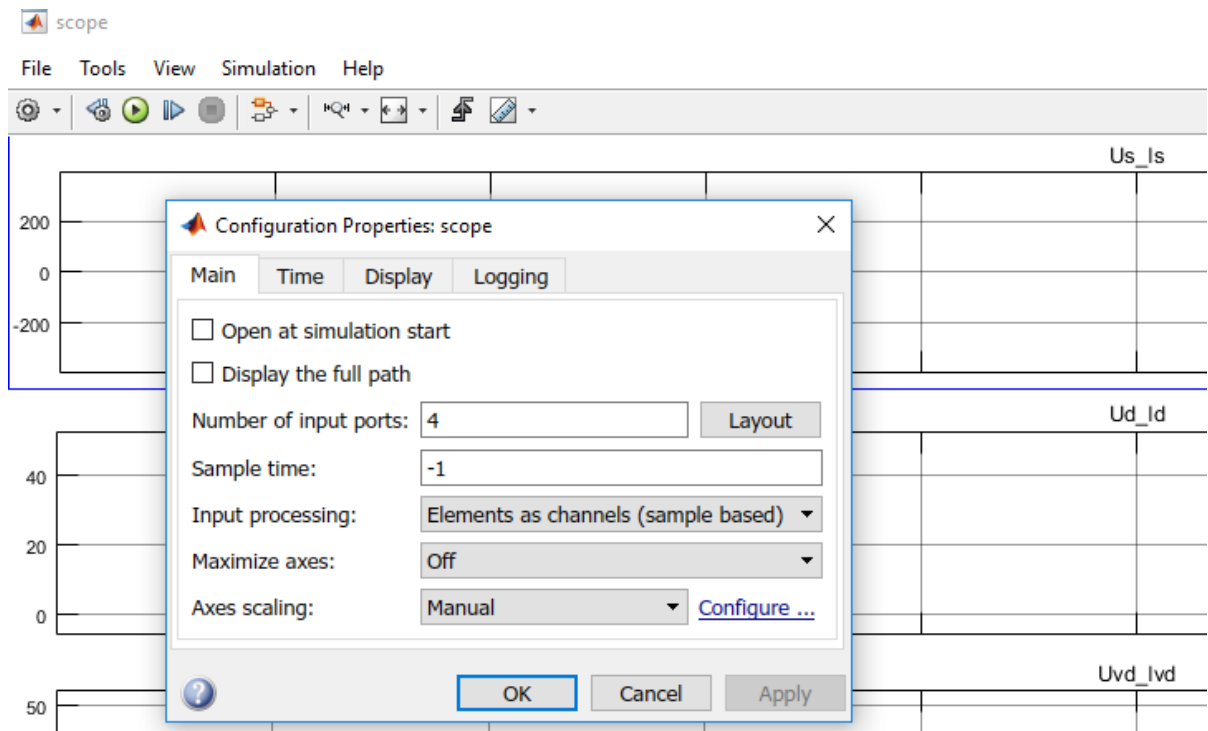


Figure 1.15. – Parameters window of the “Scope” block

### 1.2.2.2 The investigate of the voltages and currents forms

Timing diagrams of the scheme voltages and currents need be recorded in a steady mode of model operation during for four periods of the supply voltage, that equal is 0,08 s. Diagrams of mains current and voltage, load current and voltage, reverse voltage and forward current of the semiconductor switch (diode) are fixing. The timing diagrams need be for a scheme without a filter, with C-filter, L-filter and LC-filter.

### 1.2.2.3 External characteristics of an uncontrollable rectifier

To build an external characteristic  $U_d = f(I_d)$ , it will be necessary:

- Set five values of the load resistance  $R_{load}$ . Resistance changes need be made within the range from 10 to 100 percent of the nominal value, which is calculated in paragraph 1.2.1.

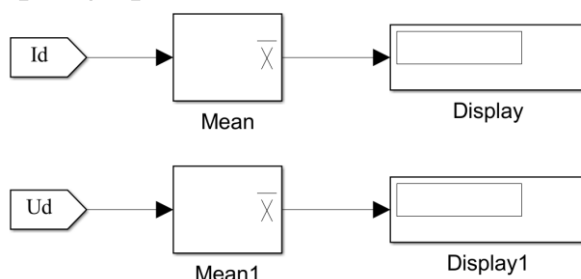


Figure 1.16 – The scheme of the average rectified voltage and current calculation

- By setting the calculated load resistance in the model, fixe the average values of the rectified current  $I_d$  and voltage  $U_d$ . To determine the average rectified voltage and current in the Matlab, "Mean" and "Display" blocks are required. In the parameters window of the "Mean" block, you

need to set the fundamental frequency that equal is ripples frequency output rectified voltage. And send a signal to the input of this block from the output of the "Voltage Measurement" block that is installed at the output of the rectifier. Similarly, you need to apply to the input of the "Mean" block a signal from the output of the "Current Measurement" block that is installed at the output of the rectifier (fig.1.16).

- Record the data in the table that is given in appendix A.2.
- Perform these steps for the rectifier scheme without filter, with C-filter, L-filter and LC-filter.
- According to received table, you need to build external characteristics. The characteristics are plotted on one graph on the same scale.
- The ripples of the rectified voltage before and after the filter, the smoothing coefficient are analyzed.

### **1.3 Report preparation**

The report on the work performed should contain: the purpose of the work, the scheme of the experiment, the calculation of the scheme elements, the datasheet of the selected scheme elements, the Matlab-model of the scheme, tables and graphs obtained as a result of the experiment, as well as time diagrams in accordance with the task of performing the work and their brief analysis.

### **1.4 Self-test questions**

1. Explain the operation of the investigated uncontrolled rectifier scheme without a filter.
2. Explain the operation of the investigated scheme of an uncontrolled rectifier with an inductive filter.
3. Explain the operation of the investigated scheme of an uncontrolled rectifier with a capacitive filter.
4. Explain the operation of the investigated scheme of an uncontrolled rectifier with an L-shaped LC-filter.
5. Explain the course of the external characteristic of an uncontrolled rectifier with a capacitive filter.
6. Explain the course of the external characteristic of an uncontrolled rectifier with an inductive filter.
7. Explain the course of the external characteristic of the uncontrolled rectifier with the L-shaped LC-filter.
8. In which filters can overvoltage occur?
9. In which filters can overcurrent occur?
10. Features of the smoothing filter chokes.
11. What capacitors are recommended for use in filters?
12. Disadvantages of the investigated filters.
13. Advantages of the investigated filters.
14. Explain the shape of the mains current  $i_s$  and the mains voltage  $u_s$  when uncontrolled rectifier operates with different types of filters.

15. Explain the shape of rectified voltage  $U_d$  and current  $I_d$  when uncontrolled rectifier operates with different types of filters.

16. Explain the waveform of  $u_{VD}$  voltage and  $i_{VD}$  current diode when working with uncontrolled rectifier with different types of filters.

## CHAPTER NO. 2

### CONTROLLED RECTIFIER

**The purpose of the work** is to study the operation of controlled rectifiers with active and active - inductive loads.

#### 2.1 Basic theoretical thesis

*Controlled rectifiers* have the ability to regulate the average DC voltage of the load - from nominal to zero. They are used to stabilize the load voltage when the mains voltage or load resistance changes, as well as to change the rotation speed of a DC motor. A controlled rectifier is obtained by replacing diodes in an uncontrolled rectifier with thyristors, which are controlled using a pulse-phase control system (SPPC). The rectified voltage  $U_d$  regulation is based on the control of the thyristors switching moment relative to the point of natural switching (cross over point).

##### 2.1.1 Single-phase bridge controlled rectifier

Figure 2.1 shows a scheme of a single-phase bridge controlled rectifier. The scheme consists of a single-phase alternating (sinusoidal) voltage source  $u_s$ , a single-phase transformer  $T$  with a primary winding  $W_1$  and a secondary winding  $W_2$ , a bridge switch on single-operation thyristors  $VS1-VS4$ , an active-inductive load  $L_{load}$ ,  $R_{load}$  and a pulse-phase control system (SPPC). In the scheme and timing diagrams, figures 2.2 and 2.3, the following designations are adopted:  $u_s, i_s$  – instantaneous voltage and current of the supply network;  $u_d, i_d$  – instantaneous rectified voltage and current at the output of the rectifier;  $u_{VS}, i_{VS}$  – instantaneous voltage and current of the thyristor;  $u_1, u_2, i_1, i_2$  – instantaneous voltages and currents of the primary and secondary winding of the transformer;  $u_c$  – control voltage;  $\alpha$  – control angle;  $\varphi_1$  – shift angle of the mains current relative to the mains voltage;  $U_d$  – average rectified voltage;  $I_d$  – average rectified current.

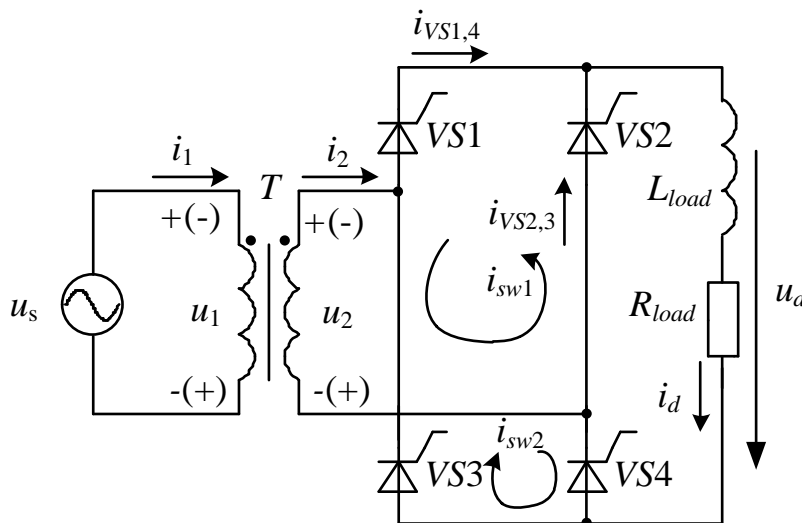


Figure 2.1. – Single-phase bridge controlled rectifier

In a single-phase bridge controlled rectifier, the diodes opening occurs at the moments when the polarity of the mains voltage changes (fig. 1.6.), when  $\omega t = 0; \pi; 2\pi; 3\pi$  etc., that is, at the point of natural switching. It is the moment when the anode potential of

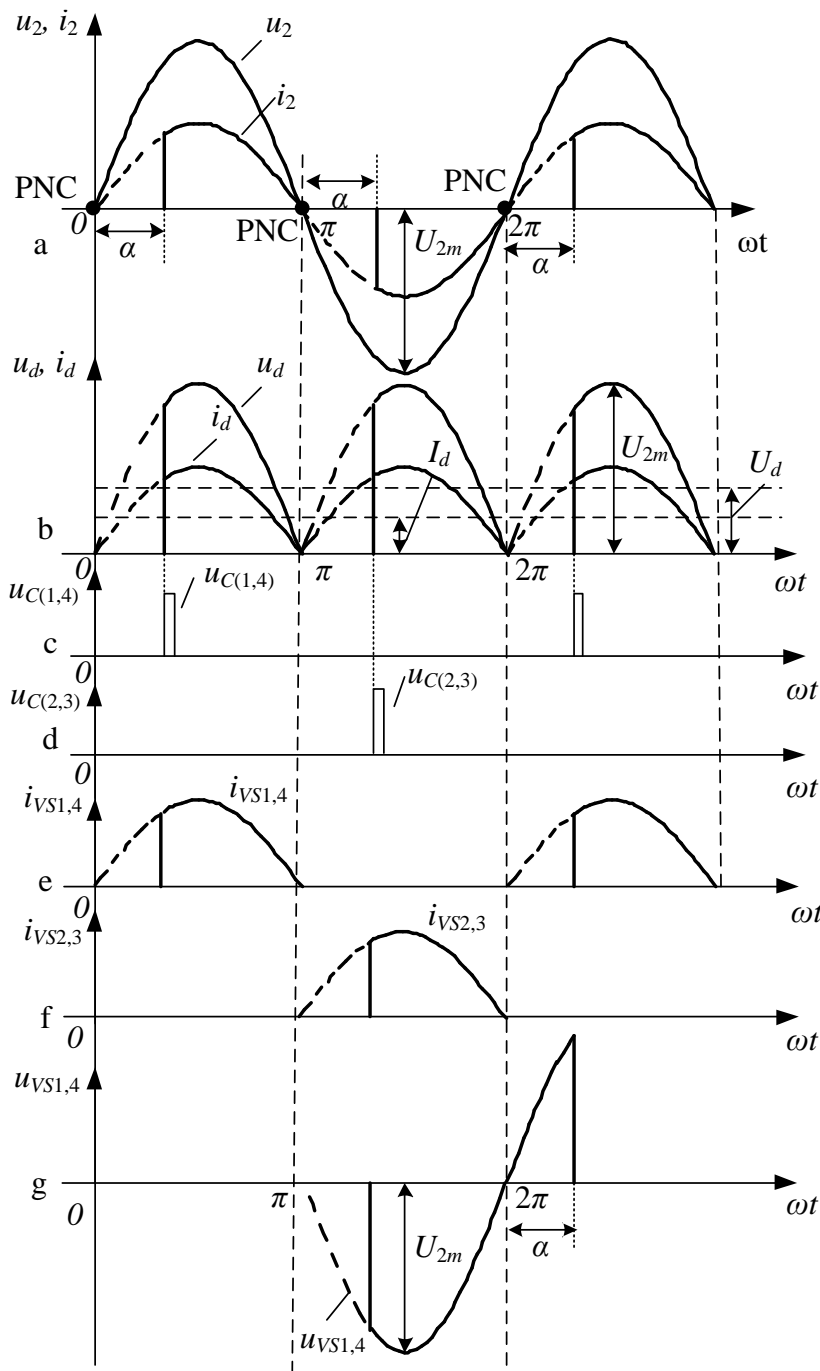


Figure 2.2 – Diagrams of single-phase bridge controlled rectifier the operation with an active load

the moment the control pulse is applied to the control electrode of the thyristor. That is, the thyristors control of the controlled rectifier is carried out by a low-power SPPC, which provides the formation of control pulses and their supply to the control electrodes of the thyristors at the required time and with a given control angle  $\alpha$ .

The timing diagrams in figure 2.2 correspond to the operation of a single-phase bridge controlled rectifier with an active load ( $L_{load} = 0, R_{load} > 0$ ).

In the time interval  $0 - \alpha$ , all thyristors are closed and the load voltage  $u_{load}$  ( $u_d$ ) is zero, the load current  $i_{load}$  ( $i_d$ ) is also zero. At the moment of time  $\omega t = \alpha$ , a control pulse  $u_{C(1,4)}$  is applied to the control electrodes of thyristors VS1,

the switch becomes greater than the cathode potential. The duration of the open state of the diode is unchanged and it is equal to 180 electrical degrees (fig. 1.6). And the average value of the rectified voltage is match expression (1.8) and depends only on the magnitude of the supply voltage.

Unlike a diode, in order to open the thyristor, in addition to the positive voltage on it, it is necessary to also apply a control pulse to the control electrode. Until the control pulse is given, the thyristor will not open. The control impulse can be applied with a time delay  $\alpha$  relative to the natural switching point. That is, the control angle  $\alpha$  is the time interval (electrical degrees or radians) counted from the point of natural commutation to the

VS4 and they are opened. The voltage of the transformer secondary winding  $u_2$  is instantly applied to the load and in the time interval  $\alpha - \pi$  the load voltage  $u_{load}$  is equal to the rectified voltage  $u_d$  and is equal to the voltage of the transformer secondary winding  $u_2$ . The load current  $i_{load}$  ( $i_d$ ) is equal to the load voltage (or rectified voltage) divided by the load active resistance  $R_{load}$  and is identical in shape to the load voltage (or rectified voltage).

At the moment of time  $\omega t = \pi$ , a negative half-period of the voltage of the transformer secondary winding  $u_2$  begins. The voltage of the transformer secondary winding becomes reverse polarity for thyristors VS1, VS4. The load current  $i_{load}$  ( $i_d$ ) begins to drop to zero, thyristors VS1, VS4 are closed.

At the moment of time  $\omega t = \pi + \alpha$ , a control pulse  $u_{C(2,3)}$  is applied to the control electrodes of thyristors VS2, VS3 and they are opened. The voltage of the transformer secondary winding  $u_2$  is instantly applied to the load and in the time interval  $(\pi + \alpha) - 2\pi$  the load voltage  $u_{load}$  is equal to the rectified voltage  $u_d$  and is equal to the voltage of the transformer secondary winding  $u_2$ . The load current  $i_{load}$  ( $i_d$ ) is equal to the load voltage (or rectified voltage) divided by the load active resistance  $R_{load}$  and is identical in shape to the load voltage (or rectified voltage). Further, the processes in the scheme are repeated.

With an increase of the control angle  $\alpha$ , the time interval of the thyristors open state decreases, and the average rectified voltage  $U_d$  also decreases. That is, when control angle is equal to zero, average rectified voltage  $U_d$  is equal to  $U_{d0}$  (maximum value), and when is equal to  $\pi$ ,  $U_d$  is equal to zero.

The load current  $i_{load}$  ( $i_d$ ) has an intermittent character and with an increase of the control angle and the current-free pauses increase.

That is, in a thyristor controlled rectifier, the rectified voltage is regulated by changing the time during which the load is connected to the supply voltage source in each half-cycle.

The network current is formed by thyristor currents, has an intermittent character and is generally not sinusoidal. This leads to the appearance of higher harmonics in the line current and a shift of the line current first harmonic relative to the line voltage (to a decrease in the power factor).

The voltage of the closed thyristor has a section of positive polarity with a duration  $\alpha$ .

The timing diagrams in figure 2.3 correspond to the operation of a single-phase bridge controlled rectifier with an active - inductive load ( $L_{load} > 0$ ,  $R_{load} > 0$ ).

The inductance in the load circuit is present initially (DC motor) or introduced to smooth the load current.

We will assume that the load inductance is large enough and the load current is continuous and perfectly smoothed. That is, the instantaneous load current  $i_{load}$  ( $i_d$ ) is equal to the average load current  $I_d$  and is equal to the average rectified voltage  $U_d$  divided by the active load resistance  $R_{load}$ .

Suppose that the active and inductive resistances of the network are equal to zero. At the moment of time  $\omega t = \alpha$ , a control pulse  $u_{C(1,4)}$  is applied to the control electrodes of thyristors VS1, VS4 and they are opened. The voltage of the trans-

former secondary winding  $u_2$  is instantly applied to the load and the load voltage  $u_{load}$  is equal to the rectified voltage  $u_d$  and is equal to the voltage of the transformer secondary winding  $u_2$ . The load current  $i_{load}$  ( $i_d$ ) flows through the transformer secondary winding  $W_2$ , thyristor  $VS1$ , active-inductive load  $R_{load}$ ,  $L_{load}$ , thyristor  $VS4$ , to the transformer secondary winding  $W_2$ .

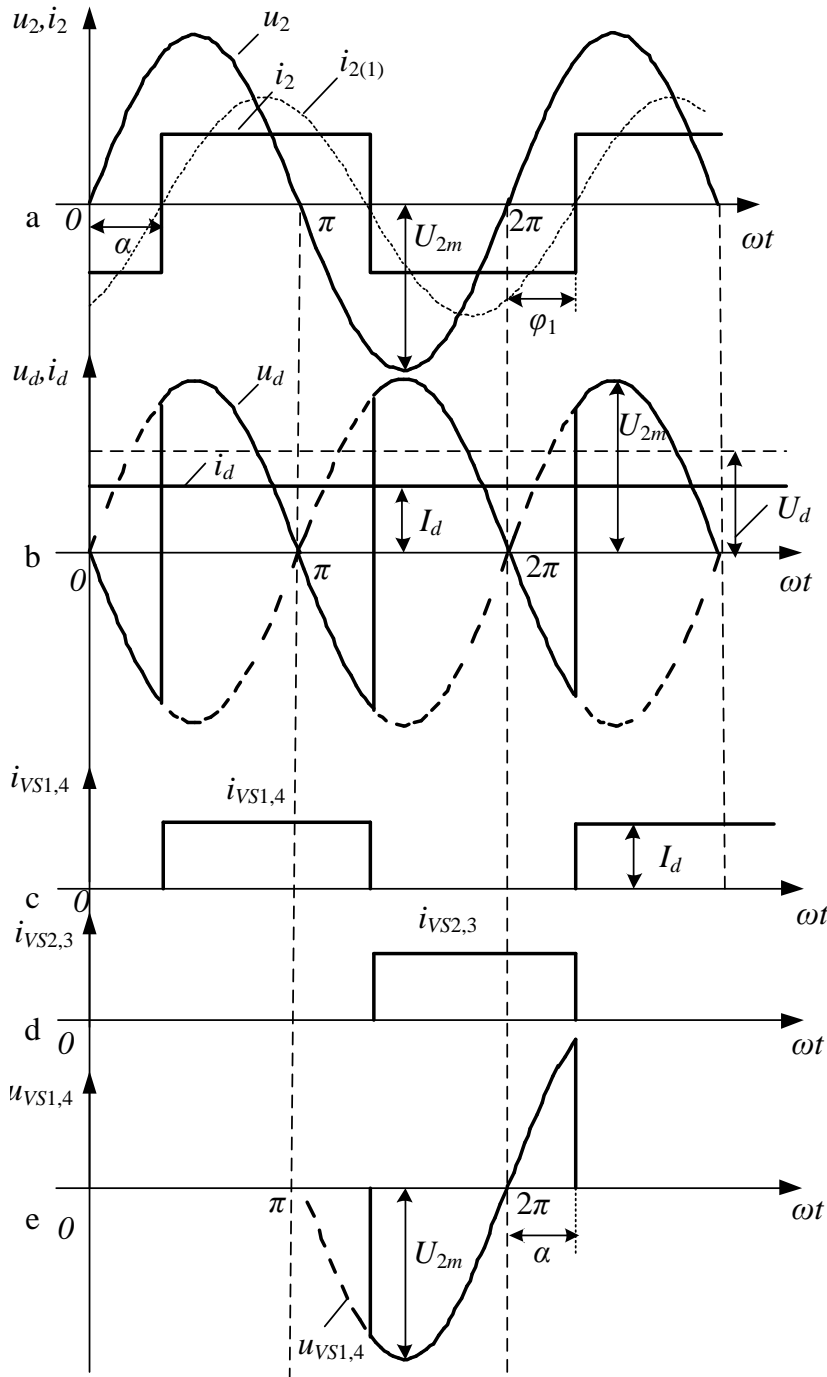


Figure 2.3 – Diagrams of single-phase bridge controlled rectifier the operation with an active - inductive load

At the moment of time  $\omega t = \pi$ , a negative half-period of the voltage of the transformer secondary winding  $u_2$  begins. The voltage of the transformer secondary winding becomes reverse polarity for thyristors  $VS1$ ,  $VS4$ . But the load current  $i_{load}$  ( $i_d$ ) is maintained unchanged due to the previously accumulated energy in the choke  $L_{load}$ ,  $L_{line}$  and the phenomenon of self-induction EMF. The thyristors  $VS1$ ,  $VS4$  remain open.

At the moment of time  $\omega t = \pi + \alpha$ , a control pulse  $u_{C(2,3)}$  is applied to the control electrodes of thyristors  $VS2$ ,  $VS3$  and they are opened. In the scheme fig. 2.1 two short-circuit contours (switching contours) are formed: the first  $i_{sw1}$  is the transformer secondary winding and thyristors  $VS1$ ,  $VS2$ ; the second  $i_{sw2}$  is the transformer secondary winding  $W_2$  and thyristors  $VS3$ ,  $VS4$ . Through the switched  $VS2$ ,  $VS3$ , the voltage of the transformer secondary winding of the reverse polarity is applied to  $VS1$ ,  $VS4$ . Thyristors  $VS1$ ,  $VS4$  closed. The current of thyristors  $VS1$ ,  $VS4$  decreases from  $I_d$  to zero, and the cur-

rent of thyristors  $VS2$ ,  $VS3$  increases from 0 to  $I_d$ . If the inductance of the network is zero, then the switching process occurs instantly. With the pulses supply to thyristors  $VS1$ ,  $VS4$  at time  $\omega t = 2\pi + \alpha$  all processes in the scheme are repeated: thyristors  $VS1$ ,  $VS4$  are opened and thyristors  $VS2$ ,  $VS3$  are closed.

Therefore, when a controlled rectifier operates with an active-inductive load, there are the following features:

1. The load current becomes continuous, that is, the load from the network is not disconnected;
2. The instantaneous values of the rectified voltage at intervals corresponding to  $\alpha$  are negative, therefore, the average rectified voltage  $U_d$  decreases; Regulation of the average rectified voltage  $U_d$  occurs by changing the duration of the control angle  $\alpha$ ;
3. Thyristor switching consists in switching a continuous rectified current  $i_d$  from one pair of thyristors to another at the moment of a control pulse.

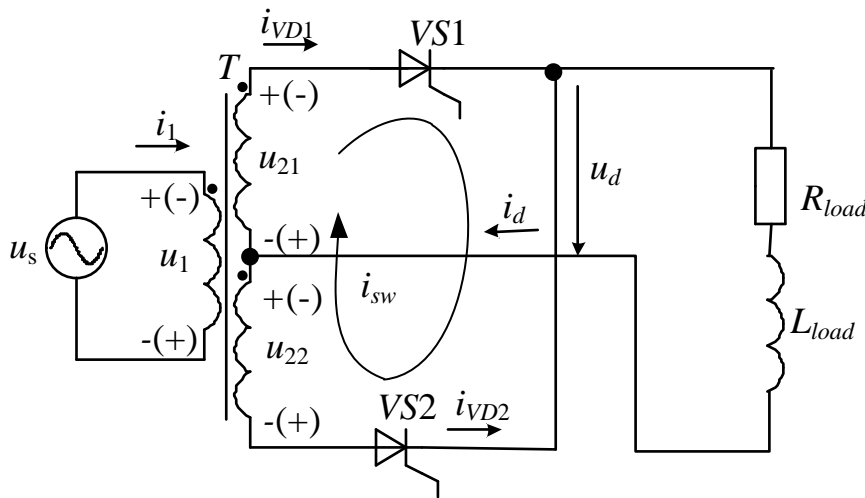


Figure 2.4 – Single-phase full-wave midpoint controlled rectifier

The operation principle of the single-phase midpoint controlled rectifier whose scheme is shown in fig. 2.4 very similar to the operation of the single-phase bridge controlled rectifier. The difference lies in the fact that not a thyristors pairs  $VS1$ ,  $VS4$  and  $VS2$ ,  $VS3$ ,

but two thyristors  $VS1$  and  $VS2$ , are involved in switching (the circuit for passing the switching current  $i_{sw}$  is shown in fig. 2.4). Time diagrams (fig. 2.2 and 2.3) illustrating the operations of the bridge scheme are also valid for midpoint scheme. In this scheme, similar to the diode rectifier scheme, a reverse voltage is applied to the closed thyristor equal to the sum of  $U_{21} + U_{22}$ , i.e. the amplitude of the reverse voltage is 2 times the amplitude of the rectified voltage.

### 2.1.2 Control and external characteristics of the controlled rectifier

Consider two main characteristics of controlled rectifiers, which have their own characteristics depending on the type of load. The dependencies below are for a single-phase bridge controlled rectifier, but they can also be used for a single-phase midpoint rectifier scheme.

The *control characteristic*  $U_d = f(\alpha)$  of a controlled rectifier is called the dependence of the rectified voltage  $U_d$  on the control angle  $\alpha$ . For a single-phase

bridge scheme of a controlled rectifier with an active load (fig. 2.1), it is determined by the expression:

$$U_d = U_{d0} \frac{1 + \cos \alpha}{2}. \quad (2.1)$$

The angle  $\alpha$  changes from zero to  $\pi$ , and the average rectified voltage  $U_d$  from  $U_{d0}$  to zero. The control characteristic  $U_d = f(\alpha)$  of a controlled rectifier is shown in figure 2.5.

The average rectified voltage of a single-phase bridge rectifier with an active-inductive load in continuous current mode is determined by the expression

$$U_d = U_{d0} \cos \alpha. \quad (2.2)$$

The control characteristic corresponding to expression (2.2) is shown in fig. 2.5 for  $L_{load} = \infty$ . The angle  $\alpha$  changes from zero to  $\pi/2$ , and the average rectified voltage  $U_d$  from  $U_{d0}$  to zero.

In practice, the load inductance is not equal to infinity and the energy stored in it may not be sufficient to maintain a constant rectified current over the entire range of the control angle. At a finite value of the load inductance, the rectified current pulsates with certain amplitude around the average value.

With an increase in the control angle, the ripple amplitude increases and at a certain value  $\alpha = \alpha_{boundary}$  ripple reaches zero (*boundary continuous current*)

$$\alpha_{boundary} \leq \arctg \frac{\omega L_{load}}{R_{load}}. \quad (2.3)$$

That is, the limit value of the control angle is determined by the time constant of the load circuit.

When  $\alpha$  is greater than  $\alpha_{boundary}$ , the rectified current becomes intermittent with current pauses. In this case, the average rectified voltage increases relative to that calculated according to (2.2) due to a decrease in the sections with negative voltage in the  $u_d$ . As a result, the control characteristic approaches the control characteristic for an active load (fig. 2.5).

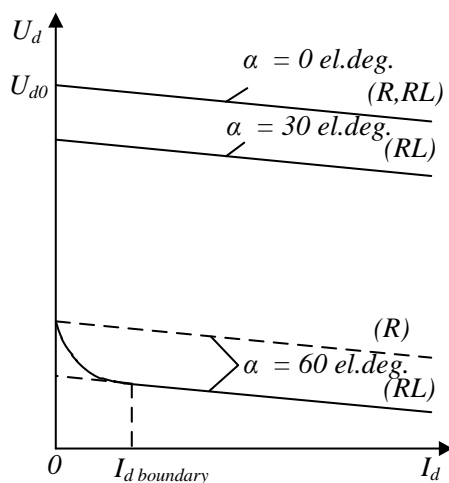


Figure 2.6 – External characteristics of the controlled rectifier

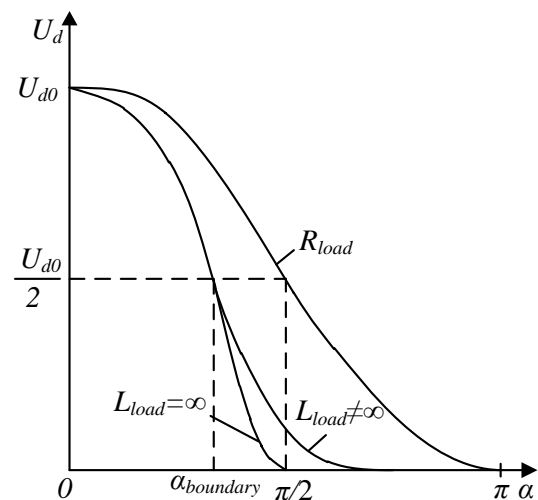


Figure 2.5 – Control characteristic of a controlled rectifier

In expressions (2.1) and (2.2), the average value of the rectified voltage  $U_d$  was given without taking into account the losses in the rectifier elements. Real transformer, switches and choke have certain values of active resistance, at which there is a voltage drop from the average value of the load current  $I_d$ . This leads to a decrease in the voltage  $U_d$  with an increase in the load current.

Dependencies  $U_d = f(I_d)$  at different values of the control angle  $\alpha$  are called *external characteristics* of the controlled rectifier, which are shown in figure 2.6. The slope is almost linear and is determined by the losses in the rectifier. When  $\alpha = 0$ , the external characteristic is the same as for an uncontrolled rectifier with active ( $R_{load}$ ) and active-inductive ( $R_{load}, L_{load}$ ) loads. With an increase in the control angle  $\alpha$ , the slope of the characteristics does not change; however, the characteristics with a active load will be higher than the corresponding characteristics with an active-inductive load. This can be explained by considering the control characteristics in figure 2.5. In practice, external characteristics with an active-inductive load at low currents  $I_d$  become nonlinear. In fig. 2.5, such a case is shown at  $\alpha = 60$  electrical degrees, when at  $I_d < I_{d \text{ boundary}}$ , the voltage  $U_d$  begins to increase. This is due to the transition of the rectifier operation from continuous mode to intermittent current mode. For comparison (at  $\alpha = 60$  electrical degrees), the dotted line shows a similar characteristic with an active load.

*Influence of network inductance on the controlled rectifier operation.* The presence of a non-zero inductance of the network  $L_s$  leads to the fact that the current transfer from one pair of thyristors to another cannot occur instantly. The network inductance maintains the current in the closing thyristors and does not allow the current to rise in the opening thyristors. During this time, all four thyristors will be open in the circuit and the instantaneous rectified voltage  $u_d$  will be zero (the load is shorted through four open thyristors).

The switching interval of thyristors caused by the processes of redistribution of energy accumulated in the inductances of the network is called the *switching angle*  $\gamma$ .

The sum of the current closing and opening thyristors in the switching interval is equal to the average rectified current  $I_d$ . the current of the closing thyristor pair decreases from  $I_d$  to zero, and the current of the opening thyristor pair increases from zero to  $I_d$ . The magnitude of the switching angle  $\gamma$  is determined by the value of the average rectified current  $I_d$  and the value of the network inductance  $L_s$ , that is, the energy accumulated in the network inductance and redistributed over the interval

$$\gamma = \arccos\left(\cos\alpha - \frac{\pi X_s I_d}{m U_{d0}}\right) - \alpha, \quad (2.4)$$

where  $X_s = 2\pi f_s L_s$  is the inductive reactance of the network.

### 2.1.3 Control system of the thyristor rectifier

With all the variety of control systems, their main task is to form control pulses, which are set by the control signal and are transmitted at certain times to

the control electrodes of the thyristors. The most widespread are vertical-type control systems with high speed.

Figure 2.7 shows a generalized block diagram of a vertical-type pulse-phase control system (PPCS) and timing diagrams for the case of controlling a single-phase bridge controlled rectifier.

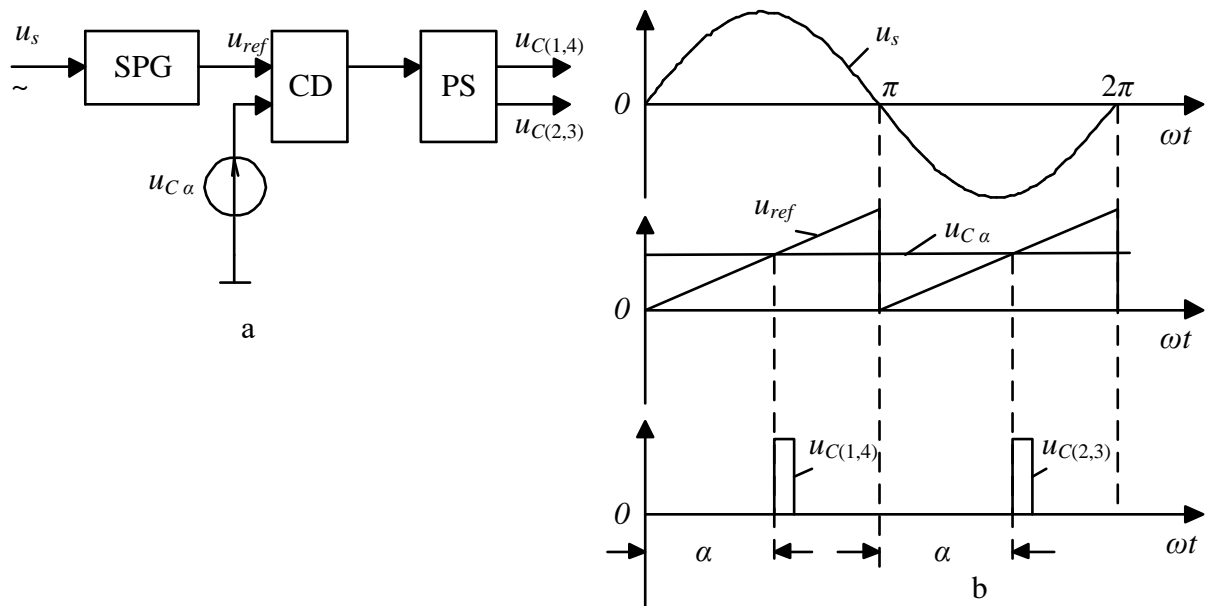


Figure 2.7 – Block diagram of the pulse-phase control system (a) and timing diagrams of a single-phase controlled rectifier (b)

Consider the principle of forming control pulses in PPCS with a vertical control method, using the timing diagrams in fig. 2.7, b. The PPCS includes a sawtooth (reference) voltage generator SVG, a comparison device CD and a pulse shaper PS (fig. 2.7, a). The operation of the SVG is synchronized with the voltage of the supply network in such a way that at the moments when the voltage  $u_s$  passes through zero, the SVG forms periodic linearly increasing voltage pulses  $u_{ref}$ . Voltage  $u_{ref}$  and control voltage  $u_{C\alpha}$  are supplied to the inputs of the control system. At the moments of their equality, the control pulses  $u_{C(1,4)}$  in the interval  $(0 - \pi)$  and  $u_{C(2,3)}$  in the interval  $(\pi - 2\pi)$ , shifted in phase relative to the moment of natural switching by an angle  $\alpha$ , appear at the output of the control system. The PS pulse shaper amplifies the  $u_{C(1,4)}$  and  $u_{C(2,3)}$  pulses, forms them in shape, and then distributes them for feeding to the corresponding thyristors  $VS1$ ,  $VS4$  and  $VS2$ ,  $VS3$ .

## 2.2 Work order

### 2.2.1 Calculation of the controlled rectifier scheme

Calculate the controlled rectifier scheme according to the task variant given in appendix B.1. Select the main elements of the scheme. From the datasheets of the semiconductor thyristor and transformer take the characteristics necessary for modeling the scheme in the Matlab / Simulink package. All actions should be performed according to the calculation example below.

### 2.2.1.1 The calculation example of the single-phase half-wave controlled rectifier

The scheme of the single-phase half-wave controlled rectifier is shown in figure 2.8.

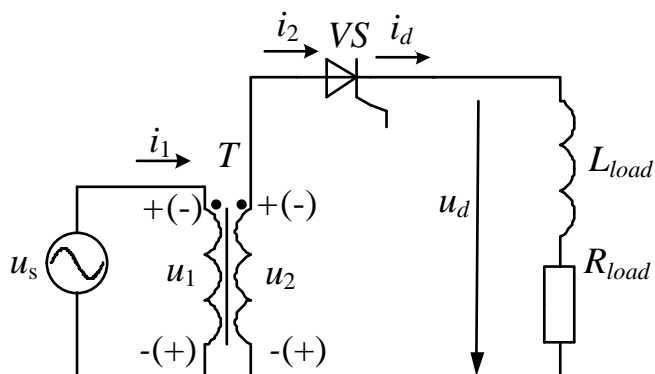


Figure 2.8 – Single-phase half-wave controlled rectifier

The calculation of the scheme (figure 2.8) need be performed according to the recommendations given in paragraph 1.2.1.1 for the scheme of a single-phase half-wave uncontrolled rectifier. The thyristor is selected according to the average forward current  $I_{VS}$  and maximum reverse voltage  $U_{VS \max}$ . Similarly to the diode from the thyristor datasheet, we

take the necessary data for modeling. We also carry out the calculation and selection of the transformer in accordance with paragraph 1.2.1.1. Let us consider in detail the calculation of the active-inductive load in the controlled rectifier scheme. The task for the calculation in accordance with appendix B.1 is given in table 2.1.

Table 2.1 - Task for the calculation of the single-phase half-wave controlled rectifier

Source		Rectifier Scheme	Load		
$U_s, V$	$f_s, Hz$		$P_{d \text{ nom}}, W$	$U_{d0}, V$	$F_p$
220	50	Single-phase half wave	220	12	0,95

Load active resistance is equal to

$$R_{load} = \frac{U_d^2}{P_{d \text{ nom}}} = \frac{12^2}{220} = 0,66 \Omega.$$

Full power of the load we are determine from the next expression

$$S = \frac{P_{d \text{ nom}}}{F_p} = \frac{220}{0,95} = 232 \text{ VA},$$

then reactive power of the load

$$Q = \sqrt{S^2 - P_{d \text{ nom}}^2} = \sqrt{232^2 - 220^2} = 74 \text{ Var}.$$

Inductance resistance is equal to

$$X_L = \frac{Q}{\left(\frac{P_d \text{ nom}}{U_d}\right)^2} = \frac{74}{\left(\frac{220}{12}\right)^2} = 0,22 \Omega,$$

then load inductance

$$L_{load} = \frac{X_L}{2\pi f} = \frac{0,22}{2 \cdot 3,14 \cdot 50} = 0,7 \text{ mH.}$$

When calculating full wave schemes of controlled rectifiers (midpoint and bridge), a frequency  $f$  is taken equal to 100 Hz.

The calculation of full wave schemes of controlled rectifiers (figures 2.1 and 2.4) need be performed according to the recommendations given in paragraph 1.2.1.3 and 1.2.1.2 corresponding.

### 2.2.2 Simulation of the controlled rectifier scheme with active-inductive load

Simulation of the controlled rectifier scheme is performed in the Matlab / Simulink package. Version 2016b is used in this teaching aid.

#### 2.2.2.1 Model building steps

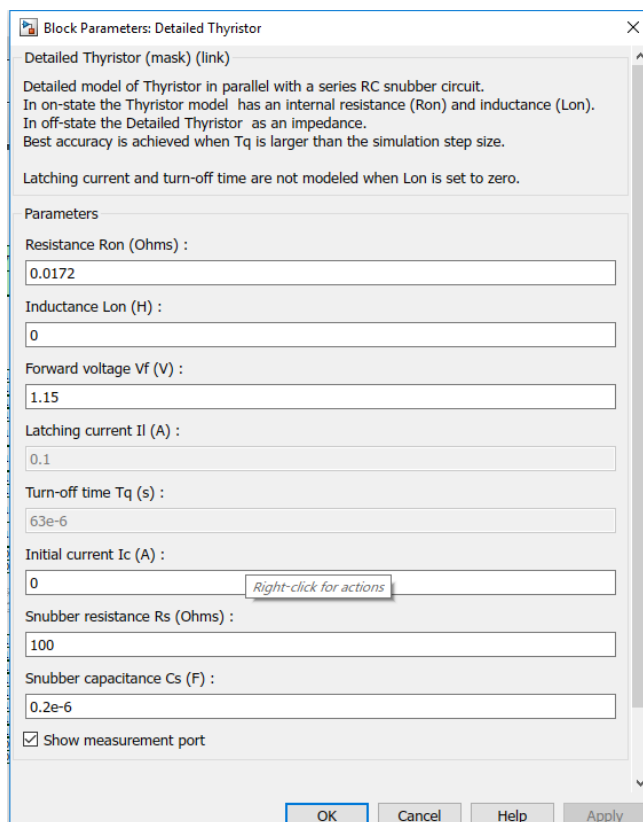


Figure 2.9 – Parameter window of the "Thyristor" block

When simulating the schemes of single-phase controlled rectifiers, it is necessary to follow the recommendations in paragraph 1.2.2.1. The difference will be in the type of semiconductor switches. The controlled rectifier uses single-operation thyristors, the parameter window of the "Thyristor" block is shown in fig. 2.9.

Also the difference will be in the type of load. In one of the parameters of the "Series RLC Branch" block, it is necessary to select the RL branch type (fig. 1.14). But the main difference lies in the need to build a model of a control system that will issue control pulses to the control electrodes of thyristors. Let us consider in more detail the modeling of the control system for

a single-phase controlled rectifier in accordance with the block diagram in fig. 2.7, a. The matlab model of the control system is shown on fig. 2.10.

The sawtooth (reference) voltage generator SVG (fig. 2.7, a) is consist of “Constant”, “Hit Crossing” and “Integrator” blocks (fig. 2.10); the control voltage  $u_{C\alpha}$  (fig. 2.7, a) is generated by blocks system of “Alfa control angle” and “Trigonometric Function” (fig. 2.10); the comparison device CD (fig. 2.7, a) is represented by the “Relation Operator 2” block (fig. 2.10) and the pulse shaper PS (fig. 2.7, a) is consist of other blocks that shown on figure 2.10. After the control system has been built, it is necessary to connect the Q output to the G input of the "Universal Bridge" block or each of the four outputs of the pulse shaper to the input of the corresponding thyristor. All other steps of building a model of a controlled rectifier coincide with the recommendations of paragraph 1.2.2.1.

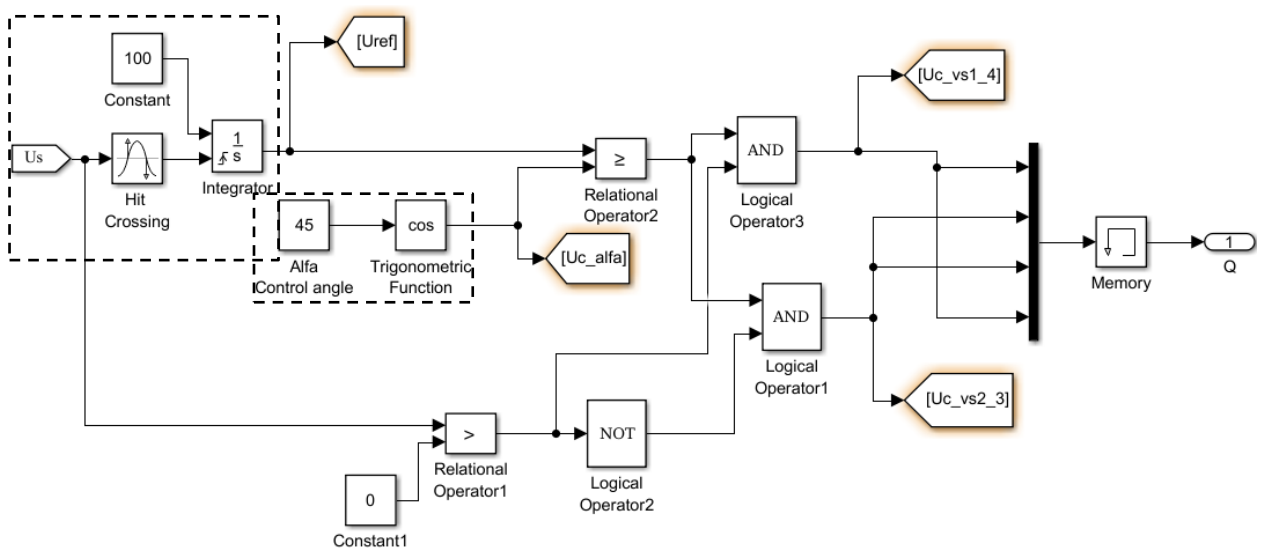


Figure 2.10 – Matlab model of the control system

### 2.2.2.2 The investigate of the voltages and currents forms

Timing diagrams of the scheme voltages and currents need be recorded in a steady mode of model operation during for four periods of the supply voltage, that equal is 0,08 s. Diagrams of mains current and voltage, load current and voltage, reverse voltage and forward current of the semiconductor switch (thyristor) are fixing. The timing diagrams need be for a scheme with different values of the control angle. The values of the control angles are set by the teacher.

### 2.2.2.3 External characteristics of the controlled rectifier

To build an external characteristic  $U_d = f(I_d) \Big|_{\alpha = const}$ , it will be necessary:

- Set one of the two values of the control angle  $\alpha$  that is recommended in appendix B.2.
- For the each values of the control angle  $\alpha$  set five load resistance  $R_{load}$ . Resistance changes need be made within the range from 10 to 100 percent of the nominal value, which is calculated in paragraph 2.2.1.

- By setting the calculated load resistance in the model, fix the average values of the rectified current  $I_d$  and voltage  $U_d$ . To determine the average rectified voltage and current that recommended in paragraph 1.2.2.3.
- Record the data in the table that is given in appendix B.2.
- Perform these steps for the rectifier scheme without and with inductive load.
- According to received table, you need to build external characteristics. The characteristics are plotted on one graph on the same scale.
- Analyze the appearance of the external characteristics of the controlled rectifier.

#### 2.2.2.4 Control characteristic of the controlled rectifier

To build the control characteristic  $U_d = f(\alpha)$ , it will be necessary:

- Set five values of the control angle  $\alpha$  that is recommended in appendix B.3.
- By setting the control angle  $\alpha$  in the model, fix the average values of the voltage  $U_d$ . To determine the average rectified voltage that recommended in paragraph 1.2.2.3.
- Record the data in the table that is given in appendix B.3.
- Perform these steps for the rectifier scheme without and with inductive load.
- According to received table, you need to build control characteristics. The characteristics are plotted on one graph on the same scale.
- Analyze the appearance of the control characteristics of the controlled rectifier.

### 2.3 Report preparation

The report on the work performed should contain: the purpose of the work, the scheme of the experiment, the calculation of the scheme elements, the datasheet of the selected scheme elements, the Matlab-model of the scheme, tables and graphs obtained as a result of the experiment, as well as time diagrams in accordance with the task of performing the work and their brief analysis.

### 2.4 Self-test questions

1. Explain how the investigated scheme works.
2. How does the load nature affect the operation of the scheme?
3. Explain the influence of the inductive resistance of the supply network on the operation of the scheme.
4. Explain the consumption of reactive power by the converter.
5. What determines the energy performance of the converter?
6. What are the reasons for switching semiconductor devices in the scheme?
7. Explain the shape of the secondary current of the transformer of the investigated converter.
8. Explain the shape of the voltage of the secondary winding of the converter transformer.
9. What is the intermittent current mode of the valve converter and what are the conditions for its occurrence?

10. Does the converter transformer in the studied scheme have a forced magnetization flux and what causes these fluxes?
11. What is the rectified voltage ripple factor and what does it depend on?
12. Explain the course of the external characteristic.
13. Explain the course of the control characteristic.
14. What are the requirements for the inverter control system?
15. What are the requirements for the converter control system in the modes of continuous and intermittent load currents?
16. Explain the form of the reverse voltage of the switch of the investigated converter.
17. Explain the form of the forward current of the switch of the investigated converter.
18. Explain the shape of the rectified current and voltage of the investigated converter.
19. What is the ideal open circuit voltage of a controlled rectifier and what is it equal to in the circuit under study?

## CHAPTER NO. 3

### PULSE WIDTH CONVERTERS

**The purpose of the work** is to study the operation of different types of the pulse width converters.

#### 3.1 Basic theoretical thesis

To regulate the DC load voltage at constant voltage DC power supplies use *pulse converters* (PC). In this case, the change of the average load voltage provided by adjusting the duration of its connection to the DC source. The on-off cycle time is called the impulse delivery period  $T$ . Time of the switched-on state – duration of a pulse  $t_i$ . It is clear that the average load voltage that is greater, than is greater the ratio  $\gamma = t_i / T$ , which is called the impulse fill factor.

Depending on the laws of change  $t_i$  and  $T$  distinguish:

- pulse width modulation (PWM) with  $T = \text{const}$  and  $t_i = \text{var}$ ;
- frequency-pulse modulation (FPM) with  $T = \text{var}$  and  $t_i = \text{const}$ ;
- time-pulse modulation (TPM) with  $T = \text{var}$  and  $t_i = \text{var}$ .

Pulse converters that reduce the voltage provide regulation of the output DC voltage (average value) in the direction of reduction relative to the source voltage.

##### 3.1.1 Step-down pulse width converter

The scheme of the *step-down pulse converter* on the transistor is shown on figure 3.1. The switch element – the transistor  $VT$  is connected in series with the

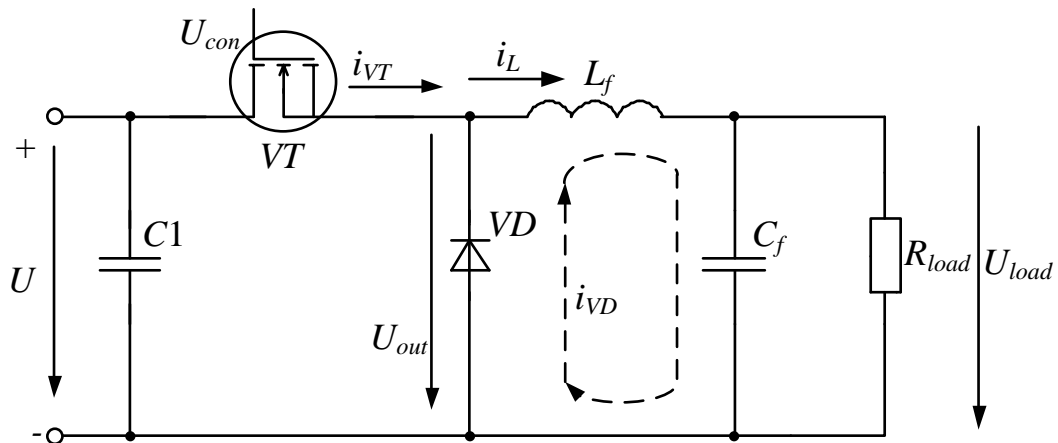


Figure 3.1 – The scheme of the step-down pulse converter

load  $R_{load}$ . To smooth the current, the choke  $L_f$  is connected in series with the load that is the nature of the load is active-inductive. At the out of the switch is connected to the reverse diode  $VD$ , which forms a circuit to short the reactive load current in the event of disconnection from the source. Capacitor  $C_f$  can be used for additional smoothing of load voltage, which is connected in parallel  $R_{load}$  (that is we get an LC-filter). At the input of the pulse converter, taking into account the inductance of the connecting wires, install a capacitor  $C_1$ , which limits the current of the

input circuit when the switch is turned off. This excludes commutation overvoltages on the transistor.

Time diagrams that explain the work of the pulse converter using PWM (fig. 3.1) are presented in figure 3.2. According to the control voltage  $u_{con}$  (control

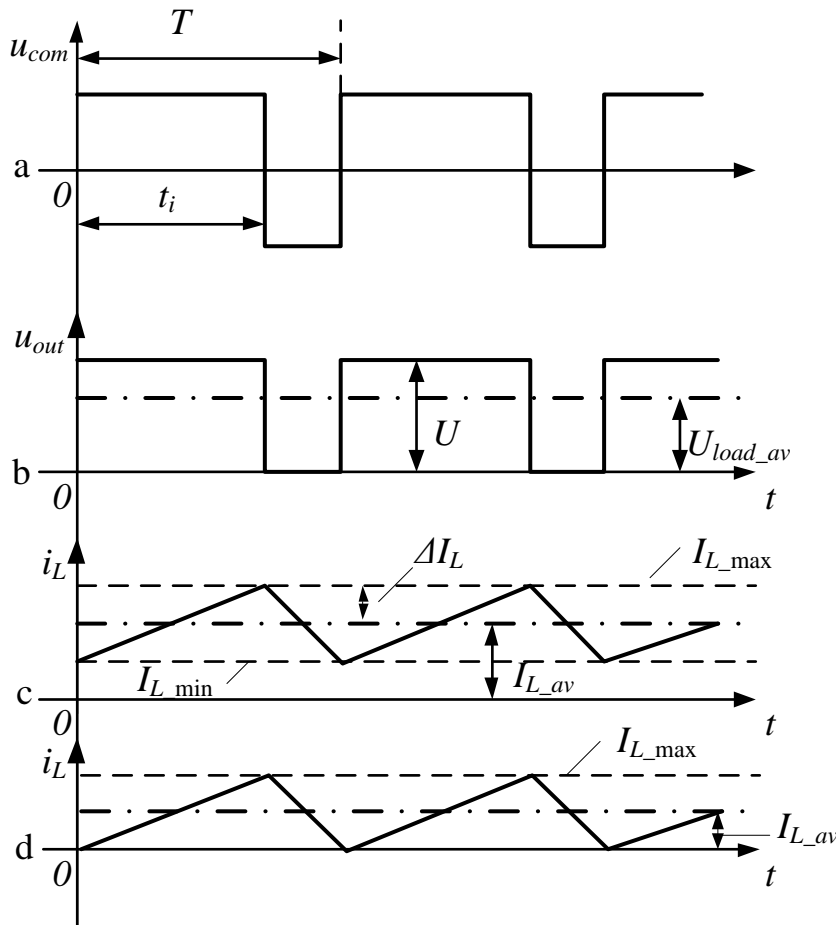


Figure 3.2 – Diagrams of work step-down pulse converter

time interval  $(T - t_i)$ , the load is switched off from the source  $U$ , that is  $u_{out} = 0$ . But the current in the output circuit cannot change instantly – it is "picked up" by the reverse diode  $VD$  ( $i_L = i_{VD}$ ), which is turned on by the EMF self-induction in the choke. Thus, in this interval, the current retains its previous direction, closing through  $VD$ . The current is decreasing. Then the processes are repeated. We assume that the capacitance  $C_f$  of the capacitor is large enough and the voltage  $U_C = U_{load} = U_{load\_av}$  is perfectly smoothed and constant. The average load voltage

$$U_{load\_av} = U \cdot \gamma. \quad (3.1)$$

The average current value (variable component  $I_L$  is closed through a capacitor)

$$I_{L\_av} = I_{load\_av} = \frac{U_{load\_av}}{R_{load}}. \quad (3.2)$$

voltage is bipolar: positive polarity corresponds to the open state of the switch element; negative polarity corresponds to close state) transistor  $VT$  opens is at time 0 and stays open during time  $t_i$ . The mains voltage  $U$  is supplied to the output of the step-down pulse converter, so its output voltage  $u_{out} = U$ . Load (taking into account the smoothing choke) is usually active-inductive, so the choke current  $i_L = i_{VT}$  is changed not by a jump, but grows slowly (energy accumulates in magnetic field). With  $VT$  switched off at the

The current varies according to a linear law and pulsates in ranges from  $I_{L\_min}$  to  $I_{L\_max}$ . Amplitude of current pulsations relative to the average value  $\Delta I_L$

$$\Delta I_L = \frac{U \cdot \gamma(1-\gamma)}{2L_f \cdot f_m}, \quad (3.3)$$

where  $f_m = 1/T$  is the modulation frequency.

Respectively maximum and minimum values of load current:  $I_{L\_max} = I_{L\_av} + \Delta I_L$ ,  $I_{L\_min} = I_{L\_av} - \Delta I_L$ . The pulsation acquires its maximum value at a value of  $\gamma = 0,5$ .

It should be noted that depending on  $\gamma$ ,  $f_m$ ,  $L_f$ ,  $R_{load}$ , the current  $i_L$  can be continuous or there are currentless pauses. The current curve is at the limit of continuity when  $I_{L\_min} = 0$  is given in figure 3.2, (bottom diagram). It is easy to see that  $\Delta I_L = I_{L\_av} = I_{load\_av} = U_{load\_av} / R_{load}$ . To ensure the continuity of the current in the load, its inductance (inductance of the smoothing choke) must be

$$L_f = \frac{R_{load}(1-\gamma)}{2f_m}. \quad (3.4)$$

Reducing the value of the inductance  $L_f$  is achieved by increasing the frequency  $f_m$ . The modulation frequency is limited by the frequency properties of the switches. The average current of the transistor and the reverse diode:

$$I_{VT\_av} = \gamma \cdot I_{load\_av}, \quad I_{VD\_av} = I_{load\_av} \cdot (1-\gamma). \quad (3.5)$$

The transistor should be chosen not by the average, but by the maximum load current, given the small value of the current overload. The considered principle of control of step-down pulse converter using PWM provides operation of the circuit as a voltage source.

### 3.1.2 Step-up pulse width converter

The *step-up pulse converter, which increases the voltage* (fig. 3.3, a), has an element that accumulates energy when connected to a source, and then gives it to the load. This is a choke, which is connected in series with the source and has an inductance  $L$ . To smooth the voltage ripple on the load  $R_{load}$  parallel to it is connected a capacitor  $C$ .

The scheme is also contains a controlled switch - transistor  $VT$  and diode  $VD$ . The control voltage  $u_{con}$  sets the duration of the turn-on state of the switch  $t_{on}$  during the period of switching  $T$ . Consider the operation of the circuit with using the method of pulse-width modulation (PWM). In this case, to simplify the analysis, we decide that the source and all elements of the circuit are ideal. Based on the fact that the capacitance of the capacitor is large enough, we consider the output voltage to be perfectly smoothed –  $u_{load(t)} = U_{load}$ . Period  $T$  of the step-up pulse converter consists of two intervals. In the first interval the transistor  $VT$  is turn-on (fig. 3.3, b) its duration is  $t_{on}$ . The choke is connected to the source, the voltage on it  $u_L = U$  and the current  $i_L = i_{VT}$  (fig. 3.4) increases according to the linear law ( $di_L/dt = U/L$ ) – energy accumulates in the magnetic field. Diode  $VD$  is turned

off by the reverse voltage  $U_{load}$  on the load side. The load is disconnected from sources. In the second interval (fig. 3.3, c)  $t_{off} = (T - t_{on})$  VT is turn-off, under the action of  $e_L$  the diode is switched on and connects the source to the load. The current  $i_L = i_{VD}$  gradually decreases – the energy accumulated in the choke is transferred to the load circuit. The choke voltage is determined by the difference between the source voltage  $U$  and load voltage  $U_{load}$ . The voltage and current diagrams of the choke are shown in figure 3.4.

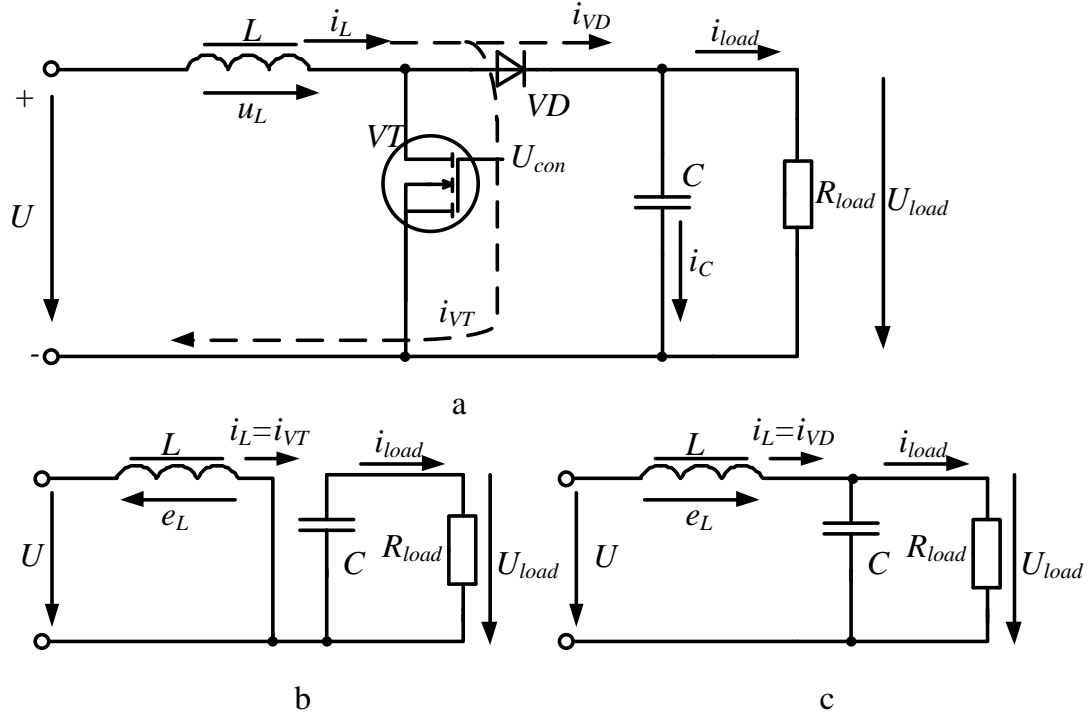


Figure 3.3 – The step-up pulse converter:  
a) scheme;

- b) the state of the circuit when the transistor is turned on;  
c) the state of the circuit when the transistor is turned off.

Average load voltage

$$U_{load\_av} = \frac{U}{1 - \gamma}. \quad (3.6)$$

Average source current

$$I_{L\_av} = \frac{I_{load\_av}}{1 - \gamma}. \quad (3.7)$$

The output voltage of the ideal converter (without energy losses in the circuit) varies from  $U$  for  $\gamma = 0$  (transistor off) to  $\infty$  for  $\gamma = 1$ .

Average transistor current

$$I_{VT\_av} = \gamma \cdot I_{L\_av}. \quad (3.8)$$

Average diode current

$$I_{VD\_av} = (1 - \gamma) \cdot I_{L\_av}. \quad (3.9)$$

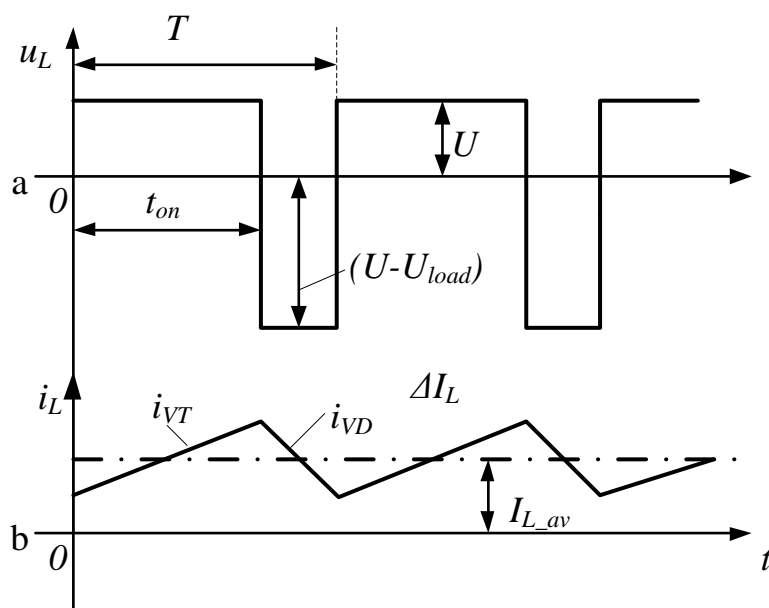


Figure 3.4 – Charts voltage and current of the step-up pulse converter

The transistor is selected according to  $I_{L\_max}$  and the value of the voltage applied to it in the off state and equal to  $U_{load}$ . The diode is selected according to  $I_{VD\_av}$  and reverse voltage, which is also  $U_{load}$ .

In the real circuit, due to the energy consumption in the circuit elements, the maximum voltage value is limited. The increase in output voltage, as in the transformer, is due to a corresponding increase in current consumed from the source.

Figure 3.4 shows the steady-state mode of operation with continuous current, when the load is reduced, the converter can switch to the mode of operation with intermittent current. Consider the limit mode of operation when the current has time to fall to zero (fig. 3.5). In this case,  $I_{L\_av} = \Delta I_L$ , where  $\Delta I_L = I_{L\_max} / 2$  is the amplitude of the ripple currents relative to the mean value.

Fluctuations amplitude of the source current

$$\Delta I_L = \frac{U_{load\_av} \cdot \gamma(1-\gamma)}{2L \cdot f_m} \quad (3.10)$$

According to (3.10) it is possible to determine the values of inductance  $L$

and  $f_m$  required to maintain the current pulsations amplitude at a given level.

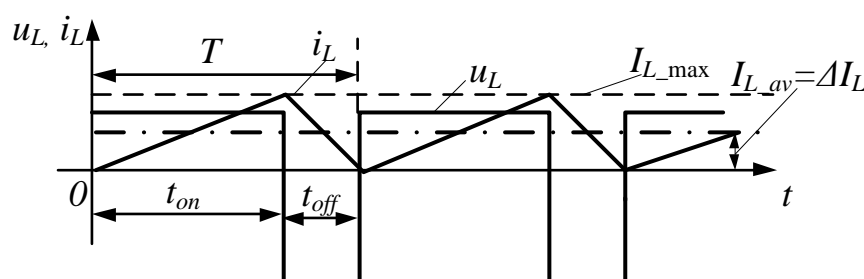


Figure 3.5 – Diagrams of the step-up pulse converter in the limit mode

*Determination of capacitor capacity.* Prior to that, it was assumed that the capacitance of the capacitor is large enough to ignore the voltage ripple on the load. In the real scheme, the value of the capacity is limited. For analysis, consider the diagrams of the converter, which are presented in figure 3.6. At the time interval  $t_{on}$  the output circuit of the converter is disconnected from the source – the capacitor is discharged, its voltage decreases (accumulated on the previous interval of energy charge is given

the value of the capacity is limited. For analysis, consider the diagrams of the converter, which are presented in figure 3.6. At the time interval  $t_{on}$  the output circuit of the converter is disconnected from the source – the capacitor is discharged, its voltage decreases (accumulated on the previous interval of energy charge is given

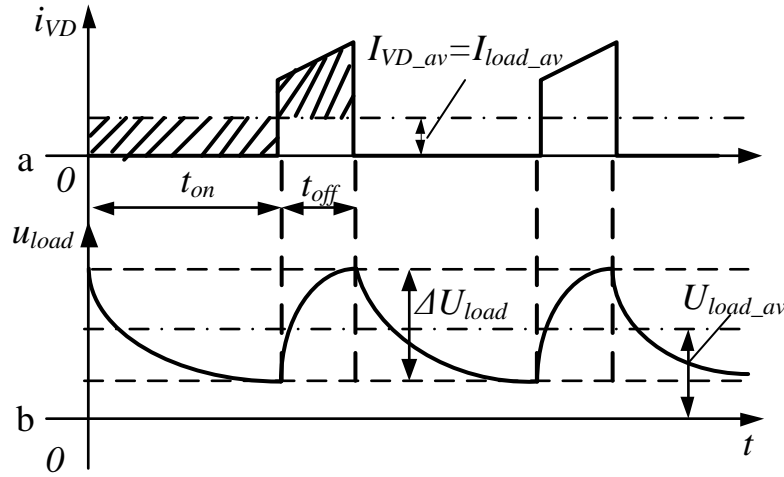


Figure 3.6 – Diagrams of diode current and output voltage of the converter

to the average value of  $U_{load\_av}$ , the amplitude of the voltage ripple  $\Delta U_{load}$ .

$$\Delta U_{load} = \frac{U_{load\_av} \cdot \gamma \cdot T}{R_{load} \cdot C}. \quad (3.11)$$

Based on (3.11), you can determine the required value of the capacitance to limit the voltage ripple on the load at a given level. To assess the real capabilities of the circuit, it is necessary to take into account the energy consumption in the circuit – active resistors: sources, inductors, transistors (diodes).

## 3.2 Work order

### 3.2.1 Calculation of the scheme

Calculate the step-down and step-up pulse converter scheme according to the task variant given in appendix C.1 and C.2 respectively. Select the main elements of the scheme. From the datasheets of the semiconductor devices (transistor and diode) take the characteristics necessary for modeling the scheme in the Matlab / Simulink package. All actions should be performed according to the calculation example below.

#### 3.2.1.1 The calculation example of the step-down pulse converter

The task for the calculation in accordance with appendix C.1 is given in table 3.1, and the scheme of the step-down pulse converter is shown in figure 3.1.

Consider the possibility of using the scheme (fig. 3.1) without smoothing capacitor  $C$ . Determine the range of adjustment of the pulse filling factor  $\gamma$ . Maximum and minimum load voltages value respectively are equal to

$$U_{nom\_max} = \Delta U_{nom\_max} \cdot U_{nom} = 1,1 \cdot 80 = 88 \text{ V},$$

$$U_{nom\_min} = \Delta U_{nom\_min} \cdot U_{nom} = 0,2 \cdot 80 = 16,6 \text{ V},$$

to the load). The charge given by the capacitor  $Q = I_{load\_av} \cdot t_{on}$  corresponds to the area of the rectangle, which in figure 3.6 is highlighted in dark. At the interval  $t_{off}$  energy accumulated in the inductor through the diode  $VD$  is transmitted to the load and simultaneously charges the capacitor – voltage on the load increases.

Thus, we obtain voltage fluctuations relative

then maximum and minimum pulse filling factors are

$$\gamma_{\max} = \frac{U_{nom\_max}}{U} = \frac{88}{110} = 0,8 \text{ V,}$$

$$\gamma_{\min} = \frac{U_{nom\_min}}{U} = \frac{16,6}{110} = 0,151 \text{ V.}$$

Table 3.1 – Task for the calculation of the step-down pulse converter

Variant	Load			Source voltage	Ripple factor	Modulation frequency
	Nominal power	Nominal voltage	Load voltage regulation range			
	$P_{nom}$ , W	$U_{nom}$ , V	$\Delta U_{nom}$			
1	800	80	1,1-0,2	110	0,005	10000

The amplitude of voltage fluctuations under active load is determined by the corresponding current fluctuations. The maximum value of the pulsations amplitude of the load current occurs at  $\gamma = 0,5$ . The load resistance is

$$R_{load} = \frac{U_{nom}^2}{P_{nom}} = \frac{80^2}{800} = 8 \Omega.$$

The value of the load current at  $\gamma = 0,5$  is

$$I_{load} = \frac{U \cdot \gamma}{R_{load}} = \frac{110 \cdot 0,5}{8} = 6,875 \text{ A,}$$

and amplitude of current pulsations is

$$\Delta I_{load} = F_r \cdot I_{load} = 0,005 \cdot 6,875 = 0,0344 \text{ A.}$$

Based on (3.3) we find the inductance of the smoothing choke

$$L_f = \frac{U \cdot \gamma(1-\gamma)}{2 \cdot \Delta I_{load} \cdot f_m} = \frac{110 \cdot 0,5(1-0,5)}{2 \cdot 0,0344 \cdot 10000} = 0,04 \text{ H.}$$

The obtained value of inductance is quite large. Consider the option using a capacitor. We assume that the angular pulsation frequency is equal to the modulation frequency

$$\omega = 2\pi f_m = 2 \cdot 3,14 \cdot 10000 = 62800 \text{ rad/s,}$$

then the capacitance of the capacitor

$$C_f = \frac{\pi}{2 \cdot \omega \cdot F_r \cdot R_{load}} = \frac{3,14}{2 \cdot 62800 \cdot 0,005 \cdot 8} = 625 \mu\text{F,}$$

we accept  $C_f = 630 \mu\text{F}$  at a voltage of at least 110 V. The inductance of the smoothing choke is chosen from condition (3.4) with  $\gamma = 0,5$

$$L_f = \frac{R_{load}(1-\gamma)}{2f_m} = \frac{8 \cdot (1-0,5)}{2 \cdot 10000} = 0,2 \text{ mH.}$$

Let's calculate the parameters for selecting the MOSFET transistor and diode. The MOSFET field-effect transistor is selected according to the maximum reverse voltage  $U_{DS}$  and the resistance in the conductive state  $R_{DS(on)}$ . Taking into account the safety factor, the range of which is equal to 1,5 – 2, the maximum reverse voltage on the transistor is equal to

$$U_{DS} = F_S \cdot U = 1,5 \cdot 110 = 165 \text{ V.}$$

The transistor should be selected according to the maximum load current

$$I_{VT} = \frac{U_{nom\_max}}{R_{load}} = \frac{88}{8} = 11 \text{ A.}$$

The resistance in the conductive state is

$$R_{DS(on)} = \frac{U_{DS(on)}}{I_{VT}},$$

where  $U_{DS(on)}$  is the voltage on the transistor in the conductive state, it is usually equal to 1 V.

$$R_{DS(on)} = \frac{1}{11} = 0,09 \Omega.$$

The calculated parameters correspond to the transistor AM30N20-78D with a voltage of 200 V, a current of 21 A and a resistance in the conductive state of 78 mΩ.

The diode is selected according to the maximum reverse voltage  $U_{VD}$  and the average forward current  $I_{VD}$ . The maximum reverse voltage of the diode  $U_{VD}$  with the safety factor is equal to 200 V. The average diode current, the maximum which will be at  $\gamma = 0,5$ , is

$$I_{VD} = I_{load\_av} \cdot (1-\gamma) = \frac{U \cdot \gamma \cdot (1-\gamma)}{R_{load}} = \frac{110 \cdot 0,5 \cdot (1-0,5)}{8} = 3,44 \text{ A.}$$

Taking into account the safety factor the average diode current is 6 A. The calculated parameters correspond to the diode 1N3881 with a voltage of 200 V and a current of 6 A. Also when choosing a diode and transistor, you must take into account the modulation frequency.

Also to build a model in the window for setting the parameters of the semiconductor diode, you need:

- The dynamic resistance  $R_{on} (r_g)$ , which is determined from the diode datasheet. Its value can be determined from the table of the device characteristics or by the slope of the forward branch of the diode I - V characteristic. In the considering example  $r_g = 0,001 \Omega$ .

- The diode threshold voltage (forward voltage)  $V_f$ , which is also determined from the diode datasheet. Its value is most often indicated in the table of the device

characteristics, if not, then it can also be determined from the direct branch of the diode I - V characteristic. In the considering example  $V_f = 1,4$  V.

- The snubber resistor and capacitance. We take their values equal to  $100 \Omega$  and  $0,2 \mu\text{F}$ , respectively.

In the window for setting the parameters of the transistor, you need:

- FET resistance  $R_{on}$  ( $r_{DS(on)}$ ), which is determined from the transistor datasheet. In the considering example  $r_{DS(on)} = 0,078 \Omega$ .

- Internal diode resistance  $R_d$ , which is determined from the transistor datasheet. Its value can be determined from the table of the device characteristics or by the slope of the forward branch of the reverse diode I - V characteristic. In the considering example  $r_g = 0,052 \Omega$ .

- Internal diode forward voltage  $V_f$  ( $V_{SD}$ ), which is also determined from the diode datasheet. Its value is most often indicated in the table of the device characteristics, if not, then it can also be determined from the direct branch of the diode I - V characteristic. In the considering example  $V_{SD} = 1,1$  V.

- The snubber resistor and capacitance. We take their values equal to  $100 \Omega$  and  $0,2 \mu\text{F}$ , respectively.

### 3.2.1.2 The calculation example of the step-up pulse converter

The task for the calculation in accordance with appendix C.2 is given in table 3.2, and the scheme of the step-up pulse converter is shown in figure 3.3, a.

Table 3.2 – Task for the calculation of the step-up pulse converter

Variant	Load voltage	Source voltage	Ripple factor		Modulation frequency	Equivalent resistance
			Voltage	Current		
	$U_d$ , V	$E$ , V	$F_{rU}$	$F_{rI}$	$f_m$ , Hz	$R_\Sigma$ , $\Omega$
1	312	12,6	0,05	0,1	1000	0,1

Find the value of the coefficient  $K_R$  determined by the ratio of the equivalent resistance of the circuit and the load

$$K_R = \left( \frac{E}{2U_{load\_max}} \right)^2 = \left( \frac{12,6}{2 \cdot 312} \right)^2 = 0,00041,$$

where  $U_{load\_max} = U_d$ . Then the pulse fill factor is

$$\gamma_{max} = 1 - \sqrt{K_R} = 1 - \sqrt{0,00041} = 0,98.$$

And load resistance is equal to

$$R_{load} = \frac{R_{\Sigma}}{K_R} = \frac{0,1}{0,00041} = 244 \Omega.$$

Find the value of maximum power as

$$P_{max} = \frac{U_d^2}{R_{load}} = \frac{312^2}{244} = 399 \text{ W},$$

Then source current is

$$I_{L\_av} = \frac{P_{max}}{\eta \cdot E} = \frac{399}{0,9 \cdot 12,6} = 35,2 \text{ A},$$

where  $\eta$  is the efficiency of the converter. Converters are classified by output power:

- low-power (1 – 100 W), they usually have an efficiency of about 0,7 – 0,8;
- average power (100 – 1000 W) – efficiency of about 0,9;
- high-power (over 1000 W) – efficiency of the order of 0,97 – 0,99.

Let's calculate the parameters for selecting the MOSFET transistor and diode. The MOSFET field-effect transistor is selected according to the maximum reverse voltage  $U_{DS}$  and the resistance in the conductive state  $R_{DS(on)}$ . Taking into account the safety factor, the range of which is equal to 1,5 – 2, the maximum reverse voltage on the transistor is equal to

$$U_{DS} = F_S \cdot U_d = 1,5 \cdot 312 = 468 \text{ V}.$$

The average value of the transistor current

$$I_{VT\_av} = \gamma \cdot I_{L\_av} = 0,98 \cdot 35,2 = 34,5 \text{ A}.$$

And amplitude of current pulsations

$$\Delta I_L = F_{rI} \cdot I_{L\_av} = 0,1 \cdot 35,2 = 3,52 \text{ A}.$$

Then the maximum value of the transistor current is

$$I_{L\_max} = I_{L\_av} + \Delta I_L = 35,2 + 3,52 = 38,72 \text{ A}.$$

The resistance in the conductive state is

$$R_{DS(on)} = \frac{U_{DS(on)}}{I_{L\_max}},$$

where  $U_{DS(on)}$  is the voltage on the transistor in the conductive state, it is usually equal to 1 V.

$$R_{DS(on)} = \frac{1}{38,72} = 0,026 \Omega.$$

The calculated parameters correspond to the transistor TK100L60W with a voltage of 600 V, a current of 100 A and a resistance in the conductive state of 18 m $\Omega$ .

The diode is selected according to the maximum reverse voltage  $U_{VD}$  and the average forward current  $I_{VD}$ . The maximum reverse voltage of the diode  $U_{VD}$  with the safety factor is equal to 500 V. The average diode current is

$$I_{VD\_av} = (1 - \gamma) \cdot I_{L\_av} = (1 - 0,98) \cdot 35,2 = 0,704 \text{ A.}$$

Taking into account the safety factor the average diode current is 2 A. The calculated parameters correspond to the diode SF28 with a voltage of 600 V and a current of 2 A. Also when choosing a diode and transistor, you must take into account the modulation frequency.

Find the value of choke inductance as

$$L = \frac{\gamma(1-\gamma) \cdot U_d}{\Delta I_L \cdot 2f_m} = \frac{0,98(1-0,98) \cdot 312}{3,52 \cdot 2 \cdot 1000} = 0,87 \text{ mH.}$$

Amplitude of output voltage ripples is

$$\Delta U_d = F_{rU} \cdot U_d = 0,05 \cdot 312 = 15,6 \text{ V.}$$

Capacitor capacity at the output

$$C = \frac{\gamma \cdot U_d \cdot T}{R_{load} \cdot \Delta U_d} = \frac{0,98 \cdot 312 \cdot 0,001}{244 \cdot 15,6} = 80,3 \text{ } \mu\text{F.}$$

Also to build a model in the window for setting the parameters of the semiconductor diode, you need:

- The dynamic resistance  $R_{on} (r_g)$ , which is  $r_g = 0,01 \text{ } \Omega$  in the considering example.
- The diode threshold voltage (forward voltage)  $V_f$ , which is  $V_f = 1,5 \text{ V}$  in the considering example.
- The snubber resistor and capacitance. We take their values equal to  $100 \text{ } \Omega$  and  $0,2 \text{ } \mu\text{F}$ , respectively.

In the window for setting the parameters of the transistor, you need:

- FET resistance  $R_{on} (r_{DS(on)})$ , which is  $r_{DS(on)} = 0,018 \text{ } \Omega$  in the considering example.
- Internal diode resistance  $R_d$ , which is  $r_g = 0,017 \text{ } \Omega$  in the considering example.
- Internal diode forward voltage  $V_f (V_{SD})$ , which is  $V_{SD} = 1,7 \text{ V}$  in the considering example.
- The snubber resistor and capacitance. We take their values equal to  $100 \text{ } \Omega$  and  $0,2 \text{ } \mu\text{F}$ , respectively.

### ***3.2.2 Simulation of the pulse converters schemes***

Simulation of the pulse converters schemes is performed in the Matlab / Simulink package. Version 2016b is used in this teaching aid.

### 3.2.2.1 Model building steps

- Open a new Simulink model window, save it.
- From the Simulink library we take the “powergui” block and set parameters in its parameters window as shown in fig. 1.10.

- From the Simulink library we take all the necessary blocks for modeling the scheme. It is “DC Voltage Source” (fig. 3.7), “Mosfet” (fig. 3.8), “Diode” (fig. 1.13) and “Series RLC Branch” for modeling the load, capacitance and inductance of the pulse converters schemes (fig. 1.14).

- We connect the blocks according to the type scheme of the pulse converters and in their parameters windows set the calculated parameters of the scheme elements (paragraph 3.2.1).

- Also, for the operation of mosfet transistors, a control pulse shaper is needed, which will generate pulses with a given modulation frequency and pulse filling factor. To implement it in Matlab, we use the "Pulse Generator" block, the parameters window of which is shown in figure 3.9. The output of the block "Pulse Generator" is connecting to the G input of the block "Mosfet".

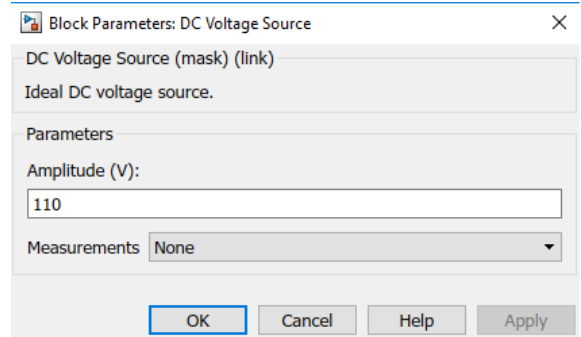


Figure 3.7. – Parameters window of the “DC Voltage Source” block

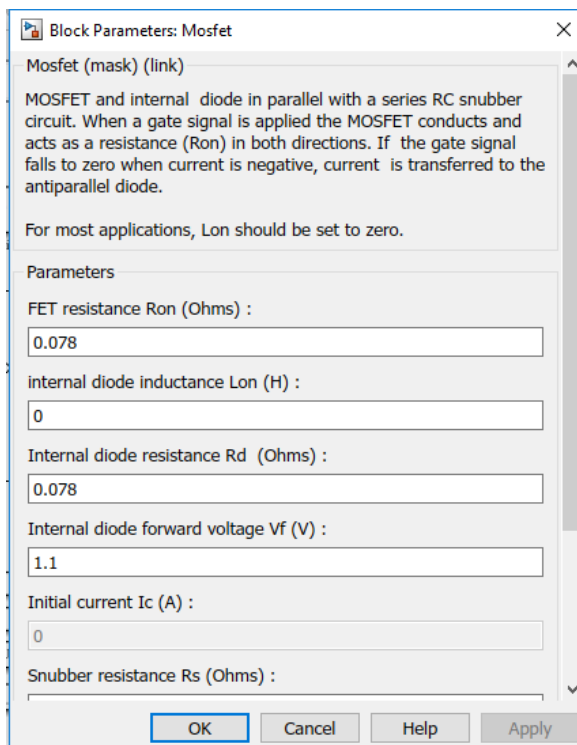


Figure 3.8. – Parameters window of the “Mosfet” block

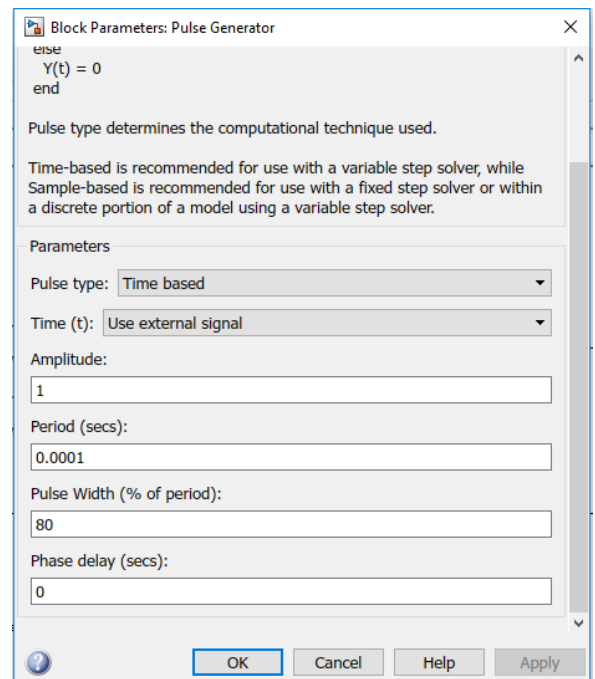


Figure 3.9. – Parameters window of the “Pulse Generator” block

- From the library we take blocks for measuring voltage and current. We connect these blocks to a scheme for the sake of measuring the current and voltage of the network, current and voltage of the load and reverse voltage and forward current of the transistor. "Voltage

Measurement" block is connecting in parallel, and the "Current Measurement" block is connecting in series.

- From the library we take a "Scope" block for studying the shape of voltages and currents in the scheme. In the dialog window set the required parameters (fig. 1.15 a,b,c). Connect the information ports of the "Voltage Measurement" and the "Current Measurement" blocks to the input ports of the "Scope" block.

- Start the simulation by clicking on the "Run" button. You need to evaluation of the correct scheme operation by the form of currents and voltages. If there is a strong discrepancy between the theoretical timing diagrams of currents and voltages with the simulation results, then check the calculations and the model scheme.

### *3.2.2.2 The investigate of the voltages and currents forms*

Timing diagrams of the scheme voltages and currents need be recorded in a steady mode of model operation during for 0,08 s. Diagrams of mains current and voltage, load current and voltage, reverse voltage and forward current of the semiconductor switches (diode and transistor) are fixing. Timing diagrams of the semiconductor switches (diode and transistor) need be recorded in a steady mode of model operation during for four period of the modulation frequency.

## **3.3 Report preparation**

The report on the work performed should contain: the purpose of the work, the scheme of the experiment, the calculation of the scheme elements, the datasheet of the selected scheme elements, the Matlab-model of the scheme, tables and graphs obtained as a result of the experiment, as well as time diagrams in accordance with the task of performing the work and their brief analysis.

## **3.4 Self-test questions**

1. Explain the operation of the investigated step-down pulse converter scheme.
2. Explain the operation of the investigated step-up pulse converter scheme.
3. Features of operation and application of the MOSFET field-effect transistor.
4. What are the parameters for choosing the MOSFET field-effect transistor?
5. What are the parameters for choosing a diode?
6. What is the purpose of inductance in buck and boost PWP?
7. Areas of application step-down and step-up pulse converters schemes.
8. What are the disadvantages of the circuits of the studied pulse converters?
9. Explain the shape of the mains current and the mains voltage in pulse converters schemes.
10. Explain the shape of load voltage and current in pulse converters schemes.
11. Explain the waveform of voltage and current diode in pulse converters schemes.

12. Explain the waveform of voltage and current transistor in pulse converters schemes.

## CHAPTER NO. 4

### AUTONOMOUS VOLTAGE INVERTER

*The purpose of the work* is to consolidation of theoretical knowledge by detailed study of electrical processes in an autonomous voltage inverter in steady state and transient modes.

#### 4.1 Basic theoretical thesis

*Inversion* is the processes of converting DC to AC. Devices that implement this process are called *inverters*. Inverters are dependent (driven by the network) and autonomous. If the inverter transmits energy from the DC network to the AC network, the frequency and voltage in which are already set by other generators, it is called *dependent* (slave).

Inverters that operate on a load that has no other generators are called *stand-alone*. In them, the current is switched by a special device, the frequency of the output current (voltage) is determined by the frequency of the control pulses.

Areas of use of stand-alone inverters:

- to supply AC consumers in installations where a rechargeable or solar battery is used as the main or backup energy source;
- in the frequency electric drive of alternating current as a part of the frequency converter with an intermediate link of a direct current;
- in electrical technology as a source of high frequencies AC;
- in the power industry with non-traditional power supplies as active filters, reactive power compensators and distortion power.

Depending on the construction of the circuit there are single-phase, two-phase, three-phase and multiphase inverters, depending on the number of voltage levels of the DC source two - and multilevel inverters.

In the general case, the structure of the inverter (fig. 4.1) consists of the following elements:

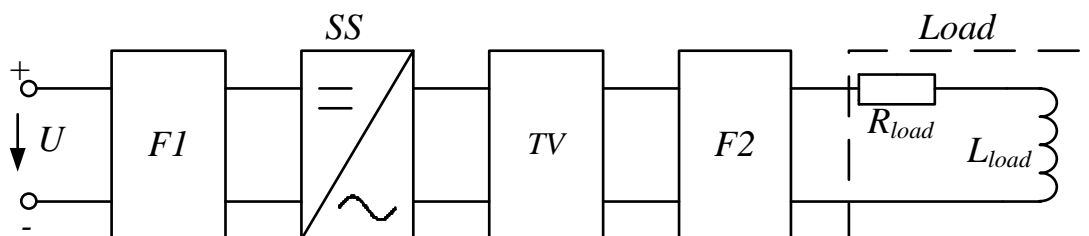


Figure 4.1 – The structure scheme of the stand-alone inverter

- input filter (F1), which provides the required quality of input current (voltage), providing the energy source with properties that ensure the normal operation of the switching scheme, as well as reduces the negative impact on the source and other energy consumers;

- switching scheme (SS) in the future is directly the inverter, which, along with the conversion, provides control of the parameters of alternating current - frequency and amplitude. The output signal, of course, has the character of pulses, the fronts of which have a significant steepness and, as a consequence, a complex harmonic spectrum. It negatively affects the work of the energy consumer, and also leads to significant additional costs during the transmission of energy over distances;

- output transformer (TV) to match the output voltage with the consumer voltage, which can be connected directly to the circuit of the switch. In some cases, it is used to obtain a multilevel output voltage curve;

- output filter (F2), which ensures the quality of the output voltage at the desired level for transmission and consumption. The capacitance of the current inverters is necessary for the normal operation of the circuit. Note that not all of these elements are required in a particular inverter circuit. In a voltage inverter, F1 and SS are usually required.

The stand-alone voltage inverter (VI) generates a voltage in the load, and the shape of the current is determined by the load parameters. The VI circuit uses fully controlled switches: transistors or thyristors that are switching is corresponding with control system. Thyristors that do not turn off in corresponding with control system, used in combination with forced switching units with a pre-charged capacitor.

Two-level VIs are powered by a DC source with two voltage levels (0,  $U$ ).

Features of VI:

1. The DC source operates in the EMF source mode. To do this, a capacitor of sufficiently large capacity is connected in parallel to the input of the VI, which gives the source the properties of the voltage generator (the voltage at the input of the VI is constant). The switches of the scheme are switching the source and are changing the value and direction of the load voltage. The input current is changed by a jump, which does not imply the presence of inductance at the input of the VI. To eliminate the influence of the inductance of the input circuits, the filter capacitor is installed directly next to the VI switches.

2. The circuit of the valve switch must have two-way conductivity, which provides energy exchange between the active-inductive load and the source (capacitor at the input, if you use a rectifier with one-way conductivity).

#### ***4.1.1 Single-phase bridge voltage inverter***

The power circuit of a single-phase autonomous voltage inverter is presented in fig. 4.2. This circuit next to the bridge on the transistors  $VT1 - VT4$  also contains a reverse bridge on the diodes  $VD1 - VD4$ , which switches the load current at intervals when the voltage and load current have opposite directions (with active-inductive load current is delayed on  $\varphi$  angle from voltage).

Let us first consider the operation of the circuit in the case of the formation of a rectangular voltage, when modulation is absent. In this case, the control pulses on the pairs of transistors  $VT1, VT4$  and  $VT2, VT3$  are given in antiphase, their du-

ration is half the period of the output frequency. With the opening of transistors  $VT1$  and  $VT4$ , the polarity of the load voltage is positive, the current  $i_{load} = i_{VT}$  slowly increases, which is due to the inductance of the load (fig. 4.3). In this case, energy is transferred to the load (active power), and also accumulates in the magnetic field of the load (reactive power). At time  $t_2$  control pulses from transistors  $VT1$ ,  $VT4$  are removed and then with some delay sufficient to turn-off  $VT1$ ,  $VT4$  (to avoid short circuits source with simultaneous switching on  $VT1$ ,  $VT2$  and  $VT3$ ,  $VT4$ ), are fed to  $VT2$ ,  $VT3$ . With the closure of transistors  $VT2$  and  $VT3$ , the load current continues to flow in the same direction due to the action of EMF self-induction  $e_L$  in the load (energy that has been accumulated in the magnetic field). This opens the reverse diodes  $VD2$  and  $VD3$  (transistors  $VT2$ ,  $VT3$  are closed until  $t_3$ ) and the current  $i_d$  consumed from the source changes direction to the opposite.

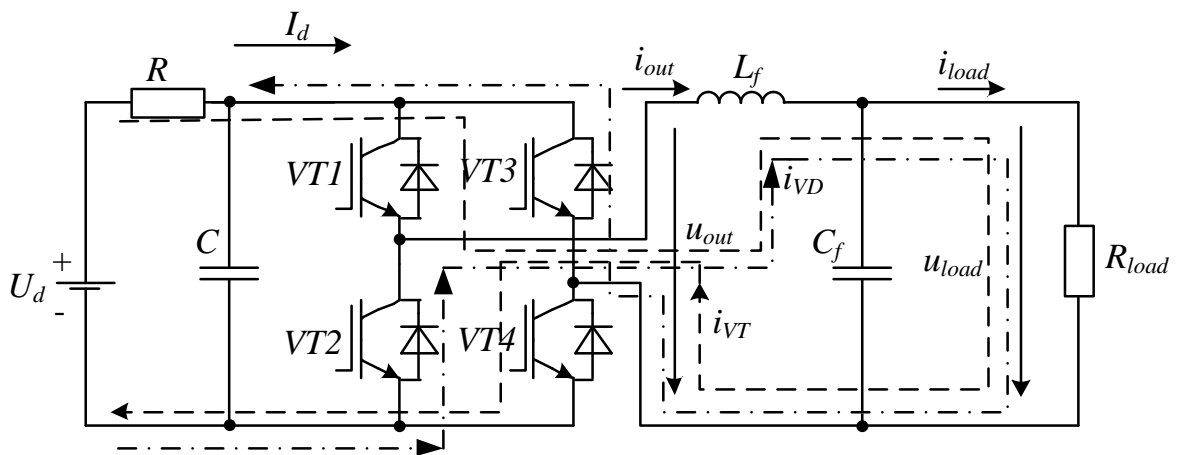


Figure 4.2 – The single-phase autonomous voltage inverter

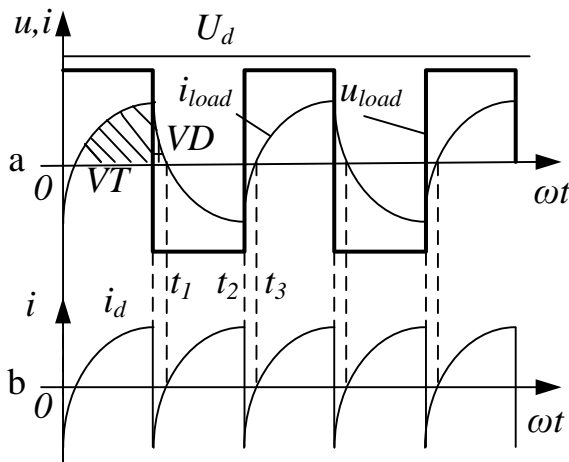


Figure 4.3 – The work diagrams single-phase VI

the polarity of  $u_{load}$  changes to negative. The current  $i_{load} = i_{VD}$  slowly decreases to zero. After the transition of the load current through zero, the next pair of transistors  $VT2$  and  $VT3$  opens, the direction of the load current  $i_{load}$  changes to the opposite. The current  $i_d$  at the input of the VI is alternating and pulsating. At intervals where the transistors are open (active power is consumed from the source), the current is positive. With the opening of the reverse diodes, the direction of the current  $i_d$  changes to the opposite because the energy accumulated in the load is returned to the source. As a rule, the source is made of diodes or thyristors and has a one-way conductivity, so the energy goes to charge the capacitor. The average value of the current

consumed by the VI from the source  $i_d$  is positive and the power consumed is  $P_d = U_d \cdot I_d > 0$ .

The amplitude and effective value of the fundamental harmonic of the output voltage, which is determined by decomposition into a Fourier series, is equal to:

$$U_{load\_max(1)} = \frac{4}{\pi} U_d, \quad U_{load(1)} = 0,9 U_d. \quad (4.1)$$

#### 4.1.2 Control system of autonomous voltage inverter

At this time, *pulse width modulation* is the main means of regulating the initial parameters of autonomous inverters. With PWM, the initial alternating voltage of the switch consists of pulses that alternate with an increased frequency relative to the fundamental frequency. For the type of modeling pulses, unipolar (fig. 4.4, a, b) and bipolar (fig. 4.4, c) PWM are distinguished. With *unipolar PWM*, an additional zero voltage level appears when the output circuit is short-circuited, and the input circuit is off.

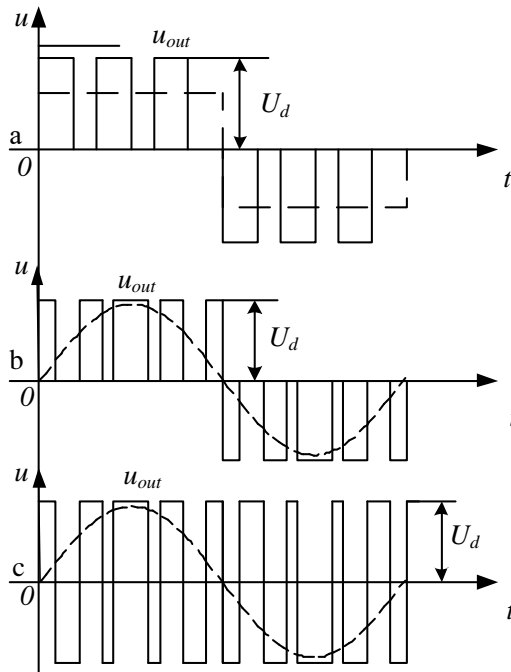


Figure 4.4 – Curves of voltage formation using PWM

Therefore, in the inverter with PWM, a structure of a step-down pulse-width converter (PWP) arises. However, due to the need to form two half-periods of the output voltage, three levels of the output voltage are used:  $+U_d, 0, -U_d$ . With *bipolar PWM*, only two output voltage levels alternate, which is easier to implement. At each PWM period, the average voltage and ripple can be distinguished. The collection of averages is called the envelope. Due to the inertia of the output circuit, the current in the load is mainly set by the envelope. By changing the duration of the modeling pulses, it can be adjusted within wide limits, starting from zero.

The possibility of wide-range regulation of the initial voltage by internal means is one of the most important advantages of AVI. By the shape of the envelope, rectangular (fig. 4.4, a) and sinusoidal PWM are distinguished (fig. 4.4, b, c). The content of low-frequency harmonics with sinusoidal PWM is less.

A single-phase bridge switch allows for all types of PWM. Levels  $+U_d, -U_d$  are realized, as in an unregulated inverter, by pairs of switches  $VT1, VT4$  and  $VT2, VT3$ . To get a zero level, you must simultaneously turn on a pair of switches  $VT1, VT3$  or  $VT2, VT4$ . To ensure an even load of the switches, the short-circuited pairs alternate.

Unipolar PWM has several advantages over bipolar PWM, namely:  
 - higher efficiency factor (efficiency);

- lower voltage ripple at the VI output, which ensures the use of a lighter output filter.

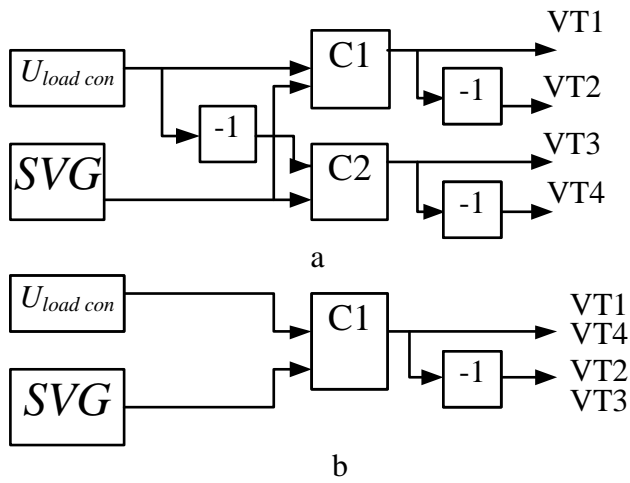


Figure 4.5 – Block diagram of the control system of the voltage inverter

the reference signal of the control signal  $U_{con}$  and with the antiphase signal of the control  $-U_{con}$ . If  $u_{con} > u_{ref}$ , then  $VT1$  opens, if  $u_{con} < u_{ref}$ , then  $VT2$  opens, similarly – if  $-u_{con} > u_{ref}$ , then  $VT3$  opens, if  $-u_{con} < u_{ref}$ , then  $VT4$  opens.

#### 4.1.2.2 Operation of the VI control system with bipolar PWM

Formed in the  $U_{load\ con}$  block, the  $u_{con}$  control signal is fed to two comparators  $C1$ . The sawtooth voltage generator (SVG) generates a reference signal  $U_{ref}$ , which is also fed to the comparator. The comparator is compared with the reference signal of the control signal  $U_{com}$ . If  $u_{con} > u_{ref}$ , then  $VT1$ ,  $VT4$  opens, if  $u_{con} < u_{ref}$ , then  $VT2$ ,  $VT3$  opens.

## 4.2 Work order

### 4.2.1 Calculation of the voltage inverter scheme

Calculate the voltage inverter scheme according to the task variant given in appendix D.1. Select the main elements of the scheme. From the datasheets of the semiconductor devices (transistor) take the characteristics necessary for modeling the scheme in the Matlab / Simulink package. All actions should be performed according to the calculation example below.

The task for the calculation in accordance with appendix D.1 is given in table 4.1, and the scheme of the voltage inverter is shown in figure 4.1.

Let's calculate the circuit for an active load.

#### 1. Calculation of load parameters

Converters are classified by output power:

- low-power (1 – 100 W), they usually have an efficiency of the order of 0,7 – 0,8;

- average power (100 – 1000 W) – efficiency of about 0,9;

- high-power (over 1000 W) – efficiency of about 0,97 – 0,99.

The power consumed from the source is equal to:

$$P_d = \frac{P_{load}}{\eta} = \frac{1000000}{0,99} = 1010101 \text{ W},$$

where  $\eta$  is the efficiency of the converter.

Input current of voltage inverter is

$$I_d = \frac{P_d}{U_d} = \frac{1010101}{3000} = 337 \text{ A}.$$

Then the load current is equal to:

$$I_{load\_max} = I_d = 337 \text{ A}.$$

Let's find the load resistance from the next expression:

$$R_{load} = \frac{P_{load}}{I_{load}^2} = \frac{1000000}{337^2} = 8,8 \Omega.$$

Table 4.1 – Task for the calculation of the voltage inverter

Load power	Input voltage	Load voltage frequency	Modulation frequency	PWM type	Permissible content of higher harmonics	
					$I_h^*$	$U_h^*$
$P_{load}$ , kW	$U_d$ , V	$f_{load}$ , Hz	$f_{mod}$ , Hz			
1000	3000	250	2000	Bipolar	0,3	0,1

## 2. Calculation of semiconductor switch parameters

In converters of high power, which use pulse-width modulation with a frequency of up to 5 kHz, it is advisable to use insulated gate bipolar transistor (IGBT) as a semiconductor switch. The selection of the IGBT is based on the maximum reverse voltage  $U_{CE}$  and the maximum forward current  $I_C$ . The maximum reverse voltage is

$$U_{CE} = U_d = 3000 \text{ V}.$$

The reverse voltage safety factor is 1,5 – 2, the maximum reverse voltage transistor taking into account the safety factor is 6000 V.

Maximum forward current of the IGBT in the conducting state

$$I_C = I_d = 337 \text{ A}.$$

The maximum forward current of the IGBT safety factor is 1,5 – 2, account the safety factor is 675 A.

For maximum reverse voltage transistor 6000 V and maximum forward current 675 A, choosing an IGBT transistor according to the ABB catalog. In the datasheet of the 5SNA 0750G650300 we find

$$\left. \begin{aligned} V_{CE} &= 6500 \text{ V}, \\ R_{(on)} &= \frac{V_{CEsat}}{I_C} = \frac{3,9}{750} = 5,2 \cdot 10^{-3} \Omega, \\ I_C &= 750 \text{ A}, \\ V_f &= 3,4 \text{ V}. \end{aligned} \right\} .$$

### 3. Calculation of the output LC filter

At the output of the VI, the main filter element or often the only one is the choke. The filter inductance is based on the permissible harmonic current in the load  $I_h$ . Assuming that all the voltage  $U_h$  is applied to the choke, we get:

$$\omega_{mod} L_f = \frac{U_h}{I_h},$$

where  $\omega_{mod}$  is the frequency of the filtered harmonic (modulation frequency).

If the fundamental harmonic of the load current is the first  $I_1$ , then they are usually set by the permissible content of higher harmonics in fractions of the first harmonic  $I_h^*$ :

$$I_h = I_h^* \cdot I_1 = 0,3 \cdot 337 = 101,1 \text{ A}.$$

$$U_h = \frac{P_{load}}{I_{load}} = \frac{10^6}{337} = 2967 \text{ V}.$$

$$L_f = \frac{U_h}{I_h 2\pi f_{mod}} = \frac{2967}{2\pi \cdot 101,1 \cdot 2 \cdot 10^3} = 2,3 \cdot 10^{-3} \text{ H}.$$

In the event that the load resistance is high, then an additional capacitor can be used. Assuming that all the current  $I_h$  flows through the capacitor, we obtain the required capacitance from the condition:

$$\omega_{mod} C_f = \frac{I_h}{U_h},$$

where  $U_h$  is the permissible content of the filtered harmonic in the voltage across the load.

If the fundamental harmonic is first

$$U_h = U_h^* \cdot U_1 = 0,1 \cdot 2967 = 296 \text{ V}.$$

$$C_f = \frac{I_h}{U_h 2\pi f_{mod}} = \frac{337}{2\pi \cdot 296 \cdot 2 \cdot 10^3} = 90 \cdot 10^{-6} \text{ F}$$

The control signal  $U_{load\ con}$  is

$$U_{load\ con} = U_{load\ max}^* \sin 2\pi f_{load} t = 0,99 \sin 2\pi \cdot 250t,$$

$$U_{loadmax}^* = \frac{U_{loadmax}}{U_d} = \frac{2967}{3000} = 0,99,$$

where  $t$  is time;

$f_{load}$  is the frequency of the load voltage.

#### 4.2.2 Simulation of the voltage inverter schemes

Simulation of the voltage inverter schemes is performed in the Matlab / Simulink package. Version 2016b is used in this teaching aid.

##### 4.2.2.1 Model building steps

- Open a new Simulink model window, save it.
- From the Simulink library we take the “powergui” block and set parameters in its parameters window as shown in fig. 1.10.

- From the Simulink library we take all the necessary blocks for modeling the scheme. It is “DC Voltage Source” (fig. 3.7), “IGBT/Diode” (fig. 4.6) and “Series RLC Branch” for modeling the load, capacitance and inductance of the voltage inverter schemes (fig. 1.14).

- We connect the blocks according to the scheme (fig. 4.1) and in their parameters windows set the calculated parameters of the scheme elements (paragraph 4.2.1).

- Also we need to build a model of a control system that will issue control pulses to the control electrodes of IGBT transistors. Let us consider in more detail the modeling of the control system for a single-phase voltage inverter in accordance with the block diagram in fig. 4.5, a, b. The matlab models of the control systems with bipolar and unipolar PWM are shown on fig. 4.7, a and fig. 4.7, b respectively.

The sawtooth (reference) voltage generator SVG (fig. 4.5) is “Repeating Sequence” block (fig. 4.7), in parameters window of it we stand modulation frequency; the control voltage  $u_{con}$  (fig. 4.5) is generated by blocks system of “Fcn”, “U\_load\_max\*”, “f\_load” and “t” (fig. 4.7); the comparators C1 and C2 (fig. 4.5) are represented by the “Relation Operator” blocks (fig. 4.7) and the pulse shaper is consist of other blocks that shown on figure 4.7. After the control system has been built, it is necessary to connect the Q outputs to the G inputs of the "IGBT/Diode" blocks.

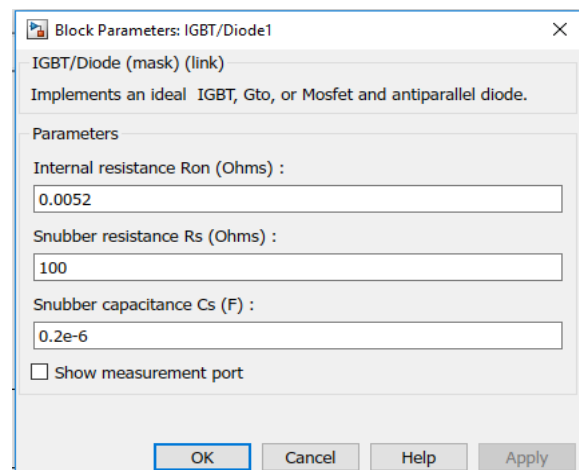


Figure 4.6. – Parameters window of the “IGBT/Diode” block

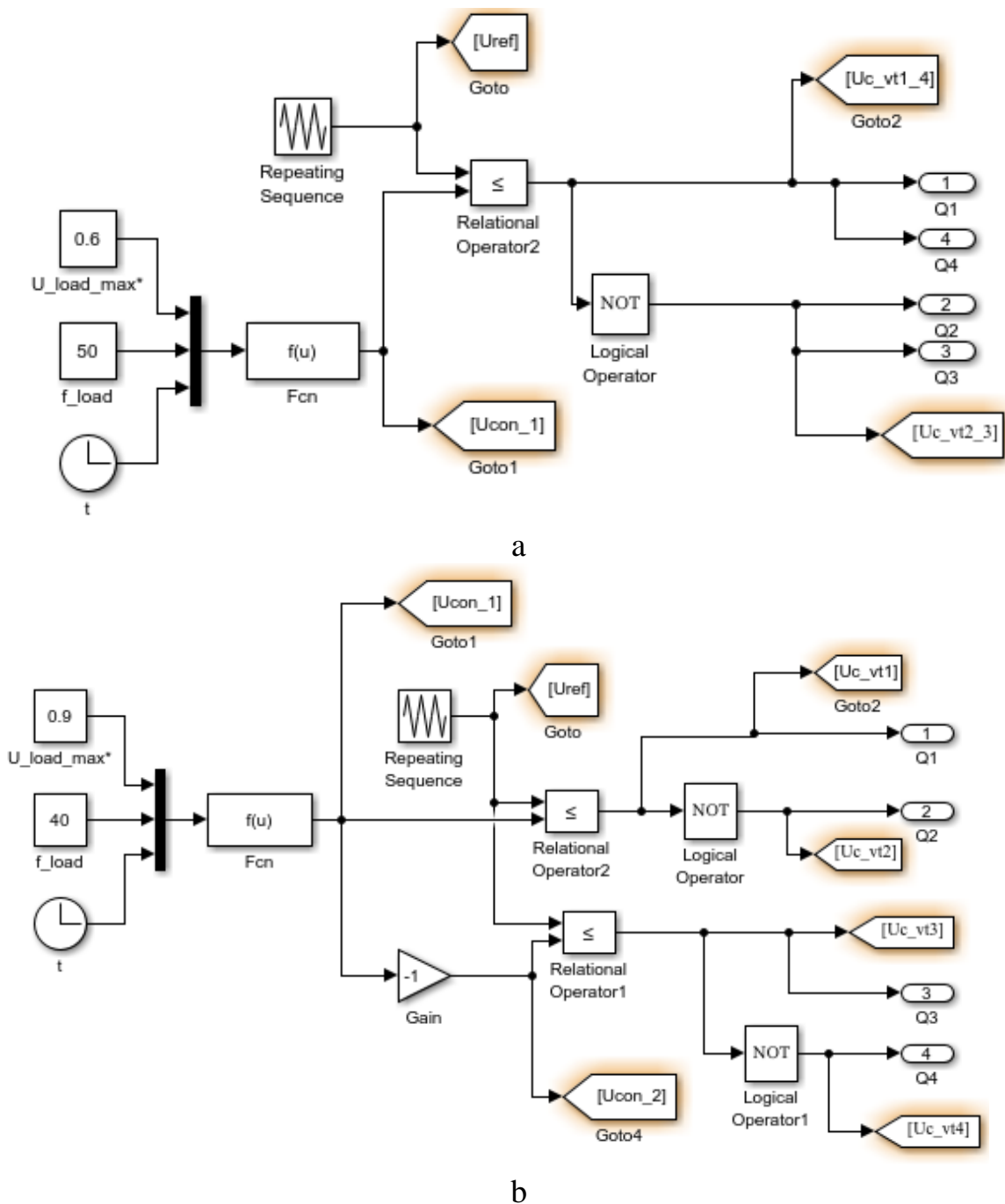


Figure 4.7 – Matlab models of the control systems of voltage inverter:

- a) Bipolar PWM;
- b) Unipolar PWM

- From the library we take blocks for measuring voltage and current. We connect these blocks to a scheme for the sake of measuring the current and voltage of the network, current and voltage of the load and reverse voltage and forward current of the transistor. "Voltage Measurement" block is connecting in parallel, and the "Current Measurement" block is connecting in series.

- From the library we take a "Scope" block for studying the shape of voltages and currents in the scheme. In the dialog window set the required parameters

(fig. 1.15 a,b,c). Connect the information ports of the "Voltage Measurement" and the "Current Measurement" blocks to the input ports of the "Scope" block.

- Start the simulation by clicking on the "Run" button. You need to evaluate the correct scheme operation by the form of currents and voltages. If there is a strong discrepancy between the theoretical timing diagrams of currents and voltages with the simulation results, then check the calculations and the model scheme.

#### *4.2.2.2 The investigate of the voltages and currents forms*

Timing diagrams of the scheme voltages and currents need be recorded in a steady mode of model operation during for 0,08 s. Diagrams of mains current and voltage, load current and voltage, reverse voltage and forward current of the semiconductor switches (transistor) are fixing. Timing diagrams of the semiconductor switches (transistor) need be recorded in a steady mode of model operation during for four period of the modulation frequency.

### **4.3 Report preparation**

The report on the work performed should contain: the purpose of the work, the scheme of the experiment, the calculation of the scheme elements, the datasheet of the selected scheme elements, the Matlab-model of the scheme, tables and graphs obtained as a result of the experiment, as well as time diagrams in accordance with the task of performing the work and their brief analysis.

### **4.4 Self-test questions**

1. Explain the operation of the investigated scheme.
2. Explain the operation of the investigated voltage inverter with unipolar PWM.
3. Explain the operation of the investigated voltage inverter with bipolar PWM.
4. What are the parameters for choosing the IGBT transistor?
5. Features of operation and application of the IGBT transistor.
6. What is the purpose of reverse diodes?
7. Areas of application voltage inverter schemes.
8. What are the disadvantages of the circuits of the studied converter?
9. Explain the shape of the mains current and the mains voltage in scheme.
10. Explain the shape of load voltage and current in scheme.
11. Explain the waveform of voltage and current diode in scheme.
12. Explain the waveform of voltage and current transistor in scheme.

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## APPENDIX

### Appendix A.1 – Task of the chapter No. 1 “Uncontrolled rectifier with smoothing filters”

Variant	Source		Rectifier Scheme	Load		Filter	
	$U_s$ , V	$f_s$ , Hz		$P_d$ , W	$U_d$ , V	$K_{r\ out}$ , %	$K_{sm}$
1	220	50	Single-phase Half wave	10	12	2	5
2	220	50	Single-phase full wave mid-point	30	14	5	10
3	220	50	Single-phase full wave bridge	50	24	8	20
4	220	50	Single-phase Half wave	100	36	10	50
5	220	50	Single-phase full wave mid-point	200	42	2	100
6	110	60	Single-phase full wave bridge	200	12	5	5
7	110	60	Single-phase Half wave	100	14	8	10
8	110	60	Single-phase full wave mid-point	50	24	10	20
9	110	60	Single-phase full wave bridge	30	36	2	50
10	110	60	Single-phase Half wave	10	42	5	100
11	220	50	Single-phase full wave mid-point	200	12	5	5
12	220	50	Single-phase full wave bridge	100	14	8	10
13	220	50	Single-phase Half wave	50	24	10	20
14	220	50	Single-phase full wave mid-point	30	36	2	50
15	220	50	Single-phase full wave bridge	10	42	5	100
16	110	60	Single-phase Half wave	10	12	2	5
17	110	60	Single-phase full wave mid-point	30	14	5	10
18	110	60	Single-phase full wave bridge	50	24	8	20
19	110	60	Single-phase Half wave	100	36	10	50
20	110	60	Single-phase full wave mid-point	200	42	2	100

## Appendix A.2 – External characteristic

Filter type	Load resistance	Average rectified voltage	Average rectified current
	$R_{load}, \Omega$	$U_d, V$	$I_d, A$
Without filter			
C-filter			
L-filter			
LC-filter			

**Appendix B.1** – Task of the chapter No. 2 “Controlled rectifier”

Variant	Source		Rectifier Scheme	Load		
	$U_s$ , V	$f_s$ , Hz		$P_{d\,nom}$ , W	$U_{d0}$ , V	$F_P$
1	220	50	Single-phase full wave mid-point	50	12	0,95
2	220	50	Single-phase full wave bridge	80	14	0,9
3	220	50	Single-phase Half wave	100	24	0,85
4	220	50	Single-phase full wave mid-point	200	36	0,98
5	220	50	Single-phase full wave bridge	300	42	0,95
6	110	60	Single-phase Half wave	100	12	0,9
7	110	60	Single-phase full wave mid-point	100	14	0,85
8	110	60	Single-phase full wave bridge	200	24	0,98
9	110	60	Single-phase Half wave	350	36	0,9
10	110	60	Single-phase full wave mid-point	400	42	0,85
11	220	50	Single-phase full wave bridge	50	12	0,98
12	220	50	Single-phase Half wave	100	14	0,95
13	220	50	Single-phase full wave mid-point	200	24	0,9
14	220	50	Single-phase full wave bridge	300	36	0,85
15	220	50	Single-phase Half wave	350	42	0,98
16	110	60	Single-phase full wave mid-point	50	12	0,95
17	110	60	Single-phase full wave bridge	100	14	0,9
18	110	60	Single-phase Half wave	200	24	0,85
19	110	60	Single-phase full wave mid-point	300	36	0,9
20	110	60	Single-phase full wave bridge	400	42	0,85

## Appendix B.2 – External characteristic

Load type	Control angel	Load resistance,	Average rectified voltage	Average rectified current
	$\alpha$ , electrical degrees	$R_{load}, \Omega$	$U_d, V$	$I_d, A$
Without inductive ( $R_{load} > 0, L_{load} = 0$ )	15			
	45			
With inductive ( $R_{load} > 0, L_{load} > 0$ )	15			
	45			

### Appendix B.3 – Control characteristic

Load type	Control angel	Average rectified voltage
	$\alpha$ , electrical degrees	$U_d$ , V
Without inductive ( $R_{load} > 0, L_{load} = 0$ )	15	
	30	
	45	
	60	
	75	
With inductive ( $R_{load} > 0, L_{load} > 0$ )	15	
	30	
	45	
	60	
	75	

**Appendix C.1** – Task of the chapter No. 3 “Pulse width converters”. Task for the calculation of the step-down pulse converter

Variant	Load			Source voltage	Ripple factor	Modulation frequency
	Nominal power	Nominal voltage	Load voltage regulation range			
	$P_{nom}$ , W	$U_{nom}$ , V	$\Delta U_{nom}$			
1	200	50	1,1-0,2	100	0,005	10000
2	500	75	1,2-0,4	190	0,009	5000
3	800	150	0,9-0,3	250	0,01	7000
4	1000	100	0,95-0,25	120	0,02	10000
5	600	400	1,15-0,5	510	0,007	15000
6	900	200	1,05-0,25	290	0,006	7000
7	700	10	0,85-0,3	12	0,002	8000
8	1000	12	0,8-0,35	24	0,015	9000
9	550	14	1,1-0,4	36	0,012	15000
10	350	24	0,9-0,3	42	0,008	10000
11	200	80	1,05-0,25	100	0,006	7000
12	500	150	0,85-0,3	190	0,002	8000
13	800	200	0,8-0,35	250	0,015	9000
14	1000	100	1,1-0,4	120	0,012	15000
15	600	450	0,9-0,3	510	0,008	10000
16	900	200	1,1-0,2	290	0,005	10000
17	700	9	1,2-0,4	12	0,009	5000
18	1000	14	0,9-0,3	24	0,01	7000
19	550	24	0,95-0,25	36	0,02	10000
20	350	36	1,15-0,5	42	0,007	15000

**Appendix C.2** – Task of the chapter No. 3 “Pulse width converters”. Task for the calculation of the step-up pulse converter

Variant	Load voltage	Source voltage	Ripple factor		Modulation frequency	Equivalent resistance
			Voltage	Current		
	$U_d, V$	$E, V$	$F_{rU}$	$F_{rI}$	$f_m, Hz$	$R_{\Sigma}, \Omega$
1	100	12	0,005	0,2	1000	0,1
2	312	24	0,009	0,1	5000	0,05
3	24	5	0,01	0,15	7000	0,2
4	42	9	0,02	0,05	1000	0,3
5	312	32	0,007	0,17	1500	0,15
6	200	12	0,006	0,2	7000	0,06
7	250	24	0,002	0,1	4000	0,12
8	36	5	0,015	0,15	3000	0,09
9	120	9	0,012	0,05	1500	0,05
10	300	32	0,008	0,17	1000	0,2
11	100	12	0,006	0,2	7000	0,1
12	250	24	0,002	0,1	4000	0,05
13	24	5	0,015	0,15	3000	0,2
14	42	9	0,012	0,05	1500	0,3
15	300	32	0,008	0,17	1000	0,15
16	200	12	0,006	0,2	7000	0,06
17	312	24	0,002	0,1	4000	0,12
18	100	5	0,015	0,15	3000	0,09
19	200	9	0,012	0,05	1500	0,05
20	312	32	0,008	0,17	1000	0,2

**Appendix D.1** – Task of the chapter No. 4 “Autonomous voltage inverter”

Variant	Load power	Input voltage	Load voltage frequency	Modulation frequency	PWM type	Permissible content of higher harmonics	
	$P_{load}$ , kW	$U_d$ , V	$f_{load}$ , Hz	$f_{mod}$ , Hz		$I_h^*$	$U_h^*$
1	20	500	30	10000	Unipolar	0,01	0,03
2	50	200	50	5000	Bipolar	0,02	0,04
3	80	1200	150	3000	Unipolar	0,3	0,2
4	1000	6000	200	1000	Bipolar	0,2	0,1
5	60	600	200	15000	Unipolar	0,01	0,03
6	9	300	60	7000	Bipolar	0,02	0,02
7	70	1700	200	3000	Unipolar	0,1	0,15
8	1000	5000	250	2000	Bipolar	0,2	0,1
9	6	300	60	25000	Unipolar	0,01	0,03
10	10	700	30	15000	Bipolar	0,02	0,05
11	100	400	70	8000	Unipolar	0,01	0,02
12	280	350	40	5000	Bipolar	0,02	0,15
13	75	900	125	3000	Unipolar	0,3	0,1
14	10	200	200	1000	Bipolar	0,2	0,03
15	65	600	250	12000	Unipolar	0,01	0,05
16	300	800	60	7000	Bipolar	0,02	0,03
17	150	450	200	3000	Unipolar	0,1	0,04
18	20	700	250	2000	Bipolar	0,2	0,2
19	15	850	60	2500	Unipolar	0,01	0,1
20	9	550	30	10000	Bipolar	0,02	0,03

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з дисципліни «Power electronics and converter technology»  
для іноземних студентів електротехнічних спеціальностей**

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