Ministry of education and science of the Republic of Kazakhstan

A. Baitursynov Kostanay State University

Department of electrical engineering and physics

Y. Martyniuk

BASICS OF ELECTRONICS AND CIRCUIT DESIGN

Manual

Kostanay, 2019

UDC 621.38
LBC 32.85
M29

Author:
Yury Martyniuk, master of natural science, senior lecturer at the department of Electricity and Physics

Readers:
Telegina Oksana, head of the department of physical and technical disciplines, candidate of technical science
Koshkin Igor, head of the department of electricity and physics, candidate of technical science
Poezjalov Vladimir, docent, candidate of physics and mathematics science

Martyniuk Yu.
M29 Basics of electronics and circuit design: Learning-methodical manual in electronics for specialty 5B060400-Physics. – Kostanay: A. Baitursynov Kostanay State university, 2019. – 70 p.

ISBN 978-601-7597-29-0

The manual includes basic information about radio-electronic components, the main units of analog and digital electronics. Also, attention is paid to the issues of calculating the units of electronic devices, basic formulas with explanations are given. The manual includes schematic diagrams of the electronic devices, their principle of operation is considered in detail.

The manual is designed for students of specialty 5B060400-Physics. It can be used by teachers of higher educational institutions in the classes of "Basics of Electronics and Circuit Design" subject, as well as by students while preparing for classes or exams.

UDC 621.38
LBC 32.85
M29

Approved and recommended by the Learning-Methodology Council of A. Baitursynov Kostanai State university, 27.06.2019 year, Protocol № 4

Contents

Introduction

The widespread use of electronics in everyday life, science and technology, and the enormous interest shown by students in radio circuits, requires a sufficiently deep preparation of the future specialist - physicist in the field of radio engineering.

Modern electronics is the collective name of a number of areas of science and technology associated with the generation, transmission, reception, transformation and storage of information [1]. The main ones are radio engineering and electronics, but there are also optoelectronics and microelectronics and functional microelectronics, digital signal processing etc.

Electronics is not limited to electromagnetic oscillations of the radio frequency range. Shorter waves up to the gamma range are also used, so electronics has also become all-wave. The main task solved by electronic devices designer is the development of methods and devices for transmitting, receiving, processing and storing information transmitted using signals of different kind.

But despite the extremely widespread use of electronic devices, students often face various problems in the study of theoretical material. Mostly this happent due to insufficiently detailed coverage of these issues in the specialized literature. The proposed manual is intended to eliminate these shortcomings.

1 Drawings of circuit elements

1.1 Passive electronic components

Resistor is a passive element of electrical circuits having a certain constant or variable electrical resistance, intended for linear current-voltage conversion (and vice-versa), limiting current, and for absorption of electrical energy. Resistors are the most common elements of electronic circuits. A typical drawing of a resistor is shown in Figure 1.

Figure 1 – Resistor drawing

This drawing may be done with various elements (e.g., strokes within the rectangle indicating the maximum possible power dissipation of the resistor). The main parameters of a resistor are DC resistance, maximum dissipation power, and maximum working voltage. Commercially available resistors may have resistance from hundredths of ohms to several hundred gigaohms, the power dissipation from 125 mW to a megawatt (e.g., brake resistors used in diesel and electric locomotives).

The second most abundant element of electronic devices is a capacitor. A capacitor is a two-terminal element with a constant or variable value of capacitance and low conductivity (high DC resistance) which is used to store electric charge and electric energy. The capacitor is a passive electronic component. In the simplest design it consists of two plane electrodes, called plates, separated by a dielectric, the thickness of which is small compared with the dimensions of the plates. Practically used capacitors have many layers of foil plates and dielectric, rolled into a cylinder or a parallelepiped with rounded edges (due to winding). Drawing of a capacitor is shown in Figure 2.

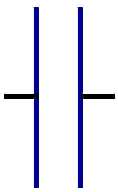


Figure 2 – Capacitor drawing

Commercially available capacitors use various organic materials (paper, polytetrafluoroethylene, polyester, and polypropylene), mineral (mica, ceramics) as a dielectric, there are also vacuum capacitors. Unfortunately, it's not so easy to make a capacitor of quite high capacitance (over tens of microfarads) of acceptable weight and size because of the low dielectric permittivity of convenient dielectric materials . Therefore, so-called electrolytic capacitors have been developed which use a thin layer of aluminum oxide on the aluminum surface as a dielectric which works in contact with a paper gasket, impregnated with acid solution. Such capacitors have a very large capacitance (up to one farad). However, they require constant polarizing voltage of the determined polarity for normal operation. Therefore, the polarity of the voltage which provides an electrolytic capacitor in “right” condition is usually shown in its drawing (sign "+") shown in figure 3.

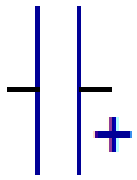


Figure 3 – Drawing of an oxide capacitor

Electrolytic capacitors are also called polar or oxide capacitors. Let’s note that while working with them when a reverse polarity is applied to an oxide capacitor the oxide dielectric breakdown occurs, sometimes accompanied by explosive depressurization of its housing (which produces a huge amount of the magic smoke).

1.2 Active electronic components

The most important and most often used semiconductor device is a diode. Diode in the most general case is an electronic element having different conductivities depending on the direction of electric current. The electrodes of the diode are called the anode and the cathode. If a forward voltage is applied to a diode (i.e., the anode has a positive potential relative to the cathode), the diode is open (the current is able to flow and it has a low resistance). In contrast, if a reverse voltage is applied to a diode (cathode potential is positive relative to the anode), the diode is closed (the resistance is large, a reverse current is small, and can be considered to be zero in many cases). The drawing of a semiconductor diode is shown in Figure 4.

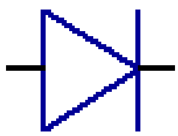


Figure 4 – Graphical symbol of a semiconductor diode

A special kind of semiconductor diodes is zener diode. Zener diode is a semiconductor diode operating at reverse bias in breakdown mode. Before the breakdown of a zener diode the current flow is minor (leakage current), and the resistance is very high. Upon the occurrence of the breakdown current through the Zener diode sharply rises, and its differential resistance falls to a value from a fraction of an ohm to several hundred ohms for the various devices. Therefore, in this mode the zener breakdown voltage is maintained at a predetermined level in a wide range of reverse currents. The main purpose of the zener is voltage stabilization. Graphical symbol of a zener diode is shown in Figure 5.

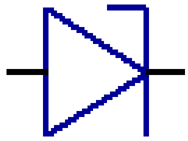


Figure 5 – Zener diode

LEDs are widely used as display and lighting devices. LED or light emitting diode is a semiconductor device with an electron-hole junction, generating optical radiation by passing electric current t in a forward direction. Light emitted by the LED is in the narrow range of the spectrum. The spectral range and wavelength of a LED emission depends on the physical properties of semiconductor used, for example, the bandgap width. Typical drawing of a LED is shown in Figure 6.

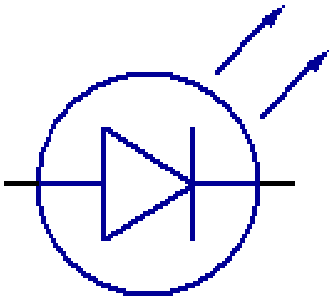


Figure 6 – LED drawing

The drawing of a LED includes a semiconductor diode symbol supplemented by the circle which is the case symbol and arrows - the symbol of optical radiation.

The main active element of electronic devices is a transistor. Transistor is a radio-electronic semiconductor component usually with three terminals, allowing an input signal to control the current in an electrical circuit. Typically a transistor is used for amplification, conversion and generation of electrical signals. Transistors are subdivided into Bipolar - in which both types of charge carriers - electrons and holes are used and field (or unipolar), in which there is only one type of charge carriers, and the control of current flowing through the device is carried out by means of an electric field . Figure 7 shows the drawing of an NPN structure bipolar transistor.

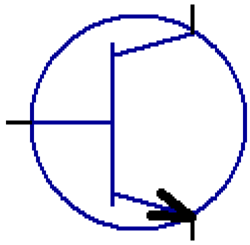


Figure 7 – Symbol of NPN bipolar transistor

Along with the NPN transistors there are PNP structure transistors (used less frequently). Drawing of this transistor is shown in Figure 8.

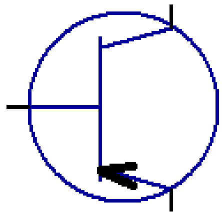


Figure 8 - Symbol bipolar transistor with pnp structure

The most common high-frequency amplifying device is channel field effect transistor. Drawing of a field effect transistor with p-channel type is shown in Figure 9.

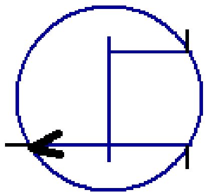


Figure 9 - Symbol of field effect transistor with p-channel type

There exist also field effect transistors with n-channel. Drawing of a field effect transistor with n-channel type is shown in Figure 10.

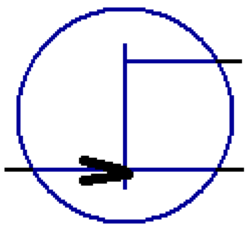


Figure 10 – Symbol of field effect transistor with n-channel type

Electronic devices use switches and of different design to turn the power on and off and select different operating modes. Switch is - a device having at least two fixed positions of the contacts (the "on" and "off") and able to change this position under the influence of external mechanical forces. Drawing symbol of a switch is shown in Figure 11.

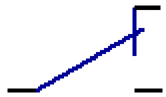


Figure 11 - Symbol of the switching contact

1.3 Questions

1. Which electronic components are passive?
2. Which electronic components are active?
3. Which properties of electronic components do you know?
4. Which physical measures are connected by the Ohm's law?
5. Where can be used Kirchoff law?
6. Which parameters of resistors do you know?
7. Which kinds of capacitors are used in electronics?
8. What is a semiconductor diode?
9. What is a voltage divider?

2 Power Supplies

2.1 Classification of power sources

Most electronic devices are used to convert or produce signals using the energy consumed from the power supply.

The power source is a device for supplying electric power to the electronic device.

Power supplies can be divided into primary and secondary ones.

Primary power supplies convert non-electric kinds of energy like thermal, chemical, mechanical, etc. into electrical energy.

Secondary power supplies are designed for converting various forms of electrical energy into others. They can step-up or step-down the voltage, change the current frequency, convert AC power to DC stabilized voltage.

In practice, the primary power supply is used only in cases when the device is impossible or unsafe to be connected to the mains (mostly - in hand-held devices). In the most cases we prefer to use secondary supplies that convert standard electrical network AC voltage into a voltage required for a given electronic device.

The vast majority of electronic devices require a constant voltage supply, which is significantly less than the nominal voltage of the electric network - 220V. For example, devices which use digital circuits generally use 3,3-5V supply voltage, analogue electronics devices require - 9-12V, at least - up to 50 V (e.g., low-frequency power amplifiers). In addition, often the supply voltage has some additional requirements: stability (remain unchanged over time, independent of the load current consumption), a certain voltage ripple (AC superimposed on DC).

2.2 Circuitry of secondary power supplies

Secondary power supplies consist of several components, each of which performs its own function. Consider a block diagram of a linear power supply (it is shown in Figure 12).

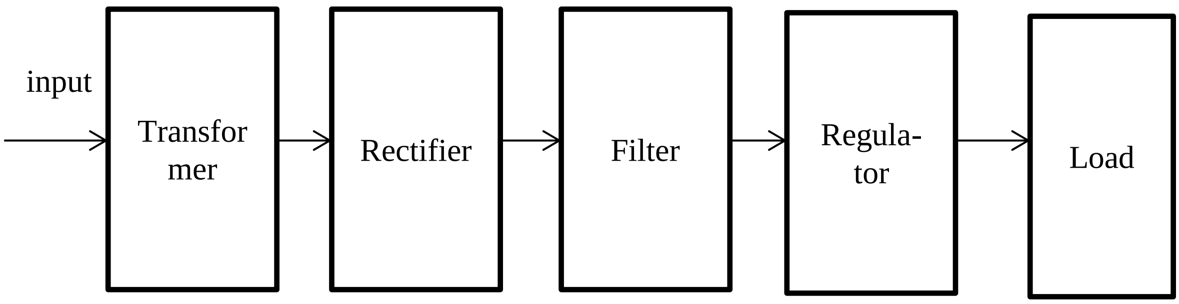


Figure 12 - The block diagram of a linear power supply

In this power supply input voltage is alternating. The transformer is used to reduce or step-down the voltage to the required value (less frequently used step-up transformers - in those cases when you want to get higher than network voltage). The rectifier converts the AC voltage taken from the secondary winding of the transformer into DC, ripple filter (usually just a capacitor) smoothes the rectified ripple voltage. Then, the obtained DC voltage is supplied to an optional unit - a regulator, which is needed only when the load sensitive to fluctuations of the supply voltage.

2.3 Rectifiers

A rectifier is a device for converting AC to DC. Most of rectifiers in modern electronics are made on the basis of semiconductor diodes of different types. The simplest type of rectifier is a half-wave rectifier. It contains only one diode. Such rectifier is shown in Figure 13.

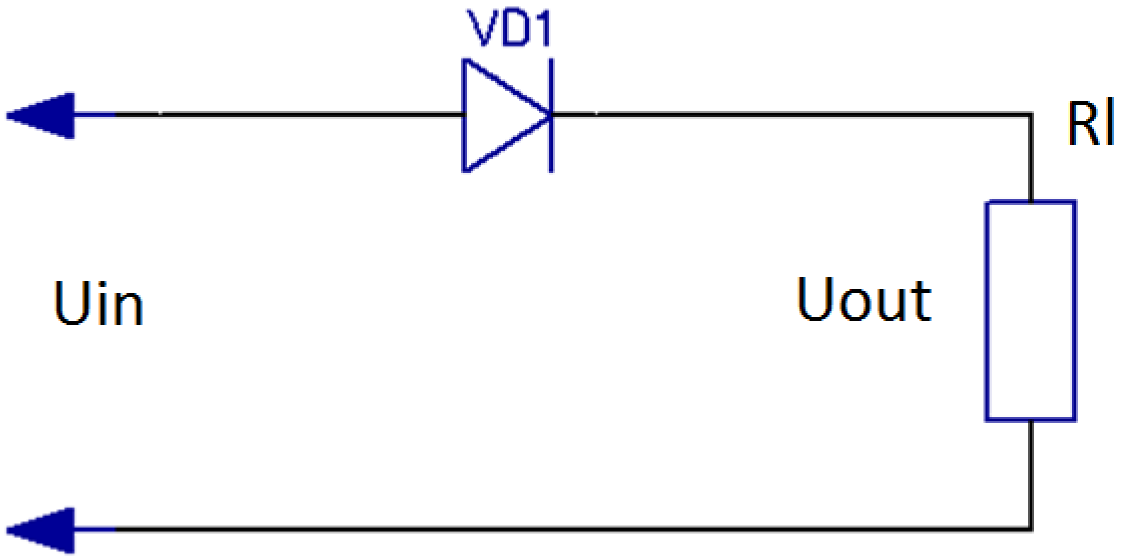


Figure 13 - Schematic diagram of a half-wave rectifier.

The half-wave rectifier works as follows: When the upper input terminal is positive, and the bottom - is negative, the diode is open because its anode is more positive than the cathode. The voltage from the input terminal passes freely the load. When changing the input voltage polarity the diode closes and does not pass negative half cycles of the input voltage to the load. Thus, the upper load terminal is always positive.

The operation of this rectifier illustrates the graph shown in Figure 14.

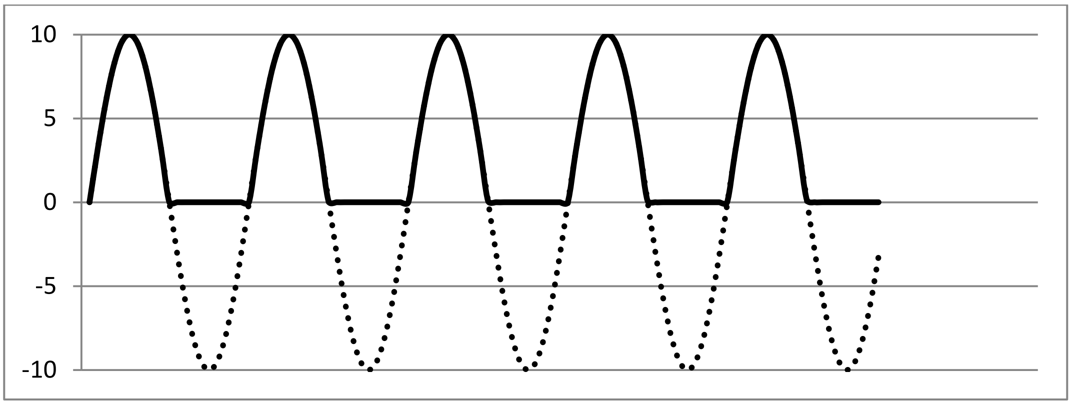


Figure 14 - Working diagram of a half-wave rectifier

The dotted line shows the AC input voltage, the solid - output. As it can be seen, the load uses only the positive half-cycles of the AC voltage, which is the main drawback of this type of rectifier: only every second half cycle of the alternating voltage performs useful work. This leads to the fact that it is necessary to use a transformer of higher power than needed, moreover, a DC current, passing through the secondary winding of the transformer, causes magnetization of the magnetic core, which reduces the efficiency of the transformer, causing excessive heating. Nevertheless, the half-wave rectifier is very simple and is used where the load consumes relatively low power. In addition, it is used in modern switching power supplies, since the shape of the current in the secondary winding of the transformer is asymmetric in such units: unused half cycles have a much smaller amplitude (at the expense of longer duration), so their use for powering the load does not make sense. Unfortunately, the limited scope of the manual does not allow to consider this type of power supply, more detailed switching power supplies described in [2].

Full-wave rectifiers have been designed to eliminate the drawbacks discussed earlier. The most common circuit of a rectifier - bridge circuit is shown in Figure 15.

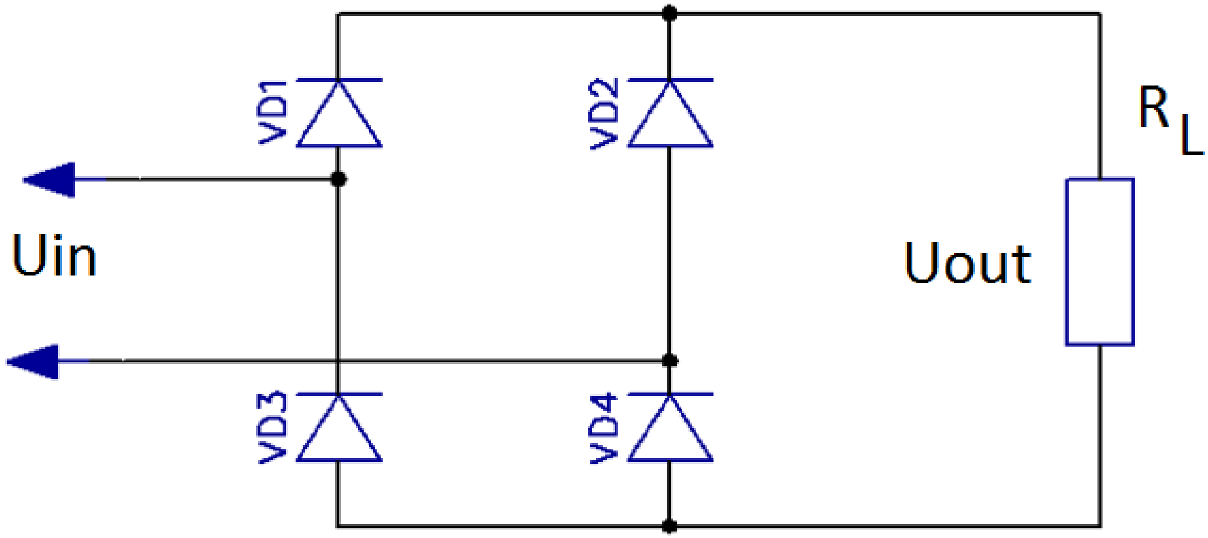


Figure 15 - Schematic diagram of a full-wave rectifier

As you can see, it consists of four diodes. Half-wave rectifier works as follows: When the top (on the diagram) input terminal is positive and the bottom is negative, diodes VD1 and VD4 are opened. The positive input voltage passes through the diode VD1 open to the top terminal of the load, and a negative voltage passes through VD4 diode to the bottom load terminal. Diodes VD2 and VD3 are closed and do not affect the operation of the circuit.

When the top input terminal is negative, and the bottom - is positive, diodes VD2 and VD3 are opened. The positive input voltage passes through opened diode VD2 open to the top load terminal, and a negative passes across VD3 diode - to the bottom. Diodes VD1 and VD4 are closed and do not affect the operation of the circuit.

Thus, whatever the input voltage polarity changes, the positive terminal is always connected to the top load terminal, and the negative - to the bottom load terminal.

The operation of such rectifier is illustrated in the graph.

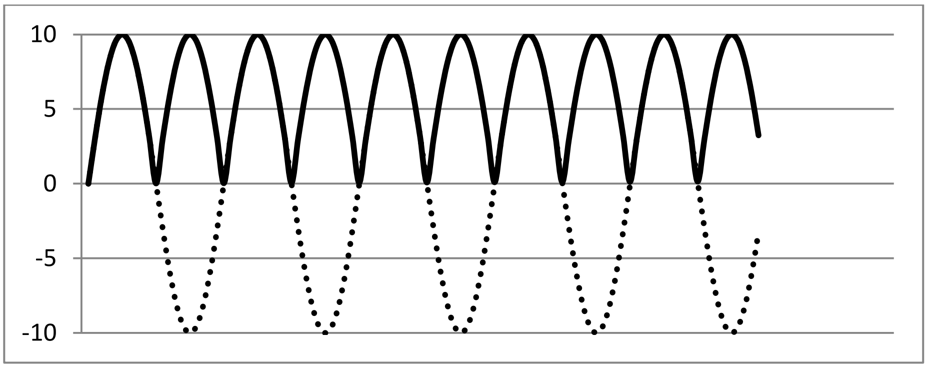


Figure 16 – Working of a full-wave rectifier

The dotted line shows the AC input voltage, a solid - output. As can be seen, the load is powered in both positive and negative half cycles of the input voltage (negative half cycle mirrored about horizontal time axis).

2.4 Smoothing Filters

Despite the fact that the full-wave rectifier allows to use both the AC voltage half-cycle, the load voltage twice per period becomes zero (so called pulsating voltage). This is a serious drawback which does not allow to feed an electronic device directly from the rectifier. For smoothing the rectified voltage ripple capacitor filters are typically used.

Capacitor filter is the simplest form of a filter, often it consists of a single capacitor connected in parallel with the load as in the case of the half-wave rectifier shown in Figure 17.

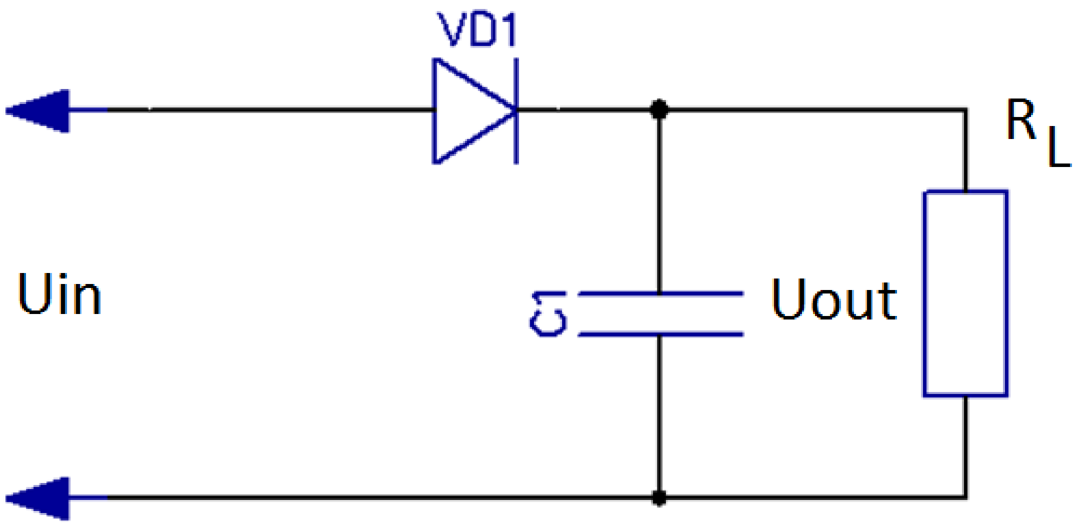


Figure 17 - Half-wave rectifier with filter

During those times when the input voltage is greater than the voltage on the capacitor, it is charged, and when the voltage at the input of the rectifier becomes lower than the capacitor, the load is supplied from the capacitor (the diode is closed, which prevents discharge of the capacitor through the transformer winding). Operation of this filter is illustrated in Figure 18.

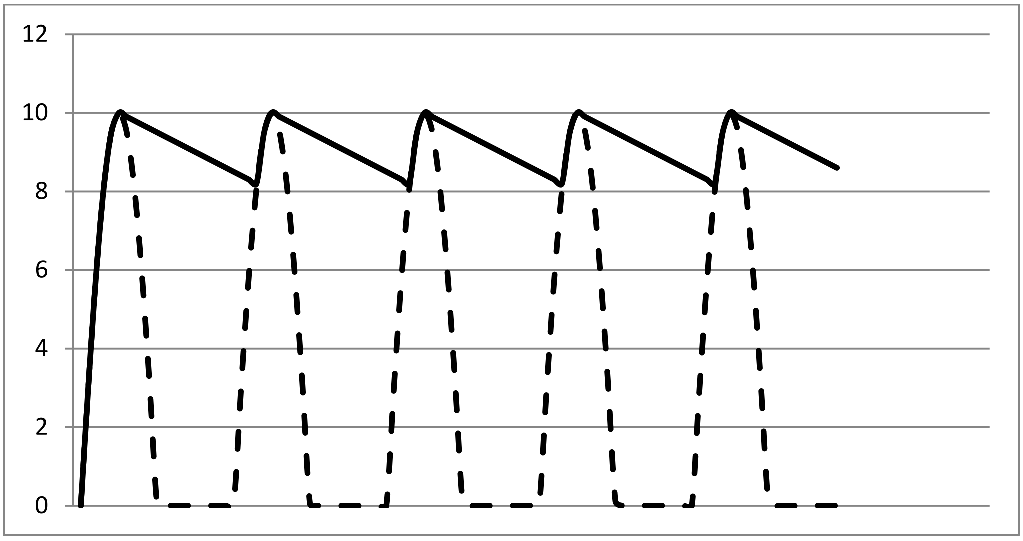


Figure 18 – Operation of a capacitor filter

The graph shown by a solid line is the voltage on the load, dotted - rectified voltage. It is easy to notice that some fluctuation (ripple) of the output voltage of the rectifier is still present, however, the current of such a kind is suitable for powering electronic devices.

Full wave rectifier with a filter capacitor is shown in Figure 19.

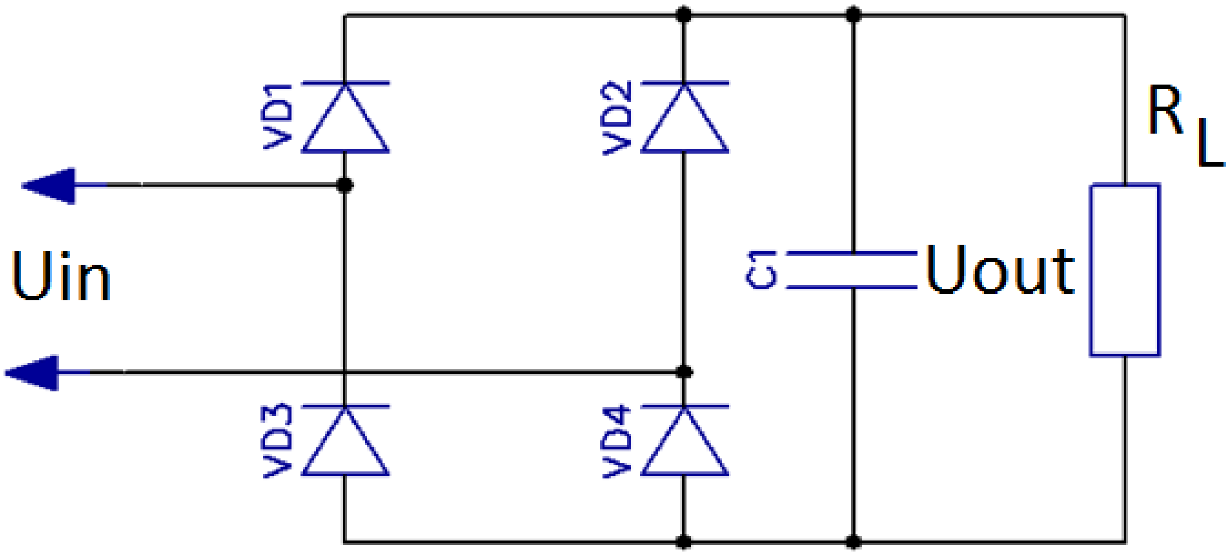


Figure 19 - The full-wave rectifier with filter

The filter operation in the case of full-wave rectification is illustrated in Figure 20.

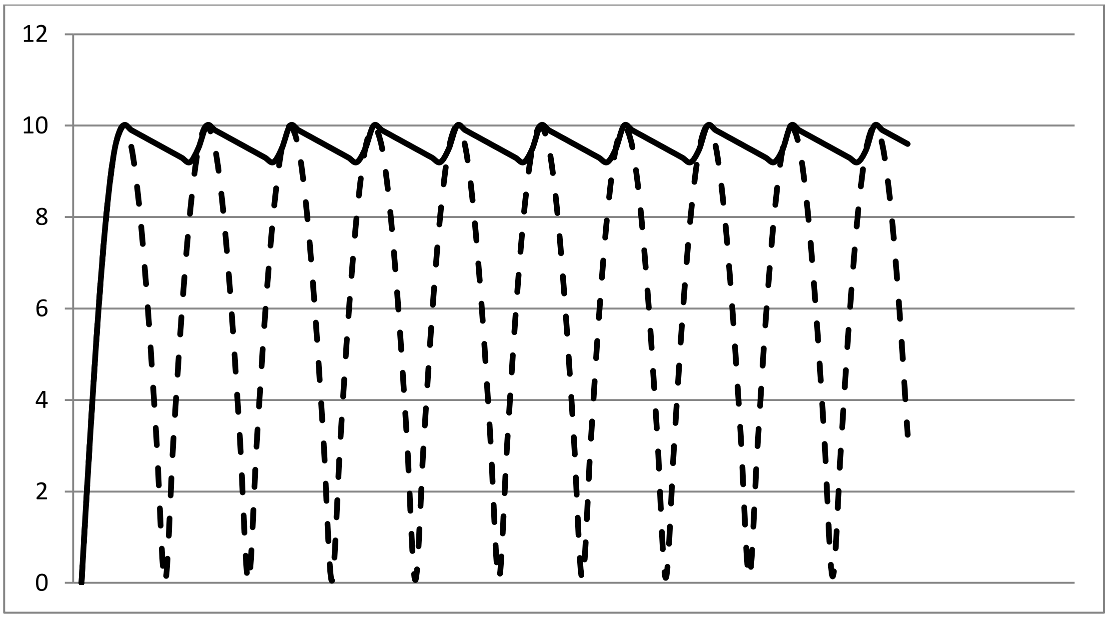


Figure 20 - Operation of the filter capacitor in full-wave rectifier

It is easy to see that the amplitude of ripple in the case of full-wave rectifier is approximately two times lower.

One of the problems that arise in the design of a power supply, is the calculation of the filter capacitor.

To calculate its capacity we are going to use the following data:

- Ur - voltage ripple
- I_L - current drawn by the load
- f - frequency of the alternating voltage

Let’s add some additional variables, as shown in Figure 21.

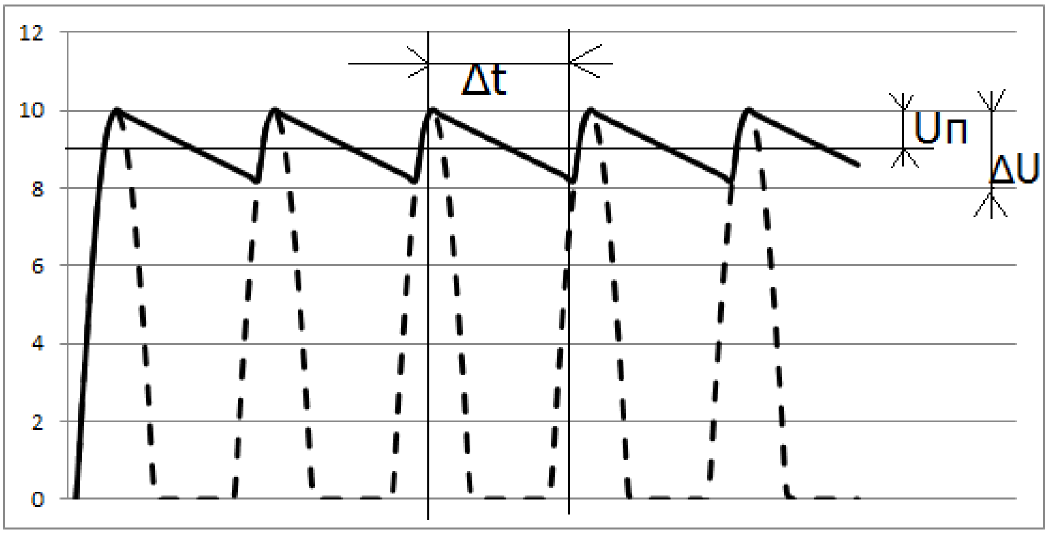


Figure 21 - The calculation of the filter

ΔU - is the peak-to peak voltage on the capacitor. Approximately it is equal to twice the voltage ripple.

$$\Delta U = 2U_r \tag{1}$$

This value designates the voltage on which the capacitor discharges during the time Δt. This time is quite difficult to determine exactly, since we will have to solve the problem with respect to the point of intersection of the two curves.

However, for practical purposes, you can take this time equal to the duration of an AC cycle for a half-wave rectifier:

$$\Delta t = \frac{1}{f} \tag{2}$$

Or half-cycle for full-wave:

$$\Delta t = \frac{1}{2f} \tag{3}$$

For the capacitor we have the following expression:

$$C = \frac{q}{U} = \frac{\Delta q}{\Delta U} \tag{4}$$

On the other hand, the load current and the amount of electricity consumed by a time Δt s associated following expression:

$$I_L = \frac{q}{t} = \frac{\Delta q}{\Delta t} \tag{5}$$

Expressing Δq of both expressions and equating them, we get:

$$C\Delta U = I_L \Delta t \tag{6}$$

We obtain an expression for the capacitance:

$$C = \frac{I_L \Delta t}{\Delta U} \tag{7}$$

For a half-wave rectifier:

$$\mathrm{C} = \frac{I_L}{2U_r f} \tag{8}$$

For a full-wave rectifier:

$$\mathrm{C} = \frac{I_L}{4U_r f} \tag{9}$$

2.5 Voltage regulators

As it has been noted earlier, the electronic devices often require a supply, the voltage of which does not depend on such factors as the input voltage and the load current.

Unfortunately, the power source units described in the previous chapter may not provide sufficient stability of the output voltage.

Therefore it is necessary to use various voltage regulators. One fairly widespread type of regulator is a zener diode regulator.

Zener diode is a two-terminal semiconductor device, in which the inverse (zener) breakdown occurs at a predetermined voltage which is called zener voltage.

The current-voltage characteristic of a zener diode is shown in Figure 22. Right branch of this characteristic is the same as that of the semiconductor diode, and in the reverse branch there is a region with a considerable increase of the current through the diode at the zener voltage.

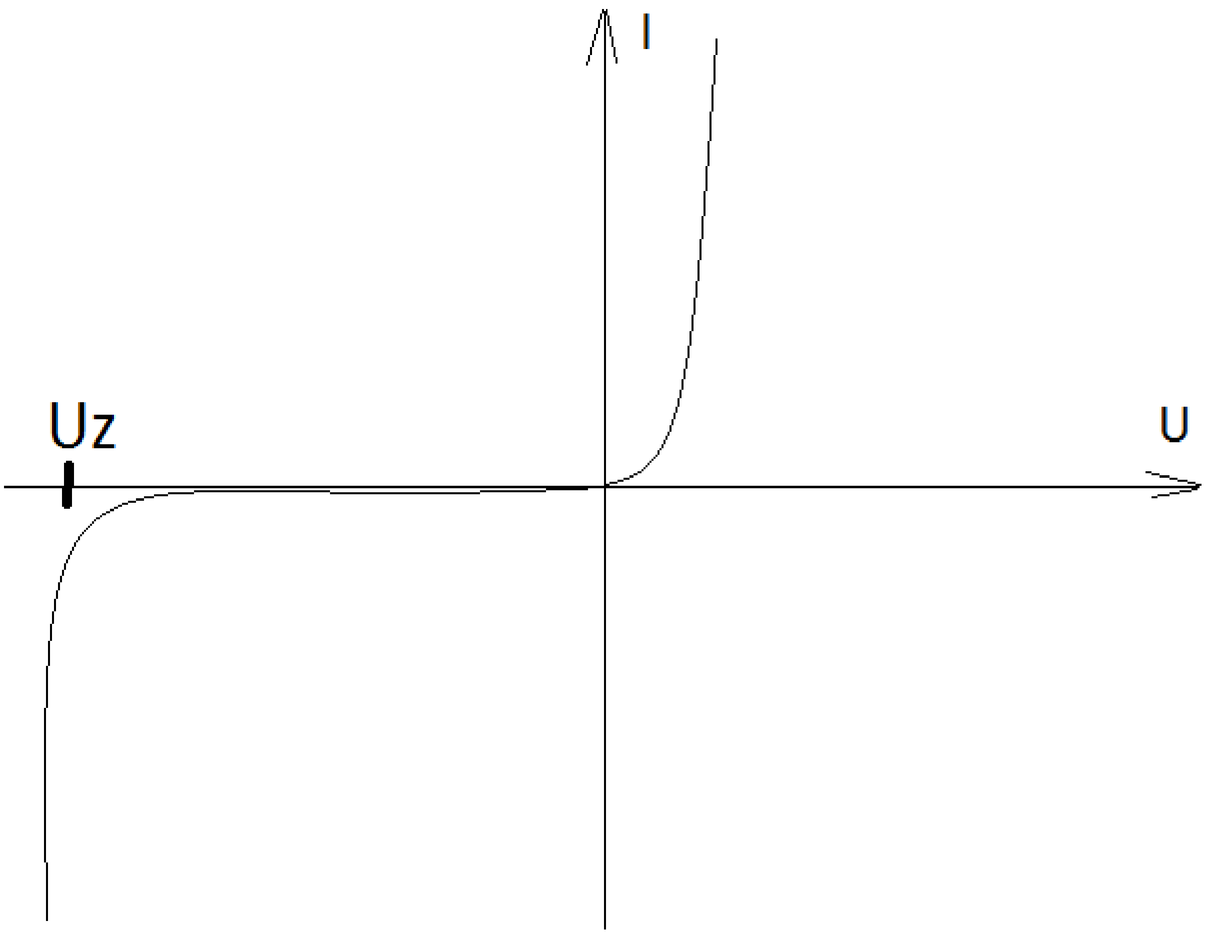


Figure 22 - The current-voltage characteristic of a zener diode

When operating in reverse breakdown region, zener diode characterized by large changes in current at a small change of voltage across it. This property can be used in voltage regulators. The circuit diagram of such a regulator is shown in Figure 23.

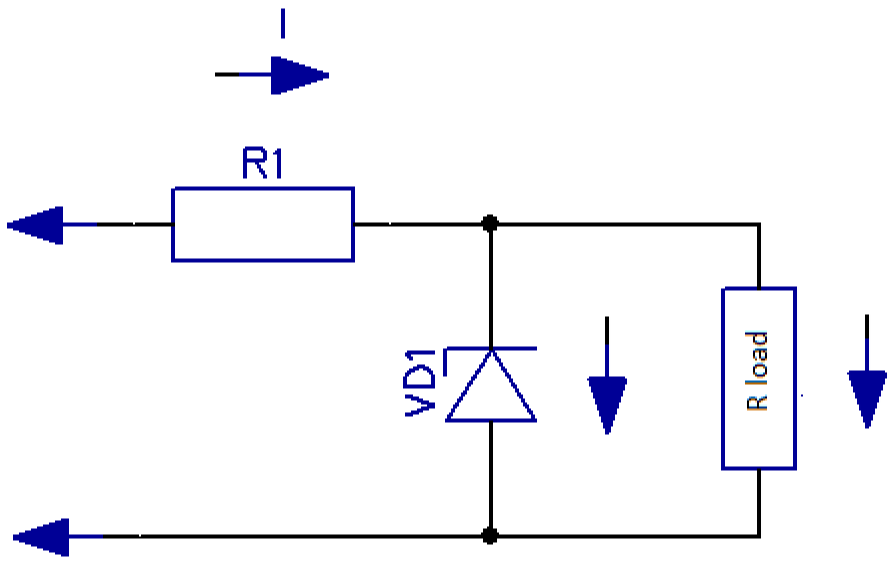


Figure 23 – Zener diode voltage regulator

In this circuit the zener diode is connected in parallel to the load, and a resistor R1 in series with them is included. Regulator work can be explained by the following example. Assume that the load current is increased. This will cause an increase in the voltage drop across the resistor R1 and corresponding decrease in the current through the zener diode substantially equal to a decrease in the load current. However, the load voltage will change only slightly. When reducing the current consumed by the load, the reverse process occurs. Similarly regulator reacts to changes in input voltage.

2.6 Questions

1. What does a half-wave rectifier consist of and how does it operate?
2. What does a full-wave rectifier with center-tapped transformer consist of and how does it operate?
3. What does a bridge rectifiers consist of and how does it operate?
4. What does a bridge rectifier with center-tapped transformer consist of and how does it operate?
5. What is the voltage ripple?
6. How does a smoothing filter reduce the voltage ripple?
7. How to design a smoothing filter?
8. What are Zener diodes used for?
9. Describe the operation of a shunt regulator.
10. How to design a shunt regulator?

3 Electronic amplifiers

3.1 Bipolar transistors

Amplification of electrical signals is the increase of their power by means of the power consumed from the power source [3]. The main elements of electronic amplifiers are transistors of different types: bipolar and field effect ones. The structure of an NPN bipolar transistor is shown in Figure 24.

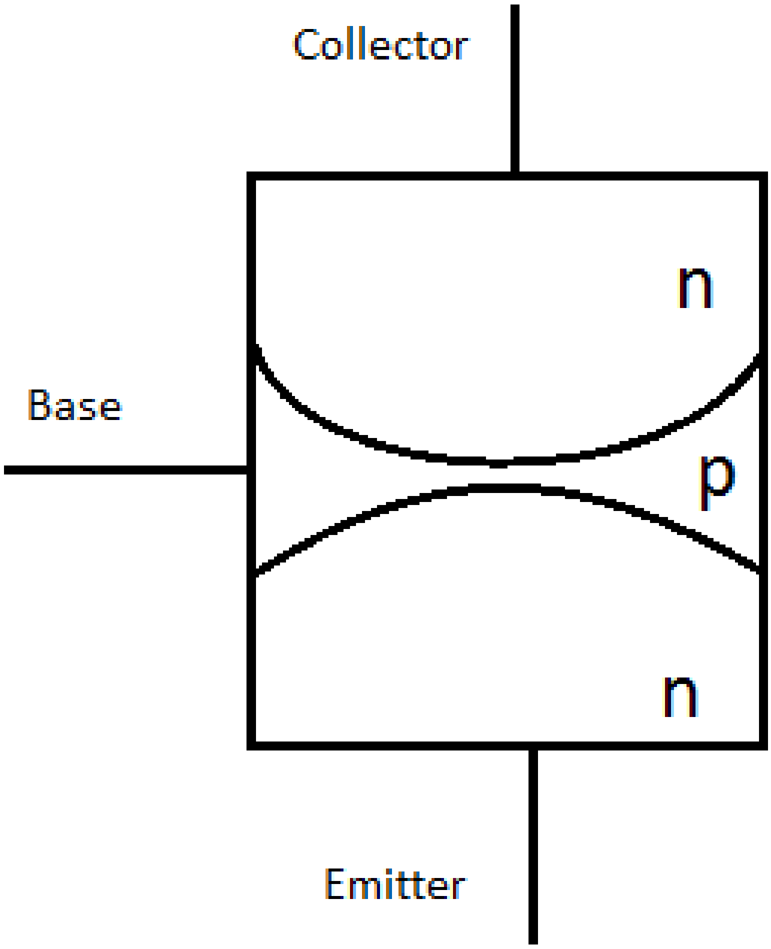


Figure 24 - The structure of a bipolar transistor

It consists of two P-N junctions, formed by three layers of a semiconductor of p and n types. Each of the layers is connected to one of three electrodes. The transistor is a three-electrode device. Base layer is the middle layer of the structure. The emitter electrode is connected to the semiconductor layer which injects minority carriers into the base and the collector - associated with the remaining layer is the layer that collects charge carriers which pass through the base.

This figure shows a NPN transistor structure, but there are commonly used transistors with opposite conductivity layers (PNP structure). The principle of operation of NPN and PNP transistors are similar except that the directions of all the currents and the polarity of the voltage applied to the transistor are reversed. Base layer is made sufficiently thin (about 1-10 micrometers), so that the emitter-base and collector-base junctions overlap. When the power supply voltage is applied to a NPN transistor the collector becomes positive with respect to the emitter potential. Given that the base thickness is very small, it creates a sufficiently high electric field in the base.

Base is also applied with a small positive potential relative to the emitter, which causes injection of electrons into the base region, which are minority carriers in that region. However, getting into the base region, most of the electrons flow into the collector region attracted by the electric field of collector.

And only a small fraction of the electrons (about one percent) is involved in the creation of the base current. Efficiency of the process also depends on the fact that the magic smoke concentration in the base is made sufficiently small (just kidding, I meant charge carriers).

Thus, the presence of a small base current causes the appearance of tens or hundreds times larger collector current.

Depending on whether the collector and emitter junctions of a transistor are open or closed, there can be four different operation modes: cutoff mode, saturation mode, active mode and inverse mode.

In cutoff mode (when both junctions are closed), the current through the transistor (in the collector and the emitter circuits) is minimal. In saturation mode both junctions are opened and the collector current becomes maximal. In the active mode collector junction is closed and emitter junction is opened. This mode is used to amplify signals. The inverse mode (emitter junction is closed, collector junction is opened) is not used in practice, since the amplification properties of the transistor in this mode are unsatisfactory.

The bipolar transistor can be used in a circuit in three different confugurations: common emitter (input signal is applied between the base and emitter, the output is between the collector and emitter), common collector (input signal is applied between the base and the collector, the output is between the collector and emitter), a common base (input signal is applied between the base and emitter, the output is between the collector and the base).

The common base configuration has low input and high output impedance, the common collector configuration has high input and low output impedance, the common emitter configuration has low input and high output impedance.

Voltage gain of common-collector circuit is close to unity, but it makes a significant increase in the current.

Common base configuration, on the contrary, has a current gain factor close to unity, but sufficiently large voltage gain. The transistor in a common emitter circuit significantly increases both the current and voltage [1].

To calculate the electronic device units, which include transistors, it is necessary to use a variety of mathematical models. The transistor is a nonlinear element, however, for most applications a linear model of transistor can be used.

We use the model which links the current of collector, emitter and base (the typical direction of the currents for the transistor in the active mode shown in Figure 25) and the potentials of the base, collector and emitter.

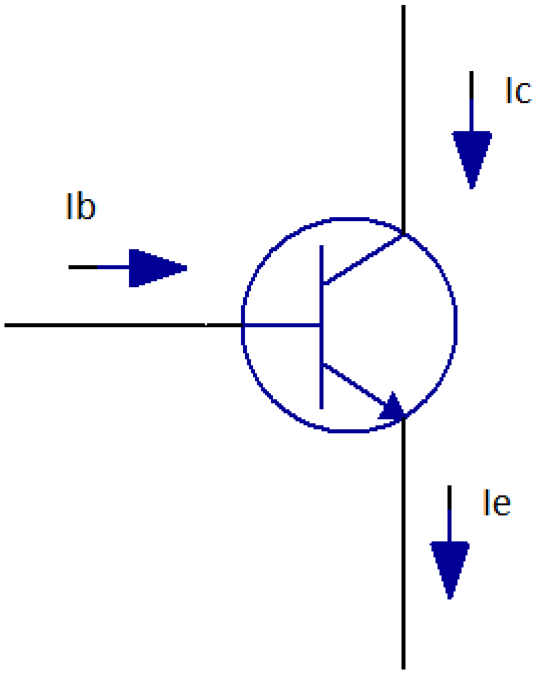


Figure 25 - The currents of bipolar transistor in the active mode

For bipolar transistors it can be approximately assumed that the current through the emitter junction begins at a certain potential difference between the emitter and the collector $U_{be} = const$ (0,6V for silicon and 0.2V for germanium transistors). The collector current depends on the base current is determined by the following relation:

$$I_c = I_b\beta \tag{10}$$

Where β is static base current transfer ratio which is the ratio of the collector current changes to the changes in the base current. Since the emitter current is the sum of the collector currents and base, the expression would be as follows for it:

$$I_e = I_c + I_b = I_b(\beta + 1) \tag{11}$$

The base current itself can be found using the potential difference between base and emitter as follows:

$$I_b = \frac{U_b - U_e - U_{be}}{R_e} \tag{12}$$

Where R_e is the differential input impedance of the emitter junction. It is related to the collector current by the following expression:

$$R_e = \frac{25}{I_c} \quad (I_c \text{unit is mA}) \tag{13}$$

Let's dicuss the operation of a transistor in common collector circuit in more detailed way. The corresponding circuit is shown in Figure 26.

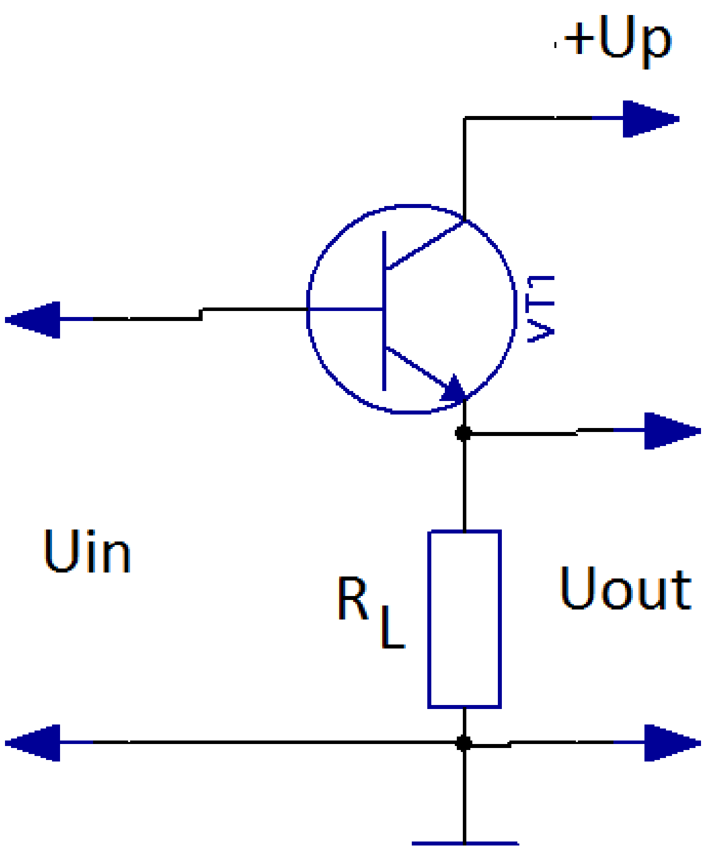


Figure 26 – Common collector bipolar transistor stage

The output voltage of the amplifier stage equals to the emitter potential. Applying the previously considered model and given that $U_b = U_{in}$ and $U_e = U_{out}$ we get:

$$U_{out} = I_e R_L = I_b(\beta + 1)R_L = (U_{in} - U_{out} - U_{be})\frac{(\beta+1)R_L}{R_e} \quad (14)$$

Through substitution of the expression for the coefficient a in the expression given by (15)

$$\frac{(\beta+1)R_L}{R_e} = a \quad (15)$$

we get:

$$U_{out} = (U_{in} - U_{out} - U_{be})a = aU_{in} - aU_{out} - aU_{be}\,, \quad (16)$$

$$U_{out}(1 + a) = aU_{in} - aU_{be} \quad (17)$$

$$U_{out} = \frac{a}{1+a}U_{in} - \frac{a}{1+a}U_{be} \quad (18)$$

Considering that the factor at Uin in this expression is close to unity for sufficiently large values of a, and in most practical cases, the final expression relating the input and output voltage of the common collector stage becomes:

$$U_{out} \approx U_{in} - U_{be} \tag{19}$$

It is easy to notice that voltage gain of this stage is close to unity:

$$G_U \approx 1 \tag{20}$$

On the other hand, the ratio of the output current (collector current) to the input (base current), it is already known to us from the transistor model:

$$G_I \approx \beta \tag{21}$$

It means that a transistor with a common collector does not amplify the voltage, but the amplifies the current. It defines its field of application: the current amplifier stages of power amplifiers, matching the signal source with a high internal resistance of the load or other amplifier stages, having low input impedance.
Now let’s get the model if a common emitter stage. It’s circuit is shown in Figure 27.

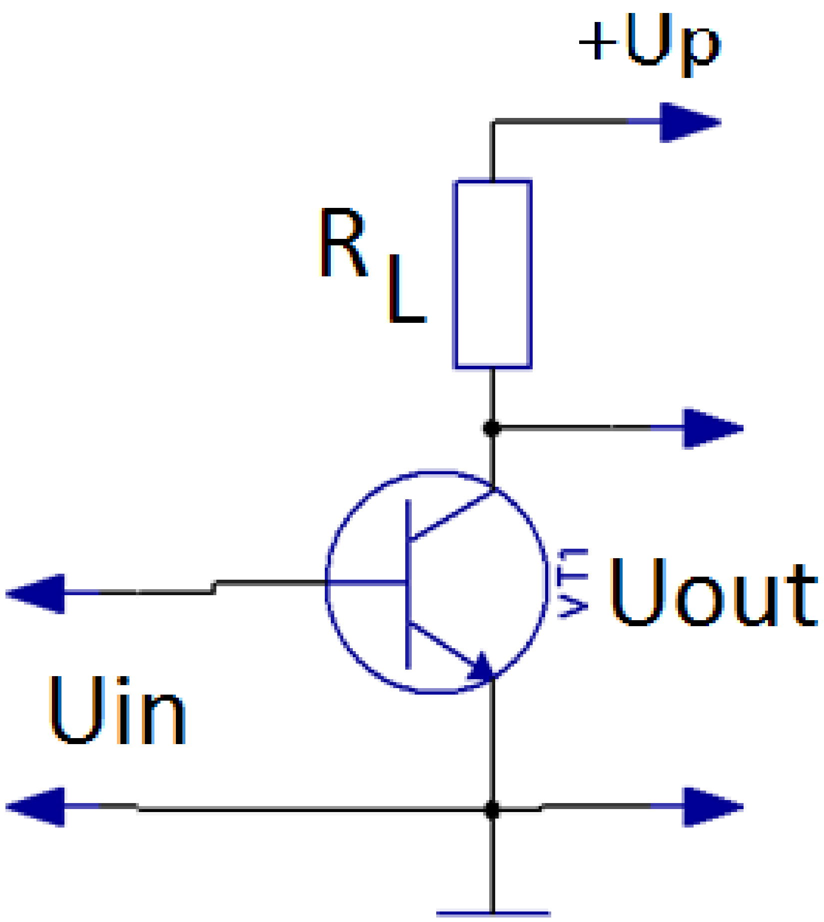


Figure 27 - Common emitter bipolar transistor stage

The output voltage of the stage equals to the power source voltage minus the voltage drop across the load resistor:

$$U_{out} = U_P - I_c R_L \qquad (22)$$

On the other hand, we know that the collector current is related with the base current by the following expression (23)

$$I_c = \beta I_b \qquad (23)$$

The expression for base current is as follows:

$$I_b = \frac{(U_{in} - U_{be})}{R_e} \qquad (24)$$

Substituting (24) into (23) we get:

$$U_{out} = U_P - \beta \frac{U_{in} - U_{be}}{R_e} R_L \qquad (25)$$

Differentiating this expression with respect to the input voltage, we can obtain the voltage gain:

$$G_U = \frac{dU_{in}}{dU_{out}} = -\frac{\beta R_L}{R_e} \qquad (26)$$

The current gain is the same as in the previous case:

$$G_I = \frac{dI_{out}}{dI_{in}} = \beta \qquad (27)$$

From (27) it follows that the voltage gain is heavily dependent on the current gain of the transistor.

On the other hand, the current gain of the transistor is strongly temperature dependent and may differ in different instances of the transistors, in practice variation reaches 7-8 times. This is due to the fact that the current transistor fabrication technology can not produce exactly the same devices, particularly because it’s hard to maintain a stable base thickness, on which the current gain depends. Therefore the gain of considered transistor stage can not be stable [2].

In order to stabilize the gain let’s include a feedback resistor into the emitter circuit, as shown in Figure 28.

It is easy to notice that the amplifier stage operates as an emitter follower in terms of the resistor R2 and the signal across this resistor is almost completely repeats the input signal.

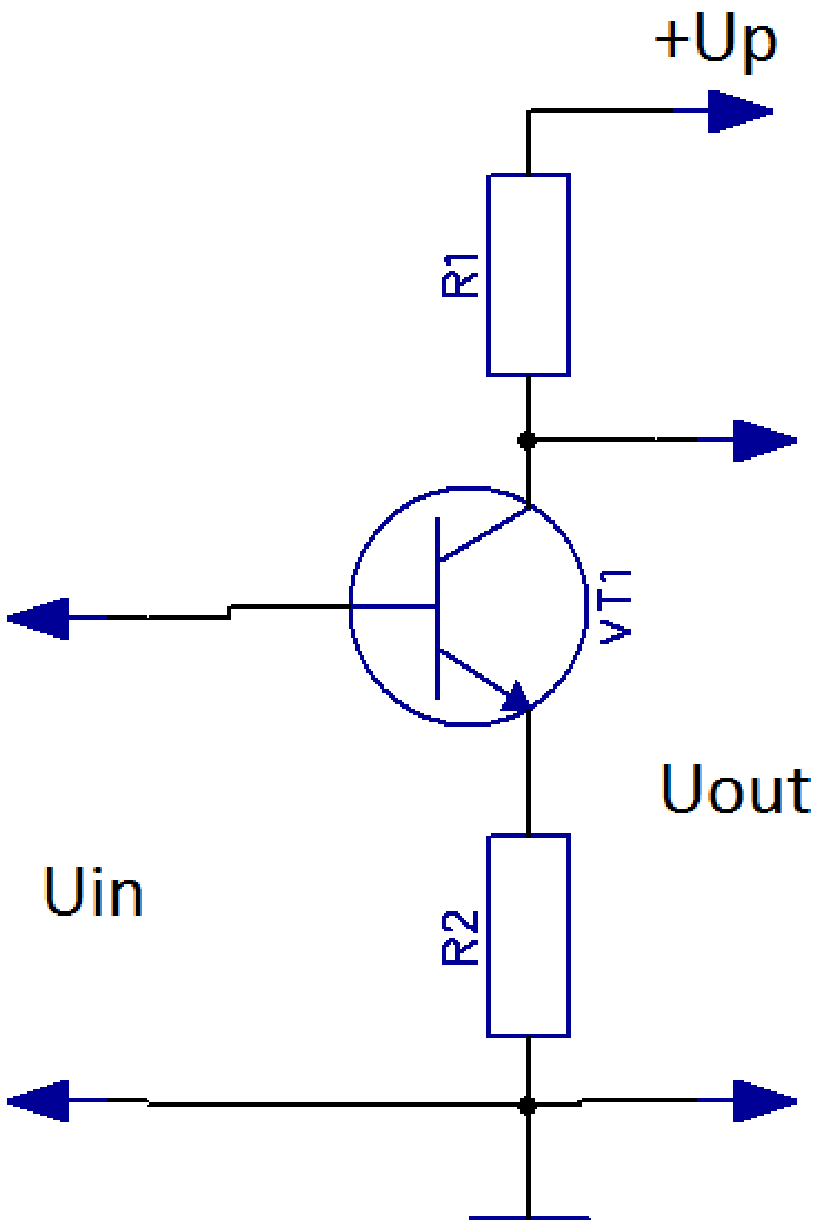


Figure 28 - The amplifier stage with a feedback resistor

This causes a certain change in the emitter current and substantially the same change in the collector current. Given that

$$R2 \gg Re \tag{28}$$

It is easy to show that the gain of this circuit will be given by the expression:

$$G = \frac{R1}{R2} \tag{29}$$

In practice, the circuits as bias voltage divider and coupling capacitors that impede the flow of constant current through the base, and the collector current - through the load. A typical diagram of the bipolar transistor amplifier stage is shown in Figure 29.

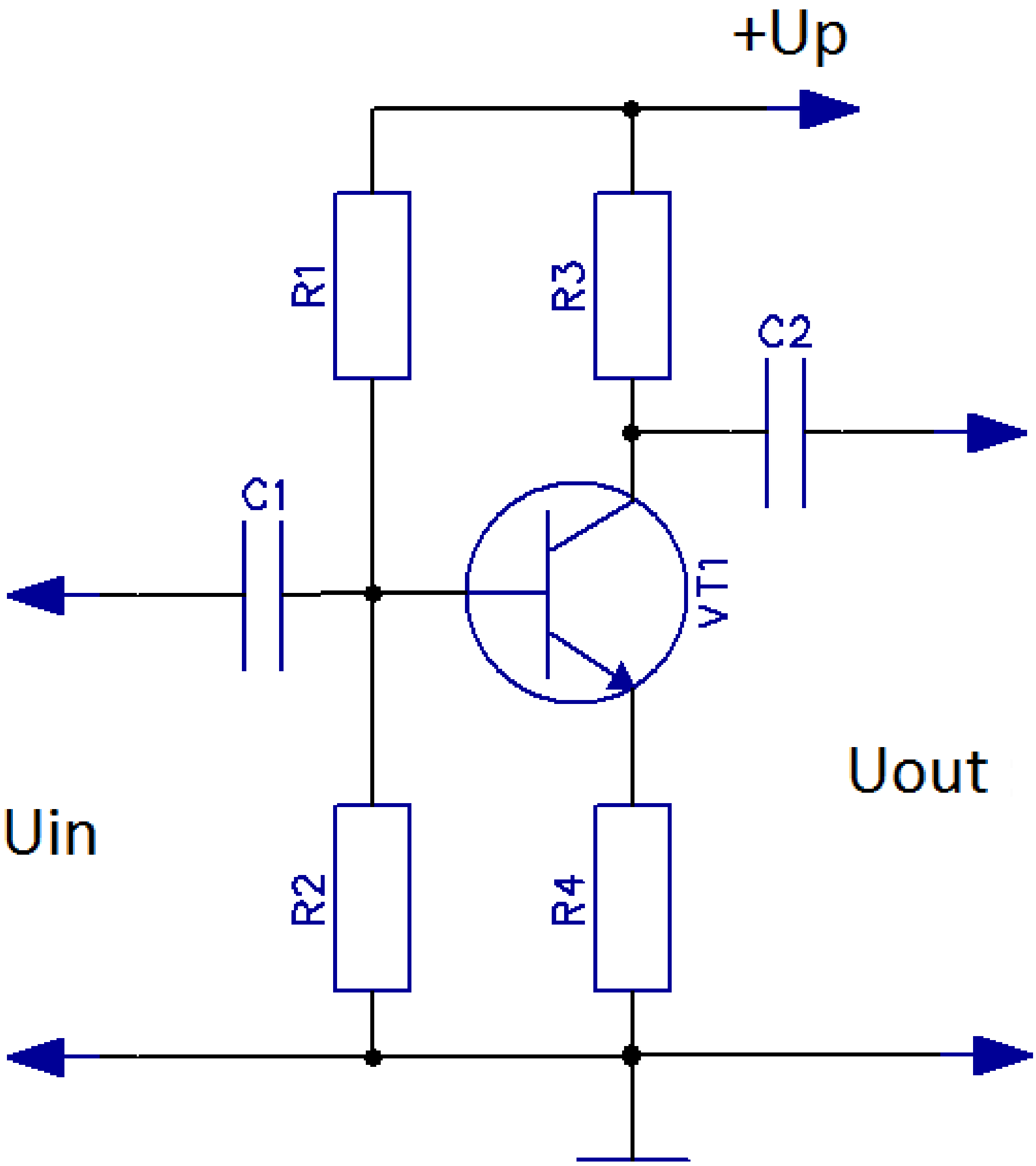


Figure 29 - Typical diagram of the amplifier stage

This amplifier stage contains four resistors and two capacitors, the parameters of which are calculated under certain operating conditions.

Resistor R3 is typically selected in several (e.g., five) times smaller than the load resistance:

$$R_3 = \frac{R_L}{5} \tag{30}$$

To make the stage transmit both positive and negative half-waves of the amplified signal, the collector voltage in the idle mode is usually selected equal to a half of the supply voltage:

$$U_c = \frac{U_P}{2} \tag{31}$$

Then it is possible to calculate the collector quiescent current by the formula:

$$I_C = \frac{U_P - U_C}{R_3} \tag{32}$$

According to it we can find the required gain resistance of the resistor R3:

$$R_4 = \frac{R_3}{G} \tag{33}$$

Given that the emitter current substantially equal to the collector current, we may find the emitter voltage in idle mode:

$$U_e = I_c R_3 \tag{34}$$

Knowing that the potentials of base and emitter of the transistor differ by almost the same value, we may find the potential of the base:

$$U_b = U_e + U_{be} \tag{35}$$

We can calculate the bias voltage divider R1R2, solving the system of equations:

$$\begin{cases} \frac{U_P R_2}{R_1 + R_2} = U_b \\ \frac{R_1 R_2}{R_1 + R_2} = 0{,}2\beta R_4 \end{cases} \tag{36}$$

It remains to calculate the capacitance of the capacitors. For this let's set the minimum signal frequency which is to be transmitted by the amplifier stage fmin and find capacitance by solving the following inequality:

$$2\pi \mathrm{f}_{min}\, C_1 > \frac{R_1 R_2}{R_1 + R_2} + R_{source} \tag{37}$$

$$2\pi \mathrm{f}_{min}\, C_2 > R_{load} \tag{38}$$

3.2 Differential and operational amplifiers

You've probably already noticed that the calculation of transistor amplifiers is quite a complicated process. It should also be noted that we have considered the amplifier stages using bipolar transistors have a significant drawback - the zero drift, which is manifested in the fact that the output voltage varies under the influence of many factors (transistor temperature, the current transmission ratio and others). This leads to the fact that such amplification stages can be used only for AC [1].

These disadvantages are eliminated in the so-called DC amplifiers, one kind of which is a differential amplifier. Circuit of such an amplifier is shown in Figure 30.

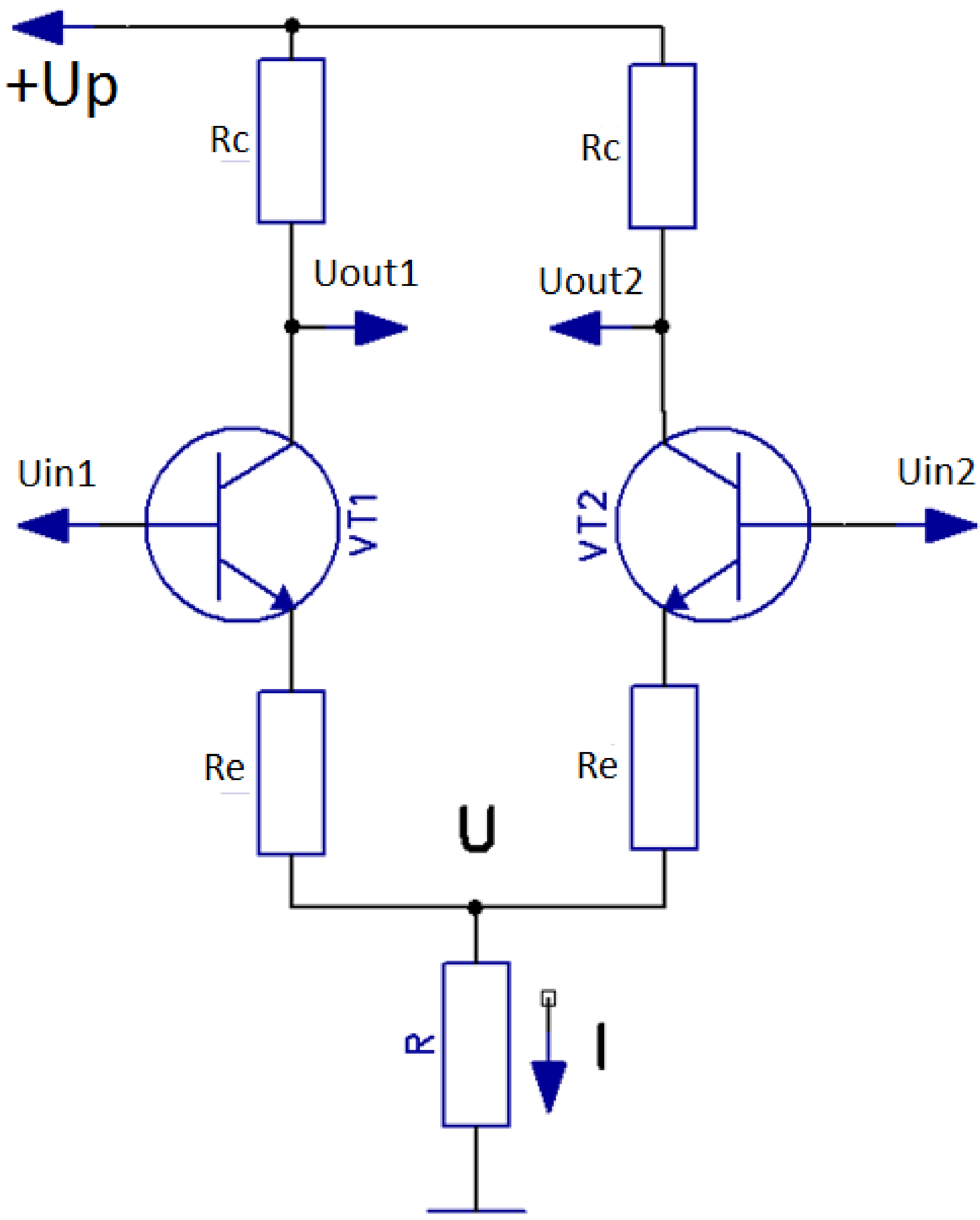


Figure 30 - The differential amplifier

In the amplifier input voltage is applied between the bases of the transistors and the output voltage is the voltage between the collectors. Let’s discuss the operation of the amplifier in more detail. Transistors VT1 and VT2 operate as emitter followers with load resistors Re and R. Therefore, for them we have the following expression:

$$U_{e1} = U_{in1} - U_{be} \quad . \tag{39}$$

$$U_{e2} = U_{in2} - U_{be} \tag{40}$$

Then the expression for the current collector and the emitter takes the form:

$$I_{c1} = I_{e1} = \frac{U_{e1} - U}{R_e} \quad . \tag{41}$$

$$I_{c2} = I_{e2} = \frac{U_{e2} - U}{U_e} \tag{42}$$

Where U is the potential at the junction point of resistors (shown in Figure 30). Let's find the value of U:

$$U = (I_{e1} + I_{e2})R = \frac{R}{R_e}(U_{e1} + U_{e2} - 2U) \tag{43}$$

$$U + \frac{2R}{R_e}U = \frac{R}{R_e}(U_{e1} + U_{e2}) \, , \tag{44}$$

$$U\left(\frac{R_e + 2R}{R_e}\right) = \frac{R}{R_e}(U_{e1} + U_{e2}) \tag{45}$$

$$U = \frac{R}{R_e + 2R}(U_{e1} + U_{e2}) \tag{46}$$

Substituting this expression into (41) we obtain:

$$I_{c1} = \frac{U_{e1}}{R_e} - \frac{R}{R_e(R_e + 2R)}U_{e1} - \frac{R}{R_e(R_e + 2R)}U_{e2} \, , \tag{47}$$

$$I_{c1} = U_{e1}\frac{R_e + R}{R_e(R_e + 2R)} - U_{e2}\frac{R}{R_e(R_e + 2R)} \tag{48}$$

$$I_{c1} = U_{in1}\frac{R_e + R}{R_e(R_e + 2R)} - U_{be}\frac{R_e + R}{R_e R_e + 2R} - U_{in2}\frac{R}{R_e(R_e + 2R)} + U_{be}\frac{R}{R_e(R_e + 2R)} \tag{49}$$

$$I_{c1} = U_{in1}\frac{R_e+R}{R_e(R_e+2R)} - U_{in2}\frac{R_e}{R_eR_e+2R} - U_{be}\frac{R}{R_e(R_e+2R)} \quad (50)$$

Now it becomes easy to find the relation between the collector voltage and the input voltage of the transistor VT1 Uin1 and Uin2:

$$U_{out1} = U_P - I_{C1}R_C \quad (51)$$

$$U_{out1} = U_P - U_{in1}\frac{R_c(R_e+R)}{R_e(R_e+2R)} + U_{in2}\frac{R_cR}{R_e(R_e+2R)} - U_{be}\frac{R}{R_e(R_e+2R)} \quad (52)$$

The expression (52) shows that Uin1 and Uin2 have different coefficients (in absolute value). However, it is easy to show that both of them tend to $\frac{Rc}{2Re}$ when R >> Rc.

By the symmetry of the circuit, you can easily find an expression for Uout2:

$$U_{out2} = U_P - U_{in2}\frac{R_c(R_e+R)}{R_e(R_e+2R)} + U_{in1}\frac{R_cR}{R_eR_e+2R} - U_{be}\frac{R}{R_e(R_e+2R)} \quad (53)$$

Subtracting the Uout1we obtain the expression for the output voltage, if it is measured between the collectors of transistors:

$$U_{out2} - U_{out1} = U_{in1}\frac{R_cR+R_c(R_e+R)}{R_e(R_e+2R)} + U_{in2}\frac{R_c(R_e+R)+R_cR}{R_e(R_e+2R)}\,. \quad (54)$$

$$U_{out2} - U_{out1} = (U_{in1} - U_{in2})\frac{R_c}{R_e} \quad (55)$$

We have shown that the output voltage of the amplifier in both cases depends on the difference between the input voltages, so the amplifier is called differential. Thus, compliance with certain conditions is required (see. above) at which the gains for the two inputs become equal. However, in practice it is difficult to provide R >> Rc, but taking the output signal between the collectors of transistors is not always usable. In order to ensure strictly identical gains of voltages applied to both inputs of the amplifier it can be powered by a current source as shown in Figure 31. The current source is usually performed by a current mirror circuit using two transistors. It should be noted that for the differential stage with a current source we may use all our earlier formula, when changing R to infinity.

If the amplifier is powered by a stable current, the following expression applies for the emitter currents:

$$I_{e1} + I_{e2} = I = const \quad (56)$$

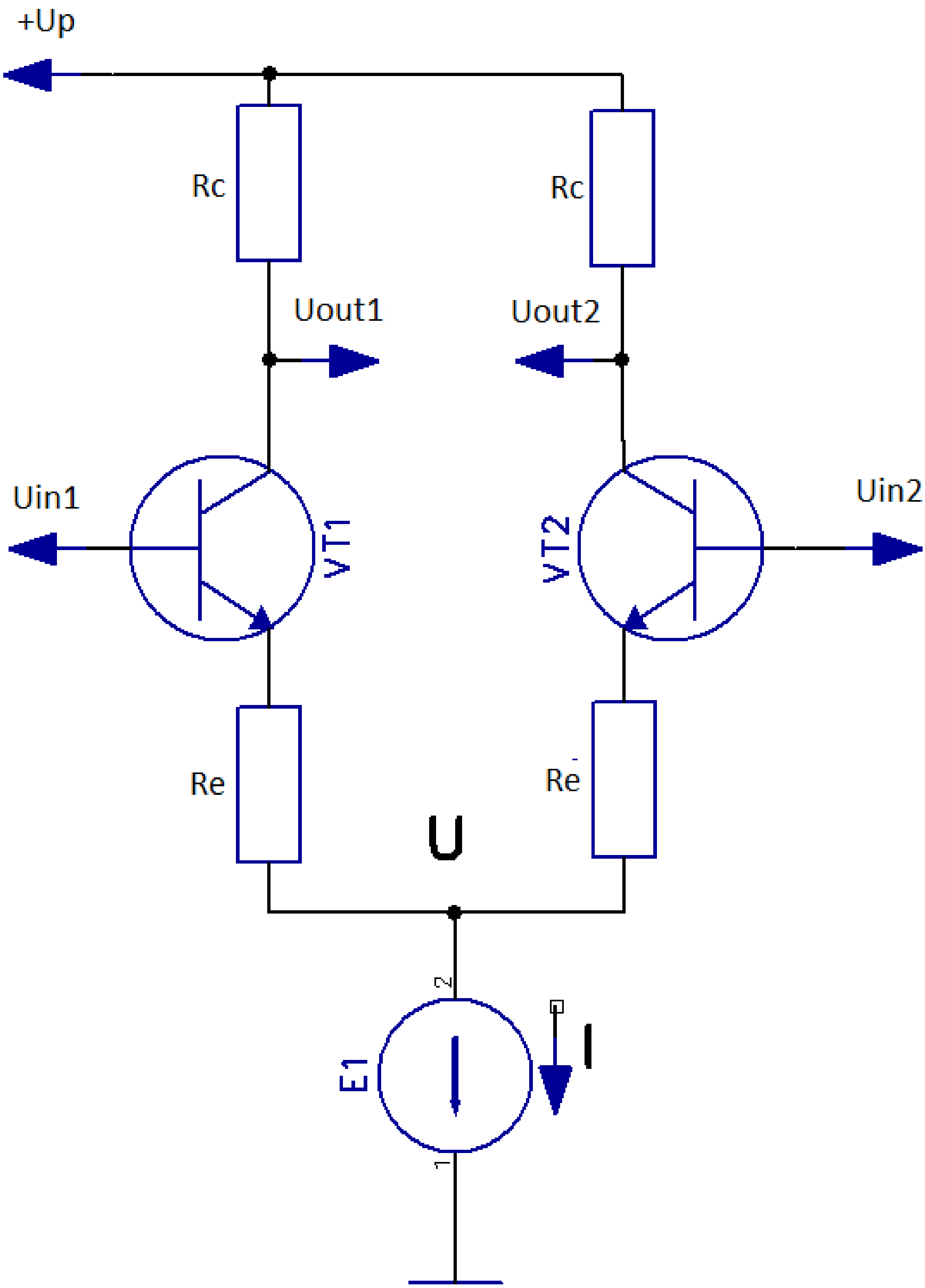


Figure 31 - The differential amplifier with a current source

It's obvious that:

$$\frac{U_{e1}-U}{R_e}+\frac{U_{e2}-U}{R_e}=I \quad (57)$$

$$\frac{U_{e1}+U_{e2}}{R_e}-\frac{2U}{R_e}=I \quad (58)$$

$$-\frac{2U}{R_e}=I-\frac{U_{e1}+U_{e2}}{R_e} \quad (59)$$

Then the voltage of junction point of the resistors U will be expressed by the formula:

$$U=\frac{U_{e1}+U_{e2}-IR_e}{2} \quad (60)$$

Substituting into (41) we find the current collector of the transistor VT1:

$$I_{c1}=\frac{U_{e1}}{R_e}-\frac{U_{e1}+U_{e2}-IR_e}{2R_e}=\frac{U_{e1}-U_{e2}-IR_e}{2R_e} \quad (61)$$

$$I_{c1}=\frac{U_{in1}-U_{in2}-2U_{be}-IR_e}{2R_e} \quad (62)$$

Then we may find the voltage at the collector of VT1:

$$U_{out1}=U_P-\frac{R_c}{2R_e}(U_{in1}-U_{in2}-U_{be}-IR_e) \quad (63)$$

As it can be seen, in this case the gain is the same for both inputs.

In practice, differential amplifiers are used, adding to them voltage amplification stages (to increase gain) and current (to increase the power), for example, as shown in Figure 32.

Such an amplifier is called operational (Op-amp). It's generally manufactured as integrated circuit.

Operational amplifier found such wide application in modern electronics that the circuit diagrams do not reflect its internal structure (it would be irrational, since operational amplifiers are often more complex than the circuits in which they are used), and there are special symbols, as shown in Figure 33.

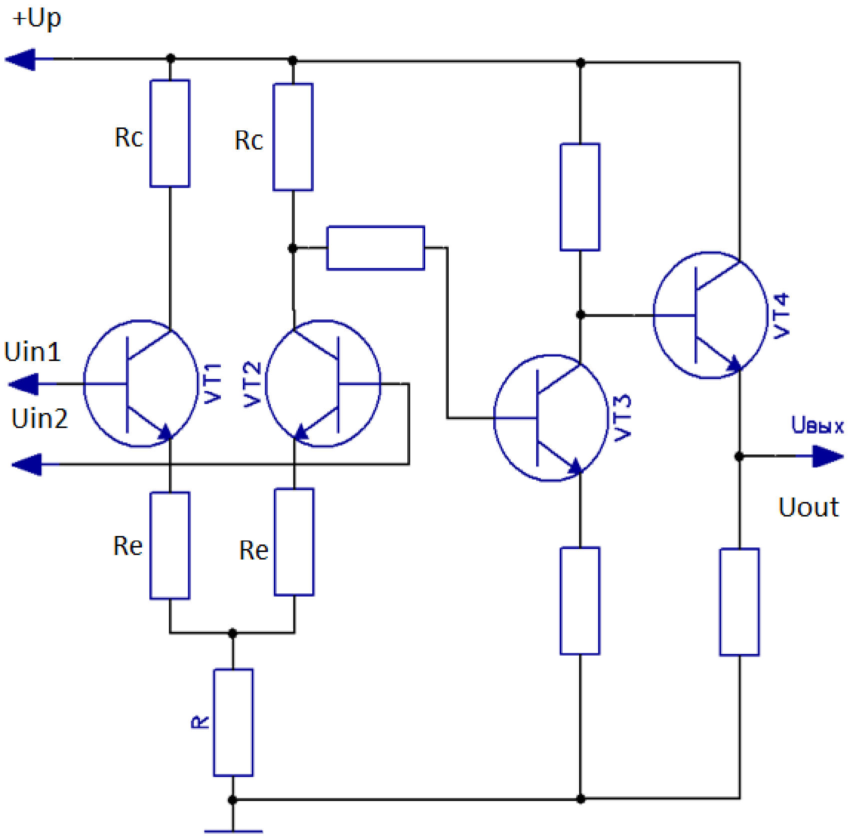
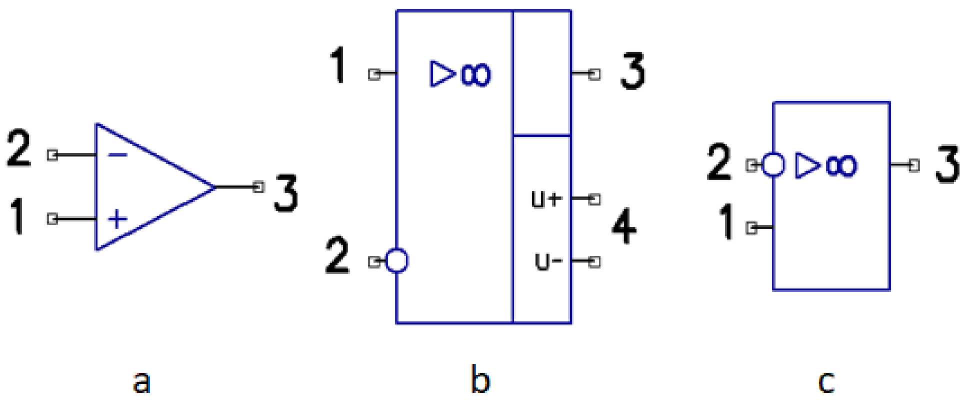


Figure 32 - Operational Amplifier

The drawing shown in Figure 33 (a) is historically the first symbol of the operational amplifier. Now this graphical symbol is used mainly in the foreign literature, though, it has certain advantages over the more recent ones, illustrated in Figure 33 (b) and 33 (c). As it can be seen, the symbol of the operational amplifier can either contain or not contain the power supply terminals. Subsequently the symbol to be used in the manual is similar to the shown in Figure 33 (a).



1 - non-inverting input
2 - inverting input
3 - Output
4 - power pins

Figure 33 – Drawing symbols of the operational amplifier

To calculate the circuits of electronic devices with operational amplifiers a simple linear model of op-amp is suitable . It connects the voltage of the output of op-amp with the potential difference between its inputs (with respect to the common wire). The points between which the potentials are measured are shown in Figure 34.

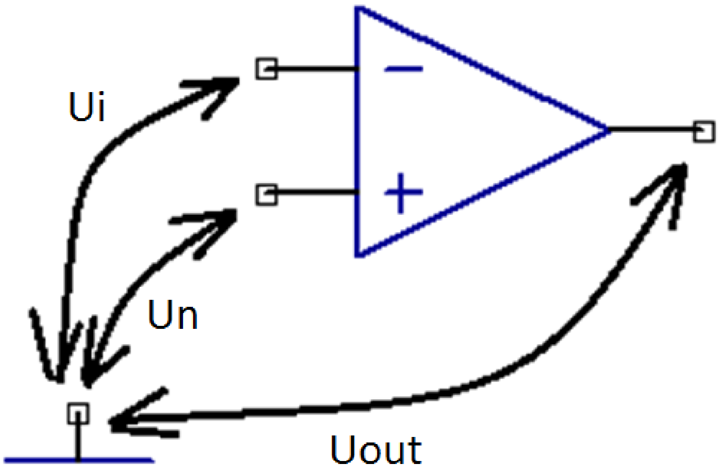


Figure 34 - The voltages of an op-amp

The following model is valid for the majority of op-amps:

$$U_{out} = k(U_n - U_i) \tag{64}$$

Where k is the differential signal gain of op-amp (usually in the range from 10^3 to 10^6), Uout is the output voltage Un is the voltage at the non-inverting input, Ui is the voltage at the inverting input.

3.3 The use of operational amplifiers

Let’s discuss the simplest op-amp circuit – the voltage follower which is s represented in Figure 35.

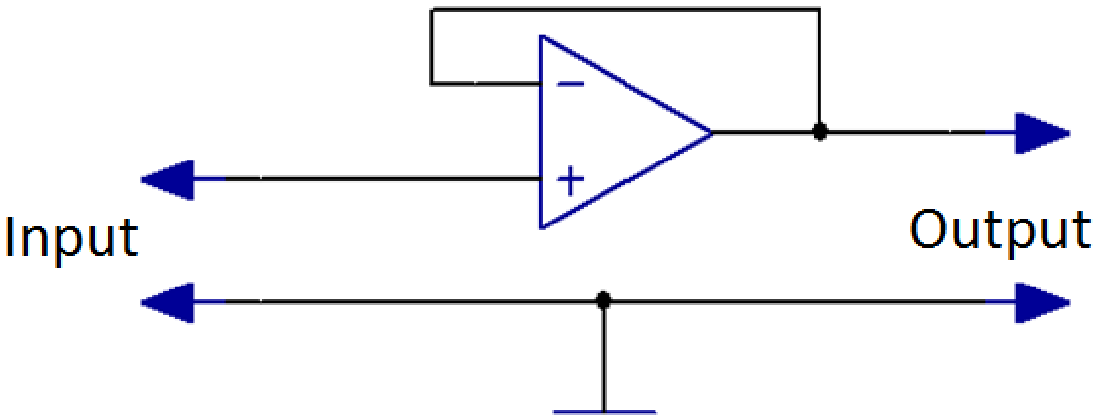


Figure 35 – Op-amp voltage follower

As it can be seen, input voltage is applied between the common ground and the non-inverting input and an inverting input connected to the output of the op-amp. Then we have the following:

$$U_n = U_{in} \; ; \; U_i = U_{out} \tag{65}$$

Substituting this in the expression for the op-amp model, we obtain:

$$U_{out} = k(U_{in} - U_{out}) \tag{66}$$

Then we get:

$$U_{out} = kU_{in} - kU_{out} \tag{67}$$

Let’s transfer all terms containing Uout to the left side, and containing Uin - to the right:

$$U_{out} + kU_{out} = kU_{in} \tag{68}$$

Taking out Uout of the brackets we get:

$$U_{out}\,(1 + k) = kU_{in} \tag{69}$$

Then we express Uout:

$$U_{out} = \frac{kUin}{1+k} \tag{70}$$

For sufficiently large k the ratio $\frac{k}{1+k}$ can be ignored because it is close to unity. Then we get:

$$U_{out} = U_{in} \tag{71}$$

So, the voltage follower circuit repeats the vltage applied to the input and it has a gain of unity.

To make an amplifier out if an op amp we add a feedback circuit consisting of the resistor divider as shown in Figure 36.

As it can be seen, the input voltage is still applied to the non-inverting input, while the output signal is applied to R1R2 voltage divider and atenuated before it is fed to the inverting input. For this circuit we have the following expression:

$$U_n = U_{in}; \;\; U_i = U_{out}\frac{R_1}{R_1+R_2} \tag{72}$$

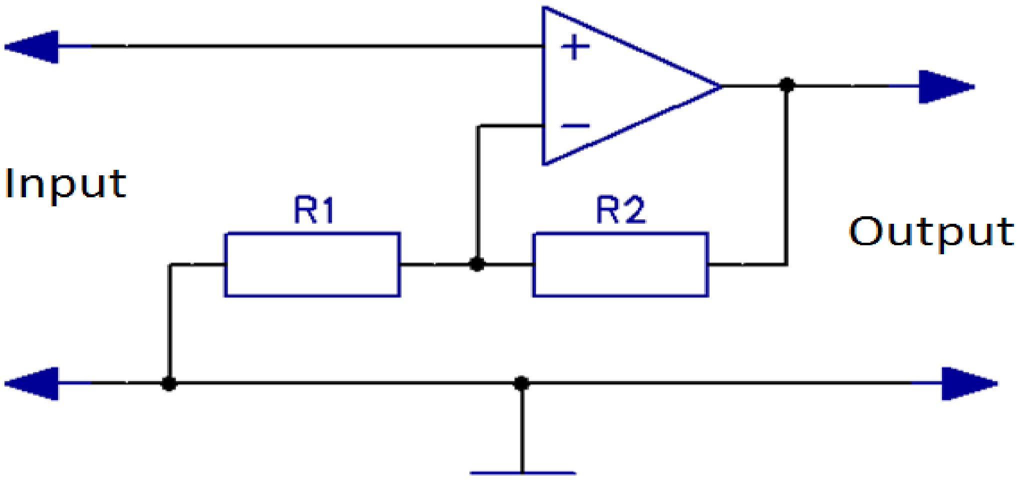


Figure 36 – Op-amp non-inverting amplifier

Substituting it in our well-known expression for the op-amp, we get:

$$U_{out} = k(U_{in} - U_{out}\frac{R_1}{R_1+R_2}) \quad (73)$$

Then we get:

$$U_{out} = kU_{in} - kU_{out}\frac{R_1}{R_1+R_2} \quad (74)$$

We transfer terms:

$$U_{in} + kU_{out}\frac{R_1}{R_1+R_2} = kU_{in} \quad (75)$$

Let's transform the expression:

$$U_{out}\left(1 + k\frac{R_1}{R_1+R_2}\right) = kU_{in} \quad (76)$$

Let's express Uout:

$$U_{out} = \frac{kU_{in}}{1+k\frac{R_1}{R_1+R_2}} \quad (77)$$

When the k factor is sufficiently large, it can be neglected, then the expression becomes as follows:

$$U_{out} = \frac{U_{in}}{\frac{R_1}{R_1+R_2}} \quad (78)$$

Or:

$$U_{out} = \frac{U_{in}(R_1+R_2)}{R_1} \quad (79)$$

The gain of the circuit is easily obtained by dividing the Uout on Uin:

$$\mathrm{G} = \frac{\mathrm{R}_1+\mathrm{R}_2}{\mathrm{R}_1} \quad (80)$$

Another typical circuit base on the operational amplifier is an inverting amplifier shown in Figure 37.

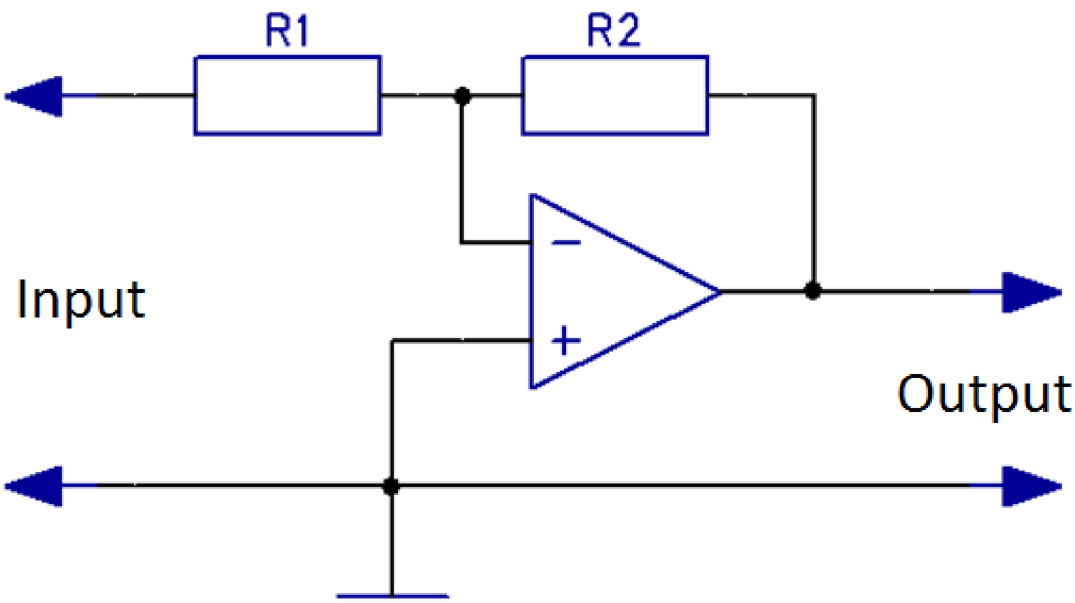


Figure 37 - Op-amp inverting amplifier

The inverting amplifier resembles the circuit of non-inverting one , with the only difference that the input signal is applied to one of the resistors of the voltage divider, while the non-inverting input of op-amp is grounded, so it is given a ground or zero potential. Expression for the amplifier will take the form:

$$U_n = 0; \qquad U_i = U_{in} + (U_{out} - U_{in})\frac{R_1}{R_1+R_2} \quad (81)$$

Substituting the expressions in the op-amp model, we get:

$$U_{out} = -k(U_{in} + (U_{out} - U_{in})\frac{R_1}{R_1+R_2}) \quad (82)$$

Opening brackets we get:

$$U_{out} = -kU_{inx} - kU_{out}\frac{R_1}{R_1+R_2} + kU_{in}\frac{R_1}{R_1+R_2} \quad (83)$$

We transfer terms:

$$U_{out} + kU_{out}\frac{R_1}{R_1+R_2} = kU_{in}\frac{R_1}{R_1+R_2} - kU_{in} \qquad (84)$$

Let’s get Uin and Uout out of the brackets:

$$U_{out}\left(1 + k\frac{R_1}{R_1+R_2}\right) = kU_{in}\left(\frac{R_1}{R_1+R_2} - 1\right) \qquad (85)$$

Performing addition in brackets we get:

$$U_{out}(R_1 + R_2 + kR_1) = kU_{in}(R_1 - R_1 - R_2) \qquad (86)$$

Simplifying this expression:

$$U_{out}(R_1(k+1) + R_2) = -kU_{in}R_2 \qquad (87)$$

Now let’s express Uout through Uin:

$$U_{out} = \frac{-kU_{in}R_2}{(R_1(k+1)+R_2)} \qquad (88)$$

For sufficiently large k expression takes the form:

$$U_{out} = \frac{-U_{in}R_2}{R_1} \qquad (89)$$

We find gain:

$$G = -\frac{R_2}{R_1} \qquad (90)$$

As you can see, it is negative, so the amplifier is called inverting.

As it was already mentioned, the differential signal gain of an op-amp is sufficiently large. This means that for typical values of the voltage at the amplifier output (about 10-20V), the potential difference between the amplifier inputs will be about several millivolts. Accordingly, the potential of the junction point of R1 and R2 resistors in the circuit we have discussed before is near zero, which means that almost all of the input voltage is applied to the resistor R1, and the output voltage depends on the current flowing through this resistor, which is easily determined from the formula:

$$I_{in} = \frac{U_{in}}{R_1} \qquad (91)$$

Respectively:

$$U_{in} = I_{in} R_1 \tag{92}$$

Substituting this expression into (89) for inverting amplifier, we get:

$$U_{out} = -I_{in} R_2 \tag{93}$$

Resistor R1 may be omitted, and then we have a device that converts current to voltage, while having a sufficiently low input impedance. The circuit of such convertor is shown in Figure 38.

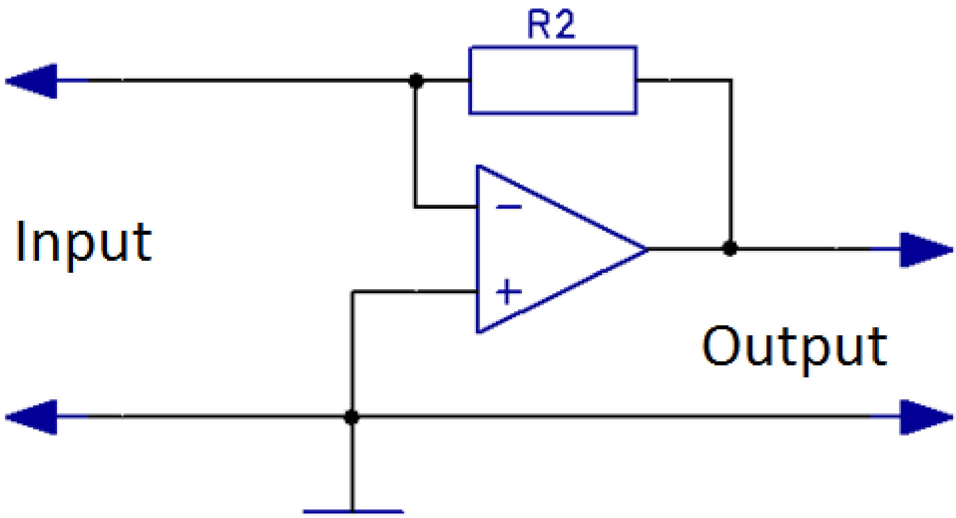


Figure 38 – Op-amp current-voltage converter

A differentiator can be built using the current-voltage converter. Its circuit is shown in Figure 39.

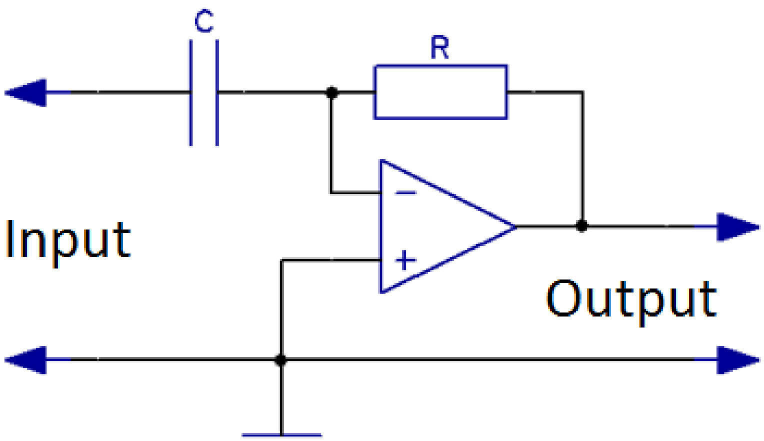


Figure 39 - Schematic diagram of the differentiator

For calculations we use the already known formula for the current-voltage converter (94)

$$U_{out} = -I_{in}R \tag{94}$$

For the capacitor C is true that:

$$\mathrm{C} = \frac{\mathrm{dq}}{\mathrm{dU_{in}}} \tag{95}$$

On the other hand, the amount of electricity can be expressed in terms of current through the capacitor and time:

$$I_{\mathrm{in}} = \frac{\mathrm{dq}}{\mathrm{dt}} \tag{96}$$

Expressing dq from two last formulas and equating them, we get:

$$\mathrm{C}\mathrm{d}U_{\mathrm{in}} = I_{\mathrm{in}}\mathrm{dt} \tag{97}$$

We express Iin then:

$$I_{\mathrm{in}} = \mathrm{C}\frac{\mathrm{dU_{in}}}{\mathrm{dt}} \tag{98}$$

Substituting Iin in the formula (94) we get:

$$U_{out} = -RC\frac{\mathrm{dU}_{in}}{\mathrm{dt}} \tag{99}$$

It is easy to notice that the output voltage is proportional to the rate of change of the input voltage. In other words, this circuit performs a mathematical operation of differentiation. Interchanging resistor and capacitor, an integrator can be obtained, a schematic diagram of which is shown in Figure 40.

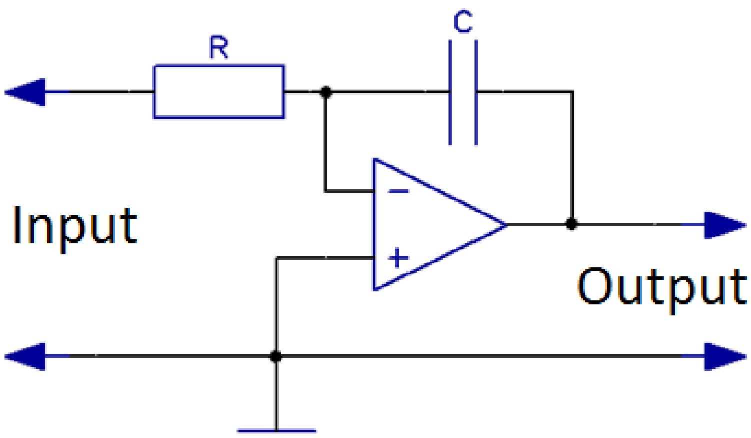


Figure 40 - Schematic diagram of integrator

Since the inverting input of an op-amp consumes almost no current, then the sum of currents flowing through the resistor and the capacitor must be zero:

$$I_R + I_C = 0 \tag{100}$$

Let’s express the current flowing through the resistor,in terms of the input voltage:

$$I_R = \frac{U_{in}}{R} \tag{101}$$

The current flowing through the capacitor is easy to express from the definition of capacitance:

$$I_C = C\frac{dU_{out}}{dt} \tag{102}$$

We equate the resulting expressions for the currents:

$$\frac{dU_{in}}{RC} = \frac{dU_{out}}{dt} \tag{103}$$

Integrating both sides of expression, bringing dt in the left side we get:

$$\frac{-1}{RC}\int U_{in}dt = \int dU_{out} \tag{104}$$

As a result, we get:

$$U_{out} = \frac{-1}{RC}\int U_{in}dt + U \tag{105}$$

We have proved that the device performs a mathematical operation of integration.

The previously reviewed op-amp circuits of electronic devices worked with negative feedback (ie, the output voltage, or a portion of it is applied to the inverting input of an op-amp). There are also circuits with positive feedback, one of which is a Schmitt trigger. Its circuit is shown in Figure 41.

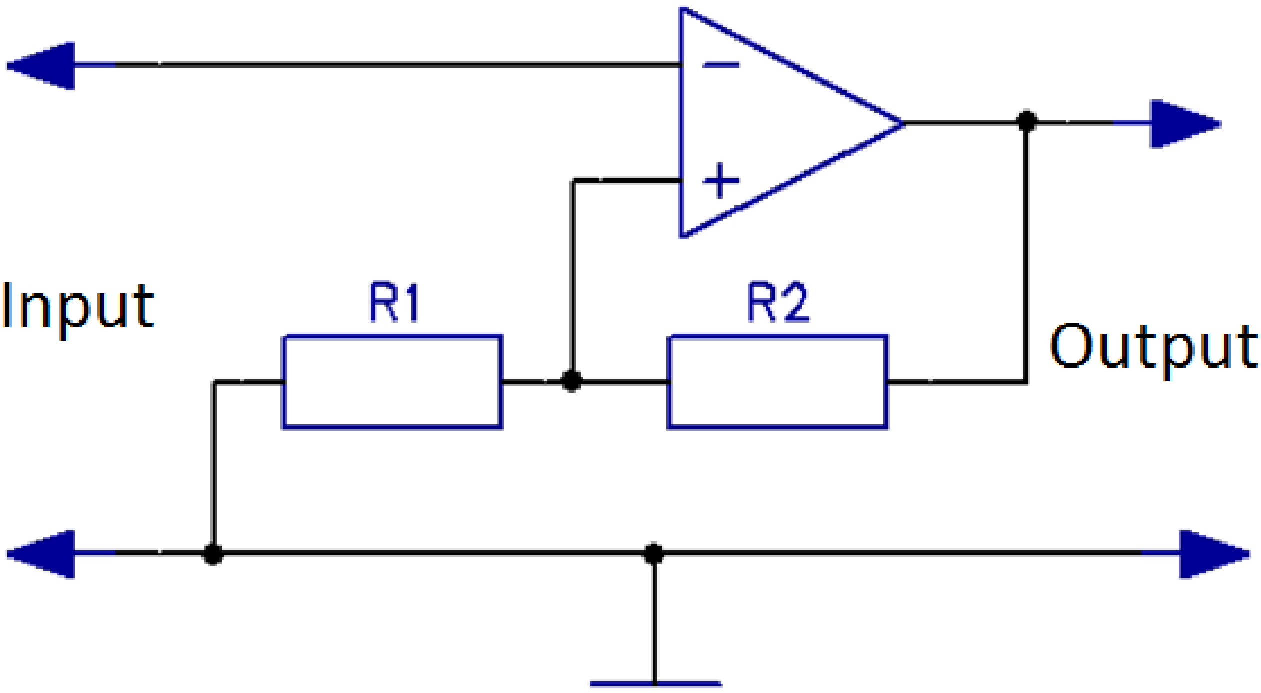


Figure 41 - Schmitt trigger

As it can be seen, the feedback divider is connected to the non-inverting input of the op-amp, and the input signal is applied to inverting input. Let's discuss the principle of operation of this circuit. The trigger can be in one of two stable states, in one of which the output potential close to the potential of the positive pole of the power source, the other one is in which the output potential is close to the potential of the negative pole (+ Up and -Up in Figure 42). In this case, the voltage at the non-inverting input of the amplifier is given by the following expression

$$Usw = \pm \frac{UpR1}{R1+R2} \tag{106}$$

Sign in this expression depends on the state in which the trigger is.

Let us assume that the trigger is in the positive state (Uout = +Up). For any input voltage is less than + Usw, the op-amp will save the state, because in spite of the previously reviewed mathematical model, it can not deliver a voltage greater than + Up. Now we will increase the input voltage from zero to + Usw. When the input voltage slightly exceeds the threshold (Usw), the output voltage will start to decrease, causing a decrease in the voltage at the noninverting input. This will lead to a decrease in the output voltage. The process will develop as an avalanche as long as the output voltage becomes equal -Up.

A further decrease in voltage at the output of op-amp is impossible by virtue of its design features. In this state, the trigger works exactly the same, but the threshold voltage has a different sign and in order to return to the state when Uout = + Up, we should reduce the input voltage to -Usw.

These processes are reflected in Figure 42.

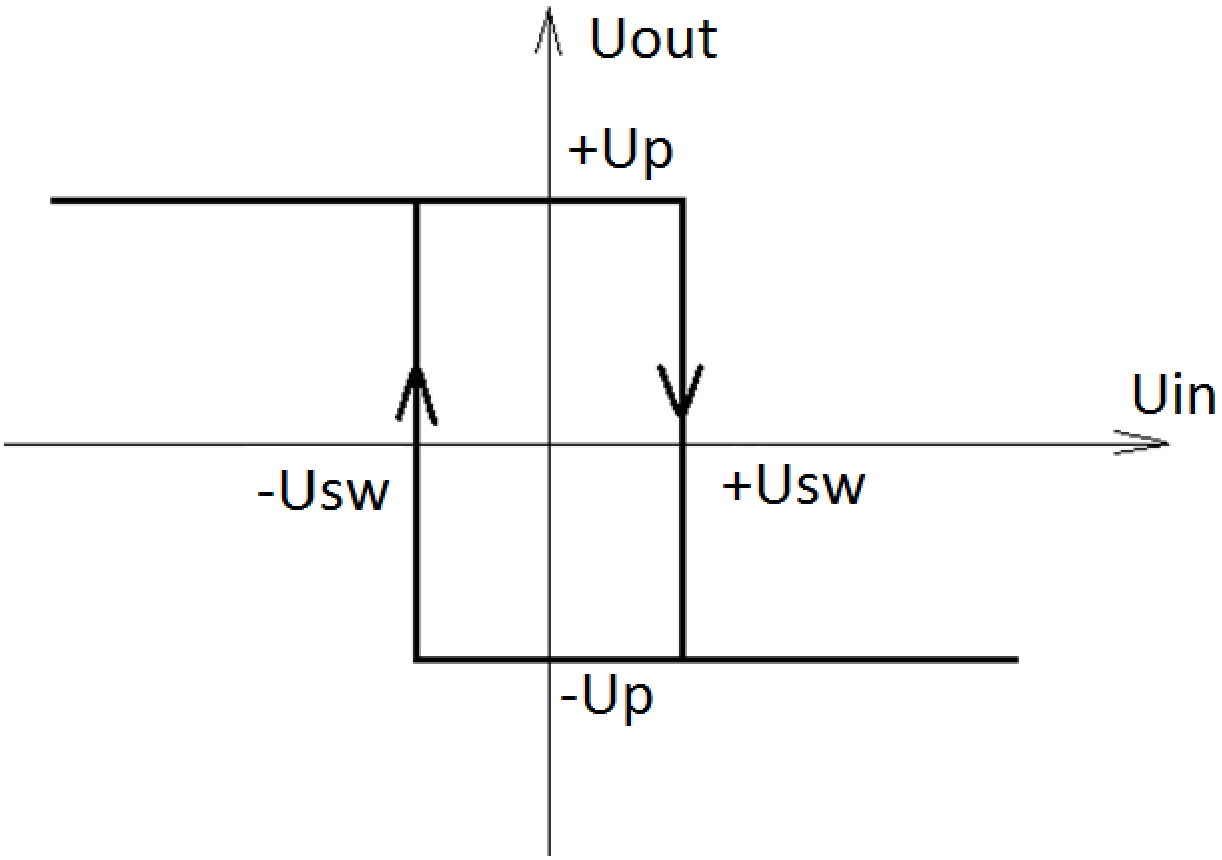


Figure 42 - The transfer characteristic of the Schmitt trigger

So, the trigger has two stable states and two different input threshold levels respectively.

3.4 Questions

1. What is a bipolar junction transistor?
2. Describe the structure of a BJT
3. Which types of BJTs are used in electronics?
4. How does a BJT work?
5. What are transistors used for?
6. Which properties of BJT do you know?
7. What is the Ebers-Moll BJT model?
8. Which configurations of transistor circuits do you know?
9. What is biasing of transistors?
10. How to design a common emitter amplifier?
11. How to design a common collector amplifier?
12. What are the main drawbacks of single-ended transistor amplifiers?
13. What is a differential amplifier?
14. What is an operational amplifier?
15. Which units can be built using op-amps?

4. Signal Generators

4.1 Main types of signals

The signals used in electronics have great variety of shapes, however, it is possible to identify the main, basic types of signals, which can somehow represent all the rest.

A sine wave is one of the most commonly used types of signals in radio engineering. Its shape is shown in Figure 43.

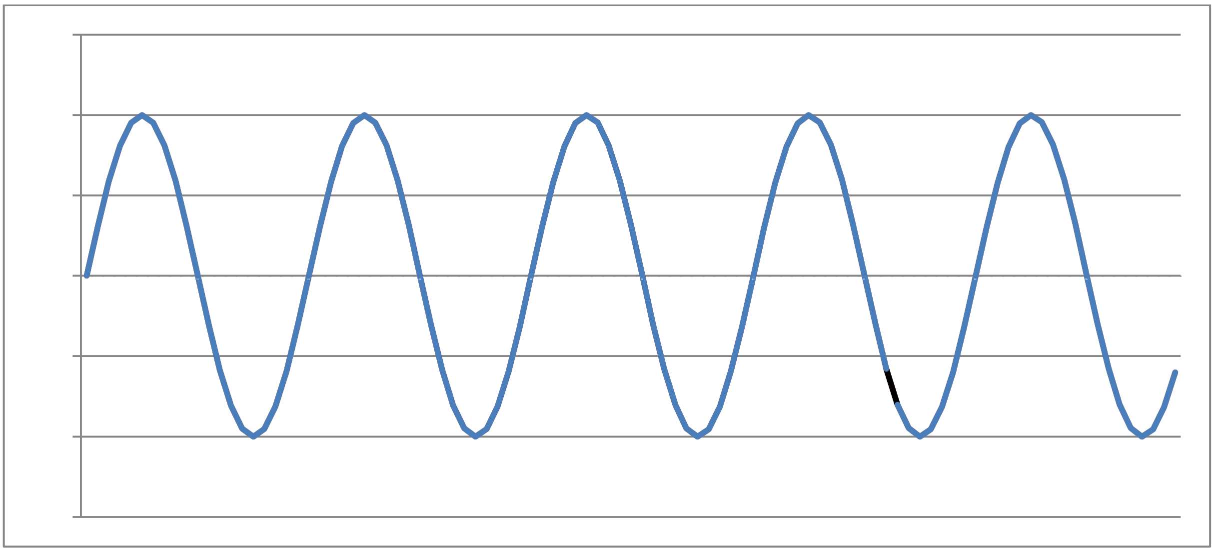


Figure 43 - Sine wave

Another type of signal - rectangular, in contrast to sinusoidal takes one of two possible values. Its shape is shown in Figure 44.

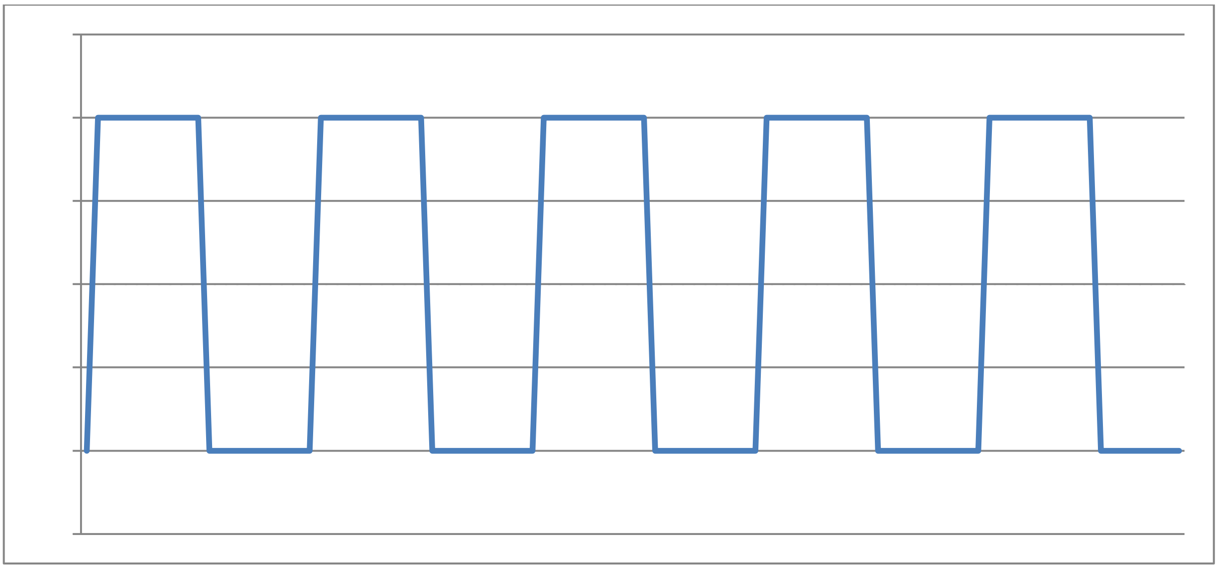


Figure 44 - Rectangular signal

Triangular (linearly) signal consists of straight line segments. Its shape is shown in Figure 45

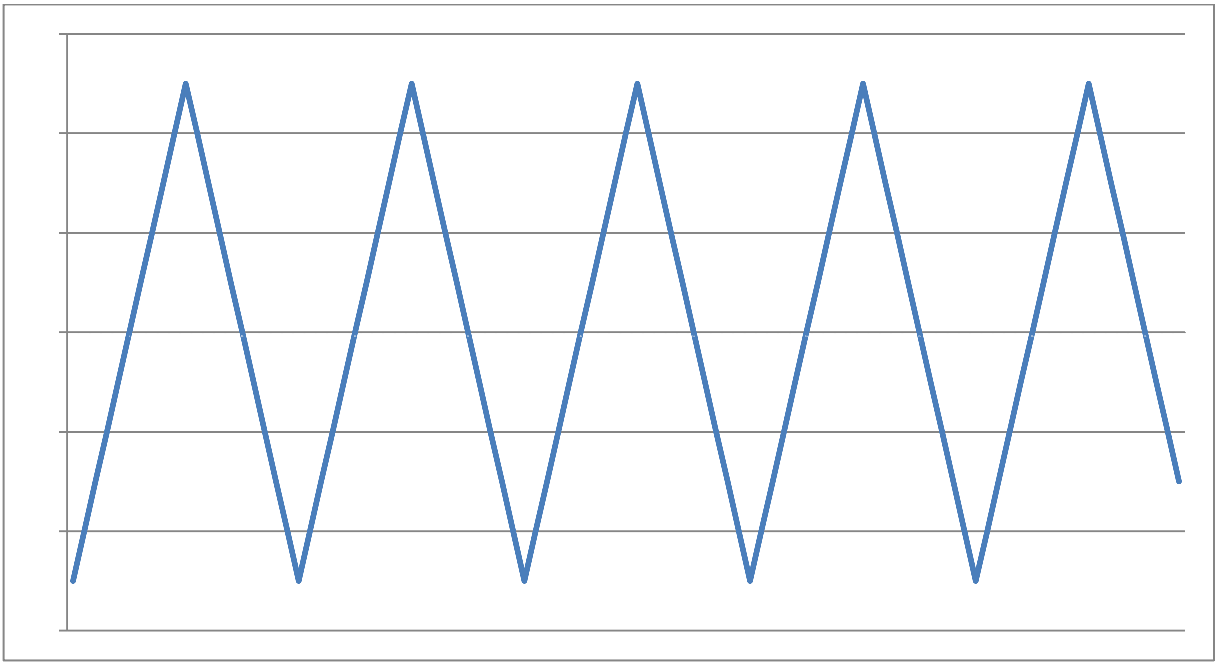


Figure 45 - The triangular signal

A sawtooth signal is used as the scanning signal in electronic oscilloscopes and television systems. Its shape is shown in Figure 46.

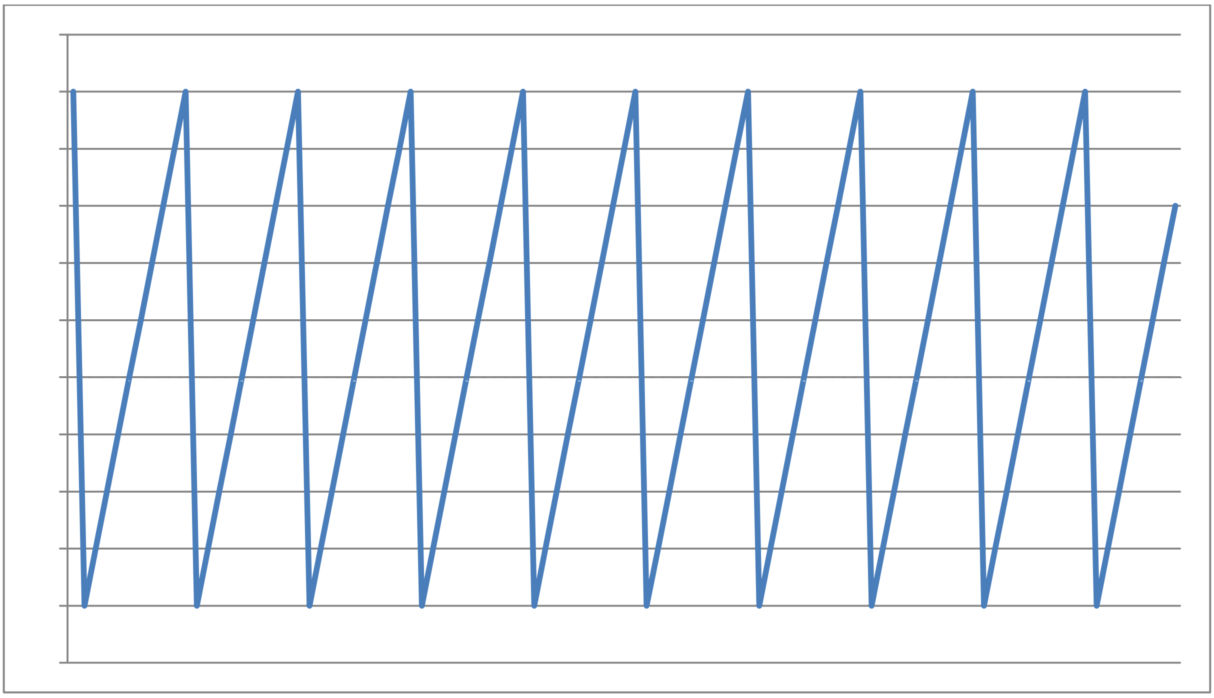


Figure 46 – sawtooth signal shape

A generator is a device for converting the energy consumed from the power supply into AC voltage of given shape. In general, any form of signal generator may be represented as a device consisting of two components: amplifier and a positive feedback circuit connected as shown in Figure 47.

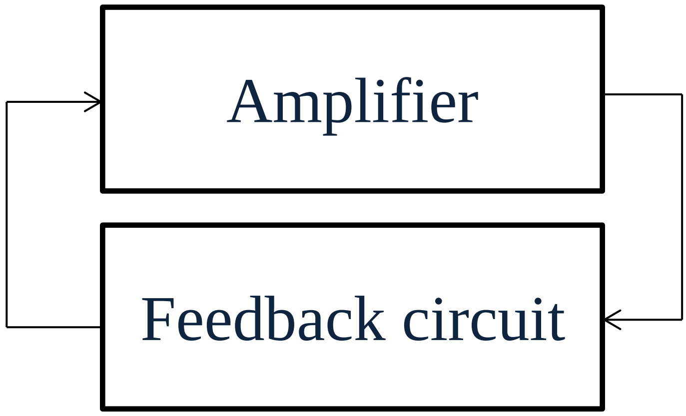


Figure 47 - Block diagram of a signal generator

As it can be seen, the signal from the positive feedback loops to the amplifier input and then from the amplifier output to the input of the feedback circuit. Typically, the shape and the spectrum of the generated signal is determined by the parameters of the feedback circuit. Usually it consists of frequency-dependent elements, such as inductors, capacitors, crystal resonators.

For the normal operation of a signal generator two conditions must be fulfilled: the amplitude balance and phase balance. In order to clarify the meaning of these terms, we introduce the concept of open-loop oscillator circuit. It consists of amplifier and feedback circuit connected in series as shown in Figure 48.

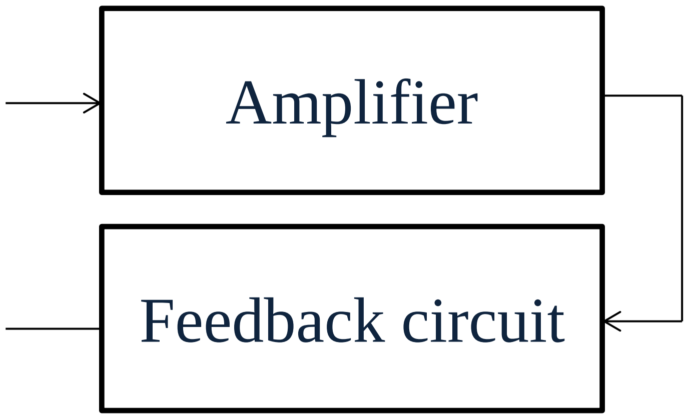


Figure 48 – Open-loop generator circuit

Given this model, the conditions for self-excitation of the generator are as follows:

The balance of the amplitudes: Gain of the open circuit at an operating frequency must be not less than unity (i.e., amplifier at least completely compensates the insertion loss of the feedback circuit)

Phase balance: The phase shift of an open-loop circuit at an operating frequency must be a multiple of 2π

If both these conditions are met for a set of frequencies, the generator may simultaneously oscillate on each of them.

4.2 LC-oscillator with feedback transformer

One of the simplest sinusoidal signal generatorы is generator with a transformer LC feedback circuit as shown in Figure 49. It consists of amplifier transistor VT1, a collector circuit of which includes an oscillating circuit L1C1, being simultaneously the feedback circuit element. This circuit also comprises inductively coupled with coils L1 L2 coil which works to supply feedback signal to the input of the amplifier - thea base circuit of the transistor VT1. R1R2 divider is used to bias transistor.

This generator produces a sinusoidal oscillation at a frequency close to the natural frequency of the oscillation circuit L1C1.

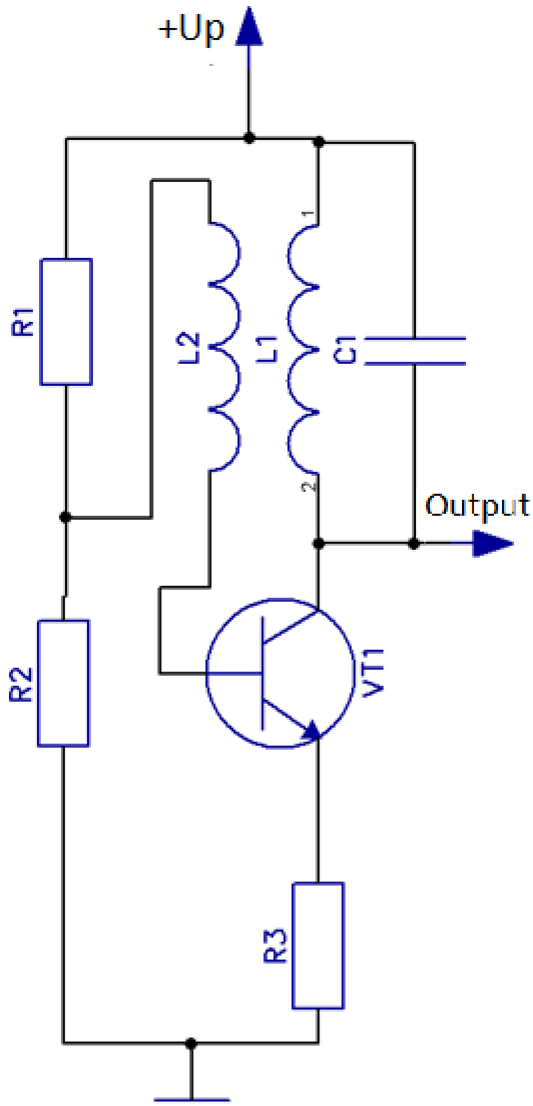


Figure 49 - LC oscillator with transformer feedback

LC oscillators have a common disadvantage - it is difficult to obtain oscillations of relatively low frequencies (less than a hundred kilohertz). This is due to the fact that for a given required frequency range a sufficiently large inductor coil and the capacitor capacity is too large that it is impossible to make them small-sized.

4.3 Wien-Robinson bridge generator

For operation at low frequencies RC oscillators are much more useful. The feedback circuit of them consists only of resistors and capacitors. Through the application of sufficiently large resistance resistors (units and tens of megaohms) it becomes possible to get frequencies down to several tenths of a hertz, while keeping the generator dimensions quite acceptable.

One of RC oscillators of sinusoidal signal is based on the Wien-Robinson bridge. The circuit of such a generator is shown in Figure 50.

The generator consists of R1R2R3R4C1C2 bridge in both diagonals of which connected an operational amplifier. It is easy to notice that the R1R2 circuit is a feedback circuit for the operational amplifier, and R3R4C1C2 is the positive feedback circuit. The natural frequency of the oscillator circuit depends on the elements values of positive feedback.

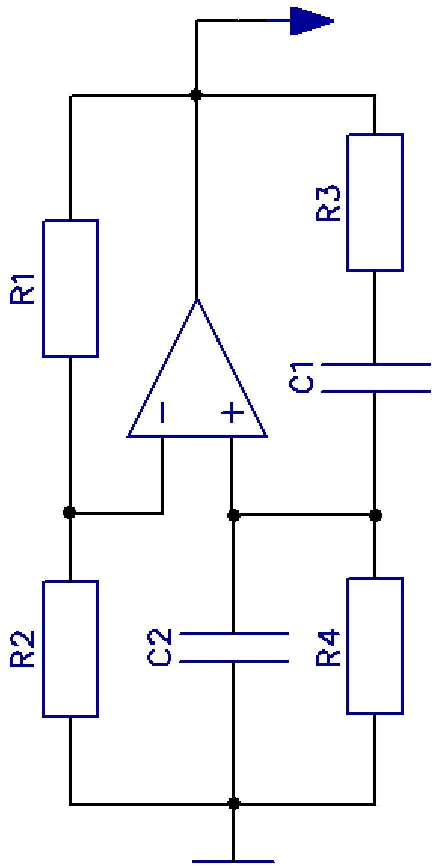


Figure 50 – Generator based on Wien-Robinson Bridge

4.4 Astable multivibrator

For generating rectangular waveform an op-amp based multivibrator can be used as shown in Figure 51. It consists of a Schmitt trigger, a feedback circuit which is a voltage divider R1R2 and integrating circuit C1R3, on which the oscillation frequency depends. Let's consider the principle of operation of a multivibratior in more detail. Assume that the capacitor has been discharged in the initial state, the Schmitt trigger is in a state in which the output voltage is positive. The capacitor begin charging to a positive potential relative to the common ground through resistor R3, while the voltage across it reaches the voltage threshold of the trigger. This will cause the trigger to switch to another state in which the voltage at the output is negative, and the capacitor begins to recharge to a negative potential. This process also continues until the threshold is reached, causing the flip-flop to switch back to the state with a positive voltage on the output. Thus, the output of the multivibrator is rectangular pulses.

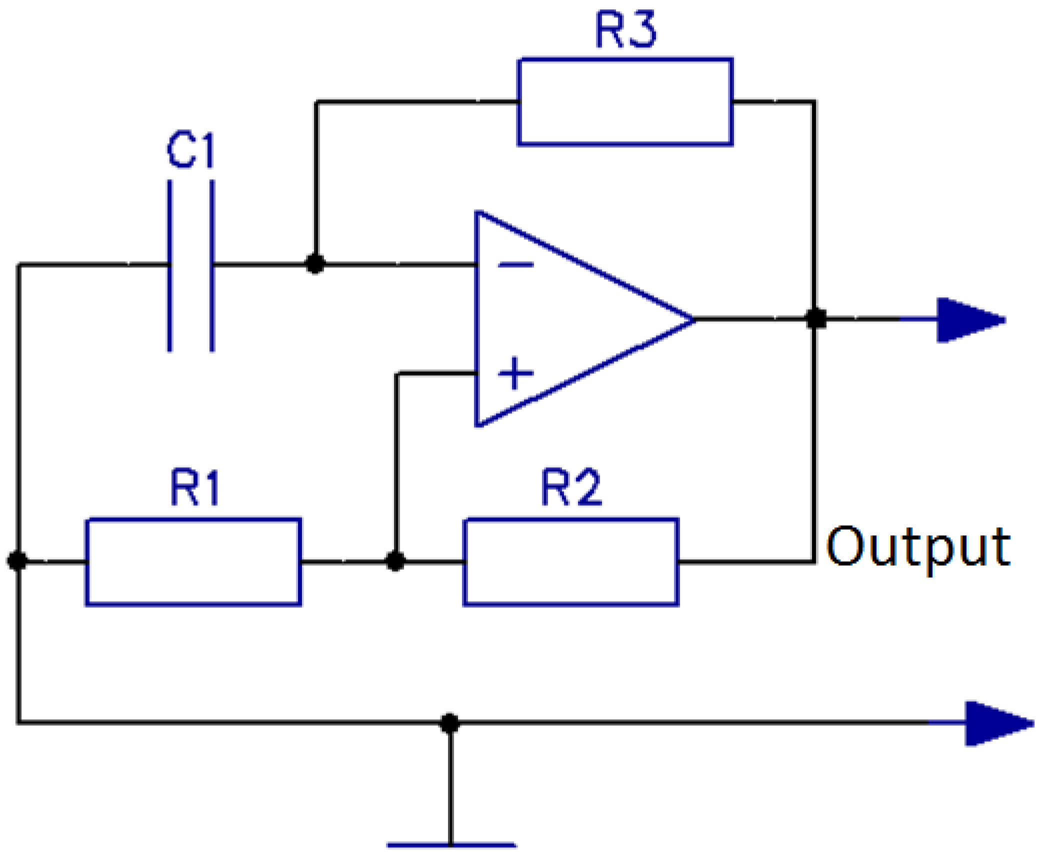


Figure 51 – Op-amp multivibrator

4.5 Function generator

A function generator may be used to obtain a signal of triangular and rectangular forms (at the same time). The circuit is shown in Figure 52. It consists of a Schmitt trigger and an operational amplifier integrator which are connected in the closed loop.

Let's consider the function generator operating principle in more detail. Assume that in the initial state the integrator output was zero, and the Schmitt trigger is in a state in which the output voltage is positive. Since the input of the integrator is applied with positive voltage, the voltage at the output will decrease linearly until it reaches the trigger threshold voltage. This will cause the trigger to switch to another state in which the voltage at the output is negative, and the voltage at the output of the integrator will increase linearly then. This process also continues until the threshold is reached, causing the trigger to switch back to a state with a positive voltage on the output. Thus, at the output of the Schmitt trigger rectangular pulses are formed, and the output of the integrator is a triangular shaped signal.

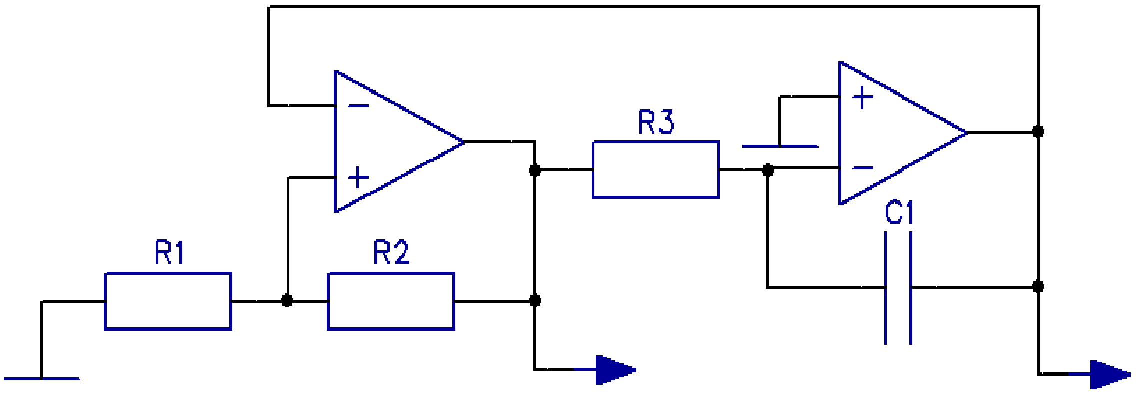


Figure 52 - Function generator

4.6 Questions

1. What is a signal in electronics?
2. Which kinds of signals do you know?
3. What is a signal generator consist of?
4. Which conditions of self-oscillation do you know?
5. Which generators can be used to produce sinewave?
6. What's the main advantage of the Wien-Robinson generator?
7. What does a function generator consist of?

5 Digital electronics

5.1 Logic elements

Along with analog electronics, discussed earlier, there widely used various devices of digital electronics. Digital electronics replaced analog electronics in many fields due to greater noise immunity, high efficiency and reliability [4].

The basis of the digital circuits are logic elements - devices for performing elementary logic operations. Each of the logic elements has one or more inputs and one output. Each of the inputs and outputs can be either in one of two logical states, which correspond two voltage levels: High (logic one, truth) and low (logic zero, false).

Let's discuss the basic logic operations in more detail. The simplest operation is negation (not). The truth table for this operation is shown in the table 1.

Table 1 - logic function "NOT"

X	$\overline{X}$
0	1
1	0

This logic function performed by the logic element "NOT", the graphic symbol of which is shown in Figure 53.

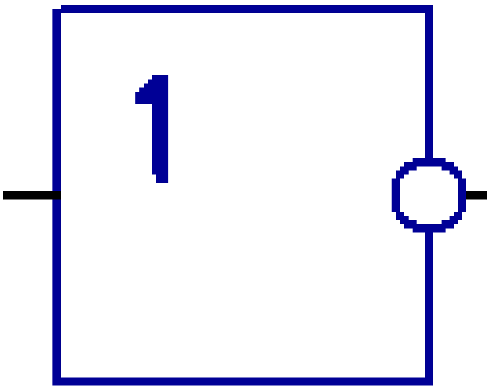


Figure 53 - "NOT" logical element

One of binary logical operations (operation with two arguments) is a logical multiplication operation, otherwise known as "AND" operation. Its truth table is shown in Table 2.

As it can be seen, this operation is true only if both of its arguments are true. It is easy to notice that it fully coincides with the multiplication arithmetic operation [5].

Table 2 - logic function "AND"

X	Y	$X \wedge Y$ ("AND")
0	0	0
0	1	0
1	0	0
1	1	1

AND function is performed by AND logic gate. Its graphic symbol is shown in Figure 54.

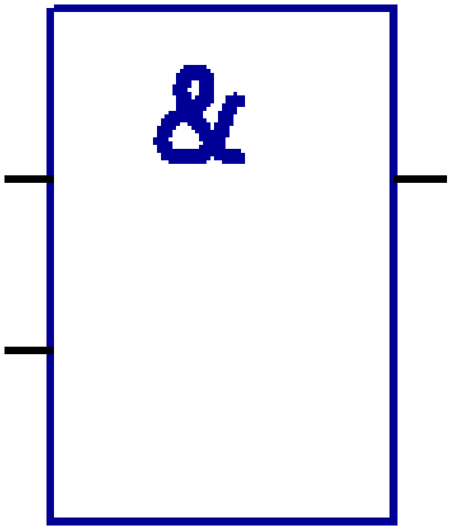


Figure 54 -"AND" logic gate

Another basic logical operation is logic addition operation which is also called "OR" operation. Its truth table is shown in Table 3. As can be seen, this operation is true if is at least one of its argument is true.

Table 3 - logic function "OR"

X	Y	$X \vee Y$ ("OR")
0	0	0
0	1	1
1	0	1
1	1	1

Logical addition function is performed by logic element "OR" graphic symbol of which is shown in Figure 55.

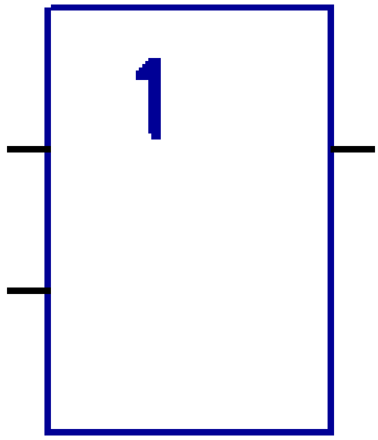


Figure 55 - "OR" logical element

Another important operation is exclusive OR ("XOR"), which is true if its operand are not equal, and false if they are equal. The truth table for this operation is shown in Table 4.

Table 4 - logic function "XOR"

X	Y	$X \oplus Y$ (Excl. "OR")
0	0	0
0	1	1
1	0	1
1	1	0

The function "exclusive OR" is performed by the appropriate logic element, the symbol of which is shown in Figure 56.

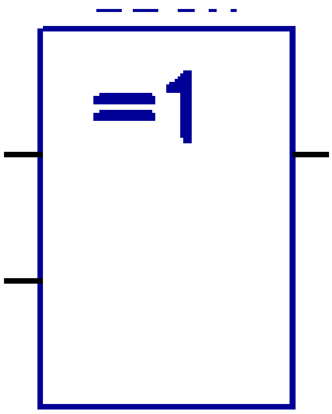


Figure 56 – XOR logic element

Boolean functions are often used together with "NOT" function One of these logical operations - "NAND", which is a negation of the logical multiplication. The truth table, for this logical operation shown in the table 5.

Table 5 - logic function "NAND"

X	Y	$\overline{X \wedge Y}$
0	0	1
0	1	1
1	0	1
1	1	0

Logical operation "NAND" is performed by the element, graphical symbol of which is shown in Figure 57.

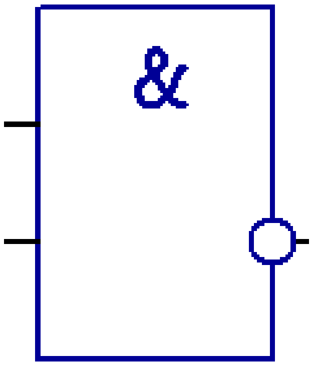


Figure 57 - gate "NAND"

Also often used the negation of logical addition - function "NOR" truth table of which is shown in the table 6.

Table 6 - logic function "NOR"

X	Y	$\overline{X \vee Y}$
0	0	1
0	1	0
1	0	0
1	1	0

This function is performed by gate "NOR" graphical symbol of which is shown in Figure 58.

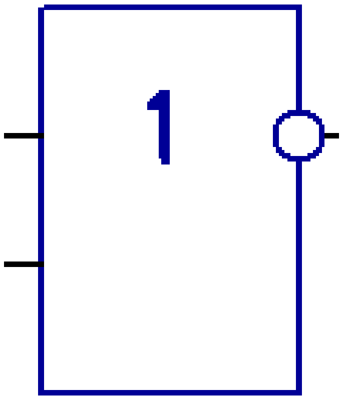


Figure 58 - "NOR" gate

The logic elements can be assembled into devices that implement more complex logic functions. There are also logical elements with a large number of inputs (up to eight), but they perform the same logic functions.

5.2 Series type logic circuits

Series logic devices are the devices which behavior is determined not only by signals applied to the inputs but also by the state in which the device is at the current moment of tme. Typically, such devices have a feedback circuit, sending signals from the outputs of the device to its inputs.

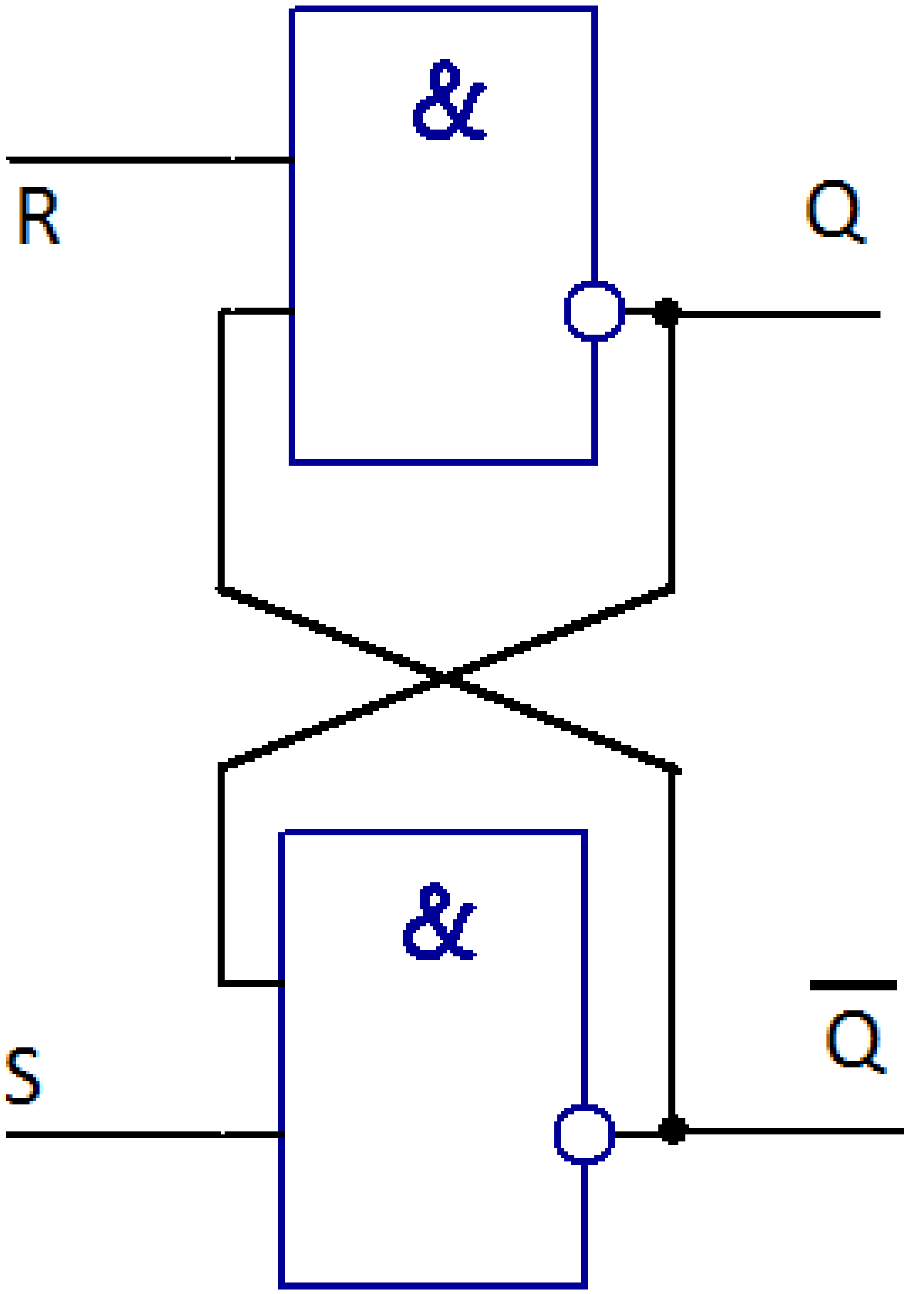


Figure 59 - RS-flip-flop

The simplest series type device is RS-type flip-flop. It is usually based on NAND logical elements and its typical circuit is shown in Figure 59. The flip-flop has two inputs R and S and two outputs: $Q\ and\ \bar{Q}$ non-inverting and inverting respectively.

Let's consider the operation of the flip-flop in more detail. Assume that both inputs of the flip-flop are in the zero state. In this case, both the outputs of the flip-flop will switch to logic one state. Now we will provide a high logic level at input R. In this case, the upper (in the circuit) logical element switches to a zero state, a logic-zero level from its output will switch the bottom (in the circuit) element to zero state. If we apply a high logic level at the S input, the lower (in the circuit) element switches to the zero state , the upper would be in the logic one state.

In the case of high logic level at both inputs of the flip-flop, it maintains a state in which it was before. The above processes are shown in Table 7.

Table 7 - RS-flip-flop truth table

R	S	Q	$\bar{Q}$
0	0	1	1
0	1	1	0
1	0	0	1
1	1	Previous state	

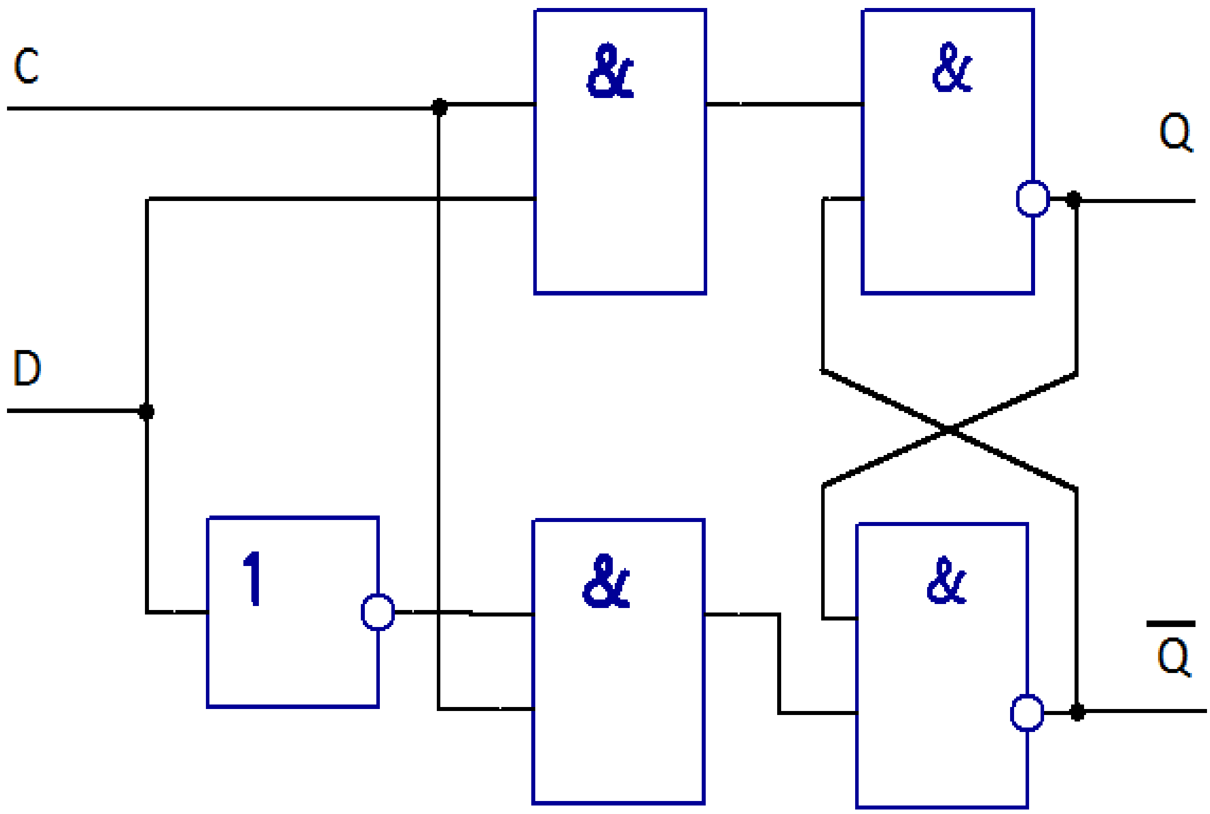


Figure 60 - D-type flip-flop

It is easy to note that the RS-flip-flop performs a memory function: feeding certain logical levels to the inputs one can change the flip-flop state, erase recorded information (supplying logic zeros on both inputs), store the recorded information by applying high logic levels at the inputs.

The disadvantage of the RS-flop-flop is that the control of information storage and transmission of the information in it is carried out using the same inputs, which is very inconvenient in practice. To eliminate this drawback D-trigger has been developed, which schematic diagram is shown in Figure 60.

It is easy to notice, that this flip-flop consists of an RS-type flip-flop, supplemented with logic elements. It has two inputs: an information input D and the clock input C.

The logic of D-type flip-flop is very simple: when a high level is applied to the input C, it switches to the state corresponding to the logical level at the input D, when the input C is in the zero state, the flip-flop keeps its previous state. Thus, in this flip-flop the information and storage control logic inputs are separated, which makes it more convenient to apply it in the of devices of digital electronics.

Graphic symbol of an D-type flip-flop is shown in Figure 61.

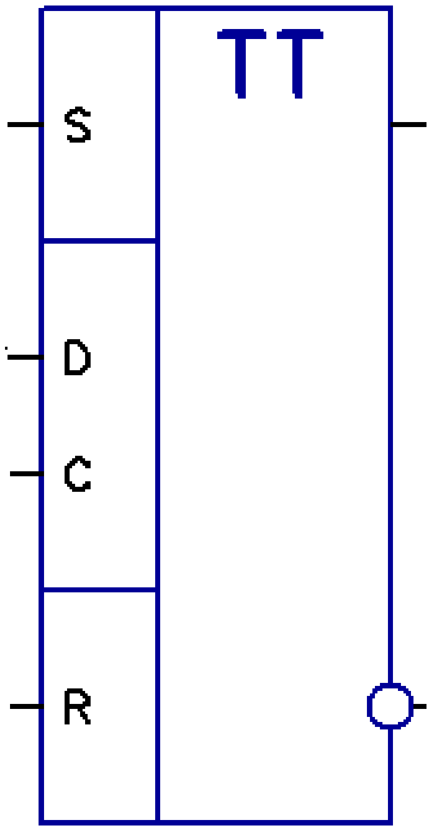


Figure 61 - Graphic symbol of D-type flip-flop

Another flip-flop based on RS-trigger is T- type flip-flop. The concept of this flip-flop is shown in Figure 62. This device, unlike D-flip-flop has no data input. The logic of the T-type flip-flop is that it changes its state to the opposite at each pulse on the input C.

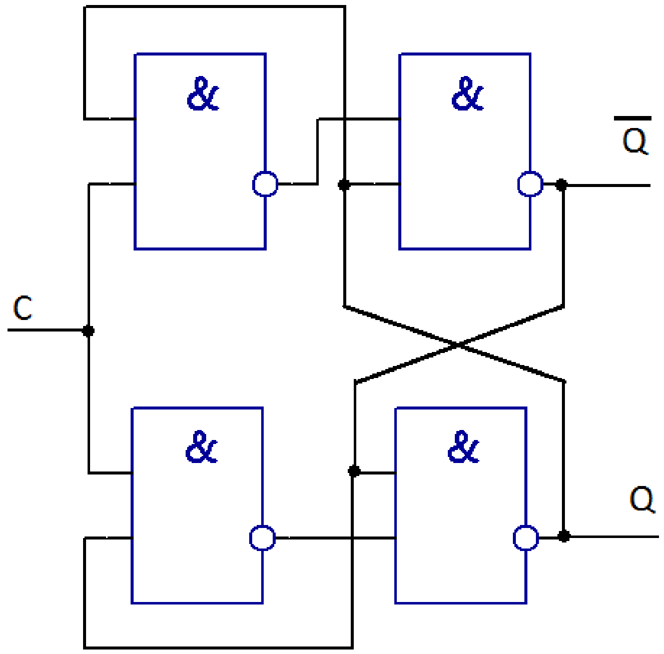


Figure 62 - T-type flip-flop

Another kind of serial type logical devices is register. Registers are used to store multiple bits of information, for converting serial data representation to parallel and vice versa, as well as for many other purposes.

Let's consider the operation of the simplest three-bit register, the schematic diagram of which is shown in Figure 63.

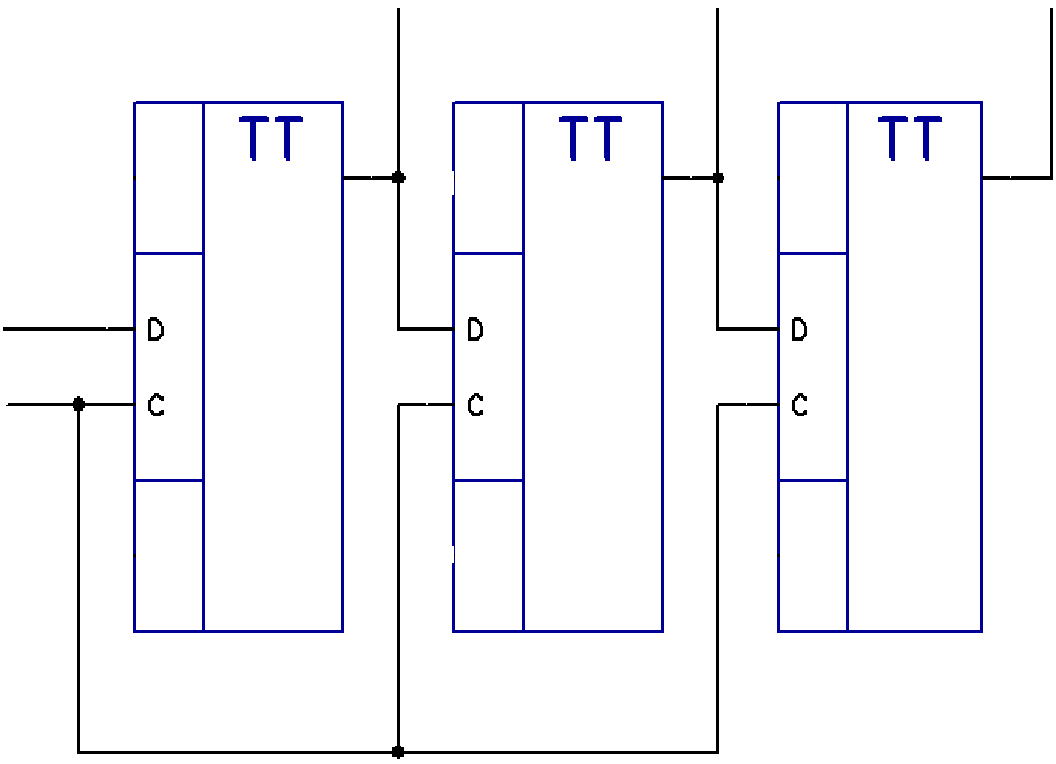


Figure 63 - Schematic diagram of register

This register consists of three flip-flops of type D, connected in series. It has a clock input C, a data input D and three outputs: Q1, Q2 and Q3. The clock signal from the input terminal C is applied simultaneously to C inputs of the flip-flops. When a high level at the input of register C stores the first trigger condition, which becomes the same as at the input of the register D, the second flip-flop stores the state of the first flip-flop and the third flip-flop stores the state of the second. Thus, the data written in the register are «shifted" one position to the right.

5.3 Questions

1. Which Boolean operations do you know?
2. Which rules of Boolean algebra do you know?
3. What is a truth table?
4. What are logic gates?
5. What is a binary coder and how does it work?
6. What is a binary decoder and how does it work?
7. Where multiplexers can be used?
8. What is a flip-flop?
9. Which kinds of flip-flops do you know?
10. Where binary counters are used?
11. What are registers used for?

6 Problems

6.1 Problem 1

Describe all the electronic device elements you know in one of the following circuits. Find the elements you're not familiar with and try to search for them in literature [1].

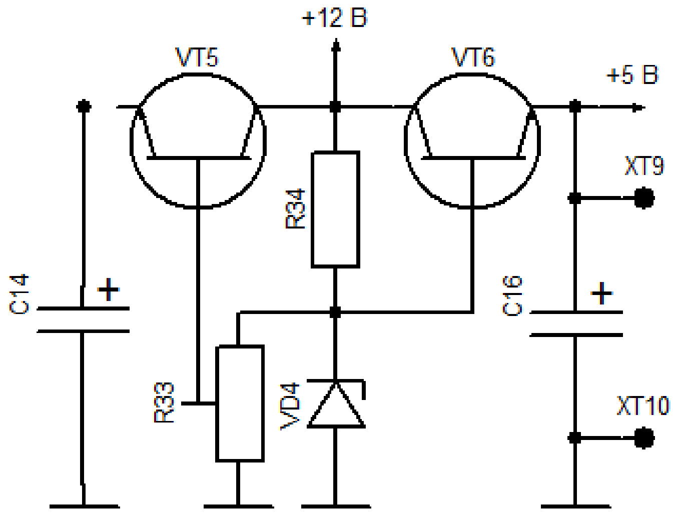


Figure 64 – Circuit 1 for problem 1

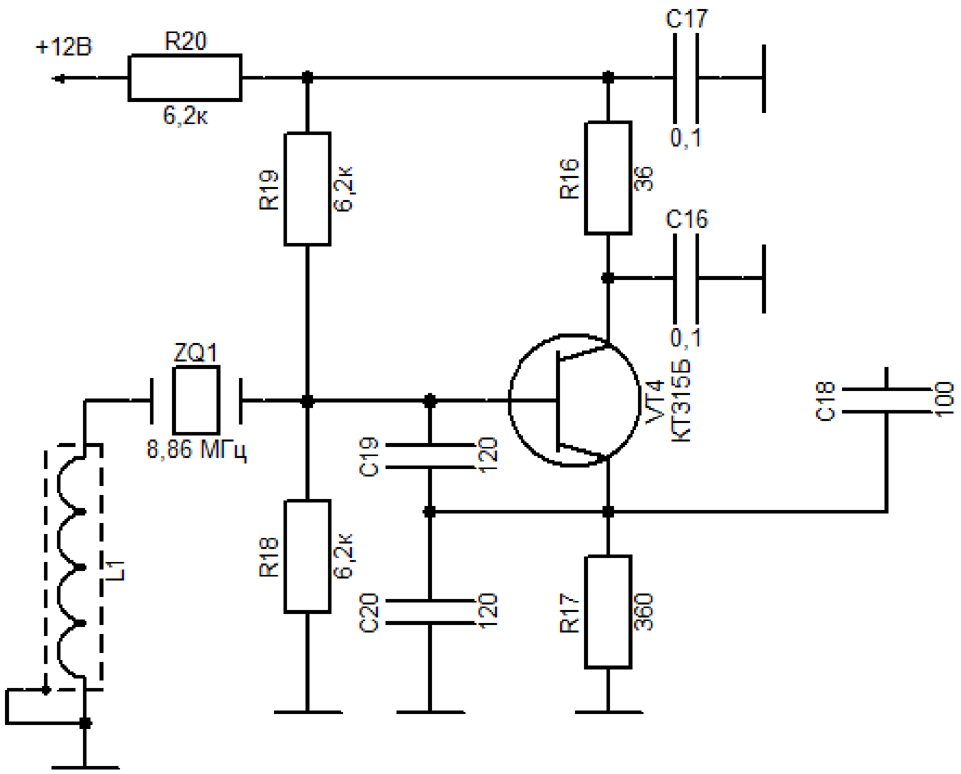


Figure 65 – Circuit 2 for problem 1

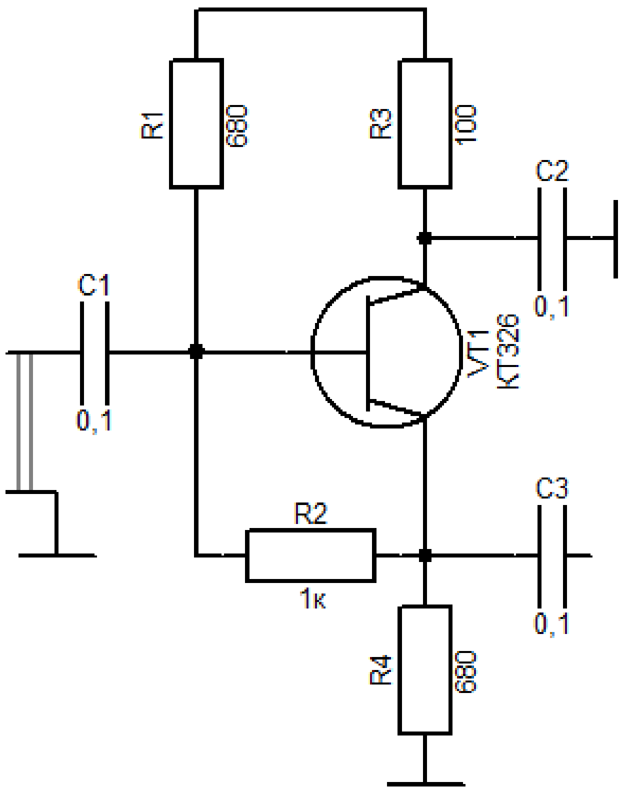


Figure 66 – Circuit 3 for problem 1

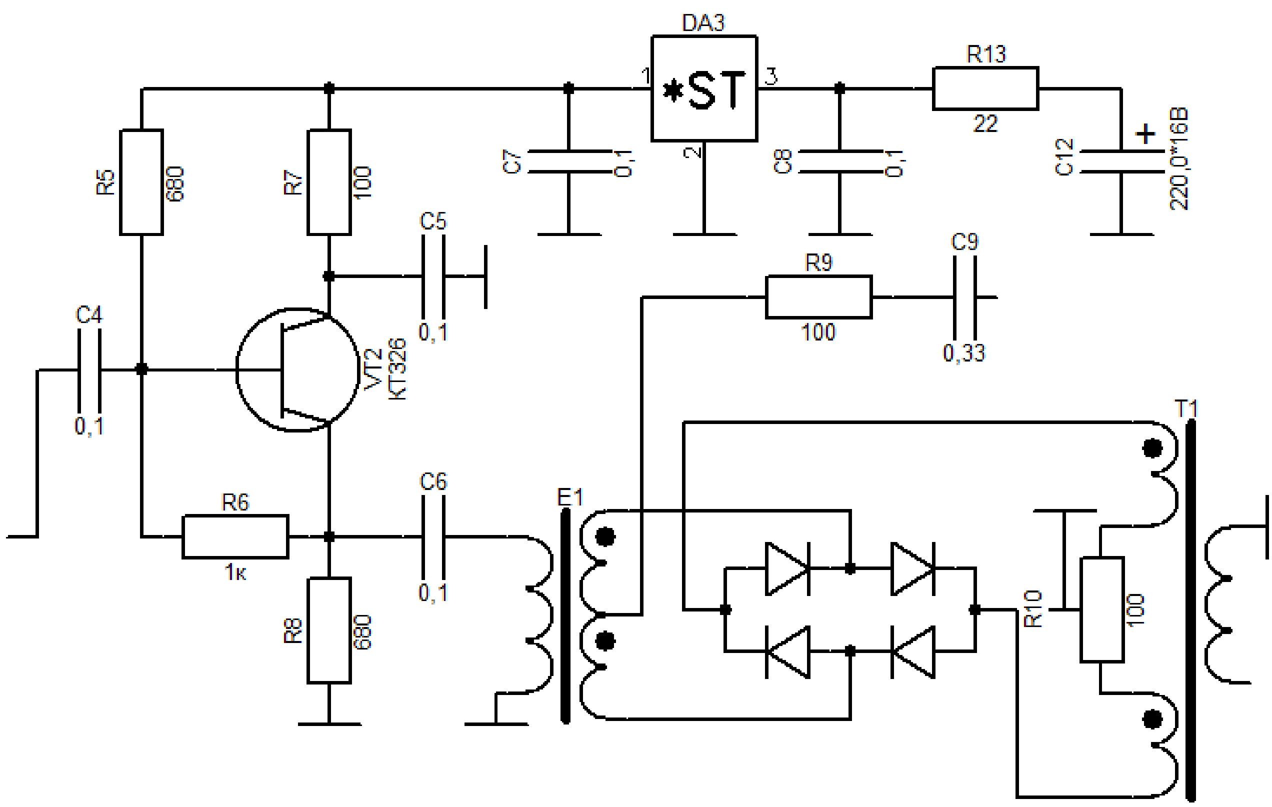


Figure 67 – Circuit 4 for problem 1

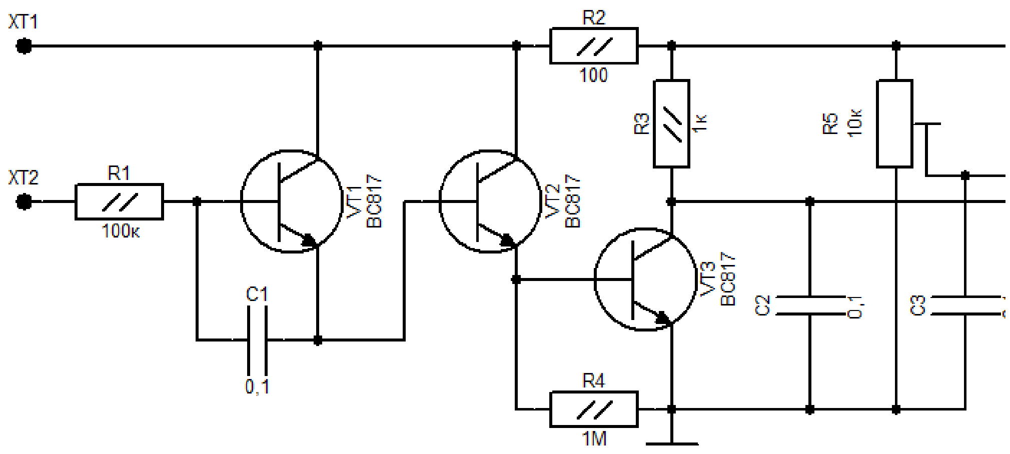


Figure 67 – Circuit 5 for problem 1

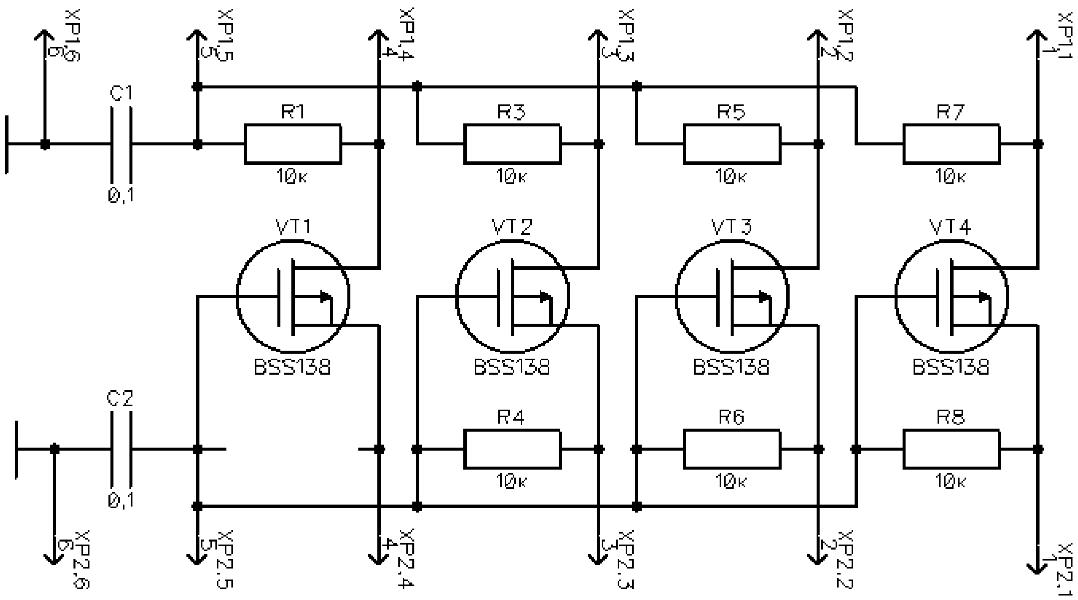


Figure 68 – Circuit 6 for problem 1

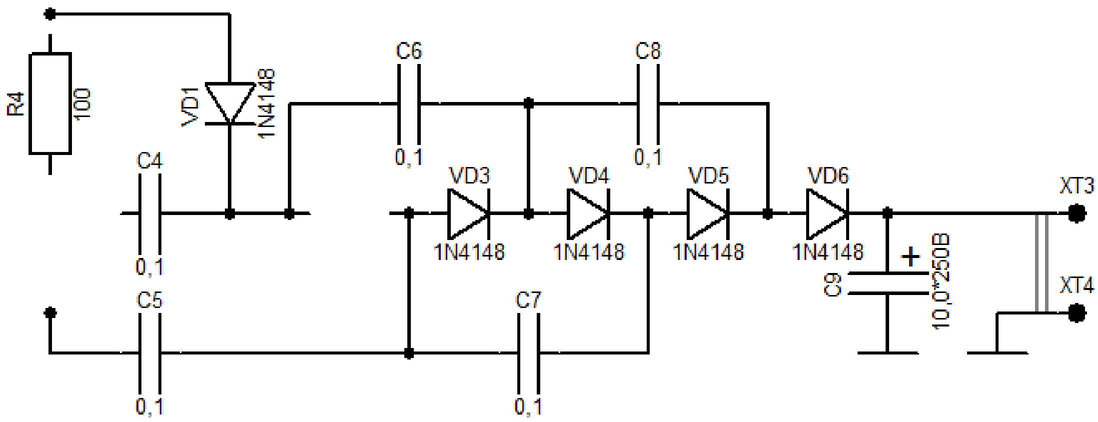


Figure 69 – Circuit 7 for problem 1

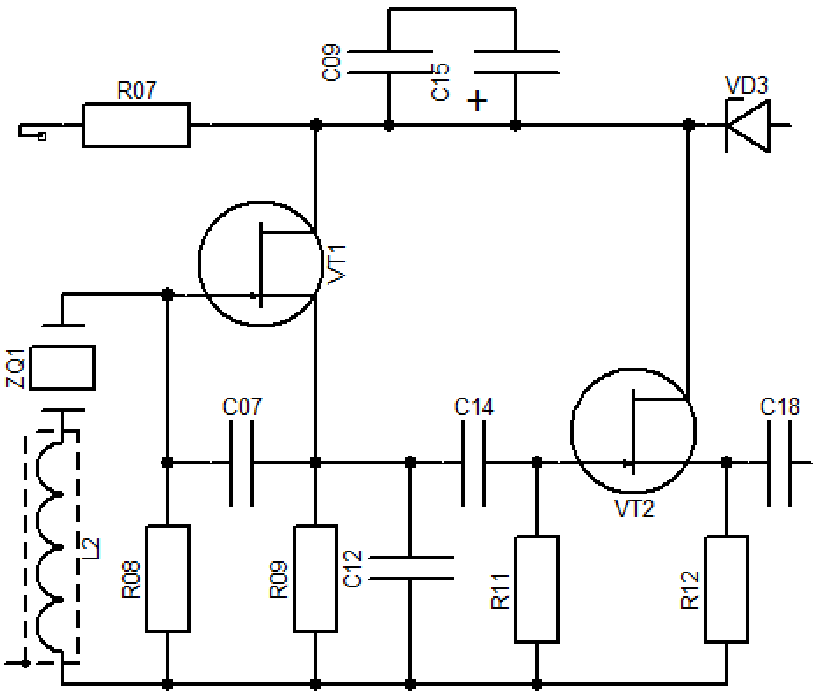


Figure 70 – Circuit 8 for problem 1

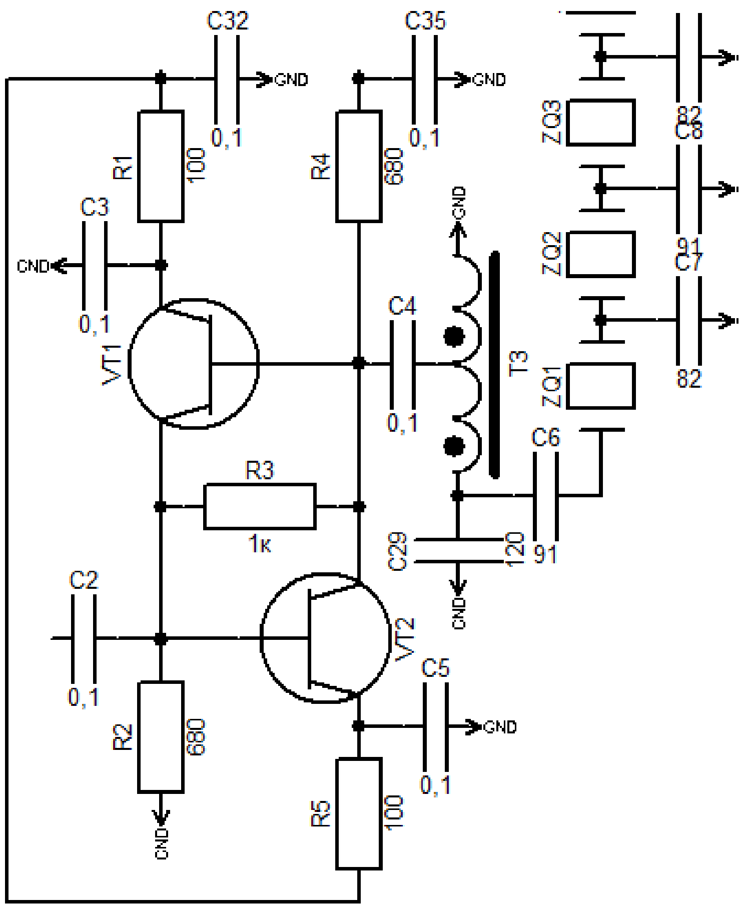


Figure 71 – Circuit 9 for problem 1

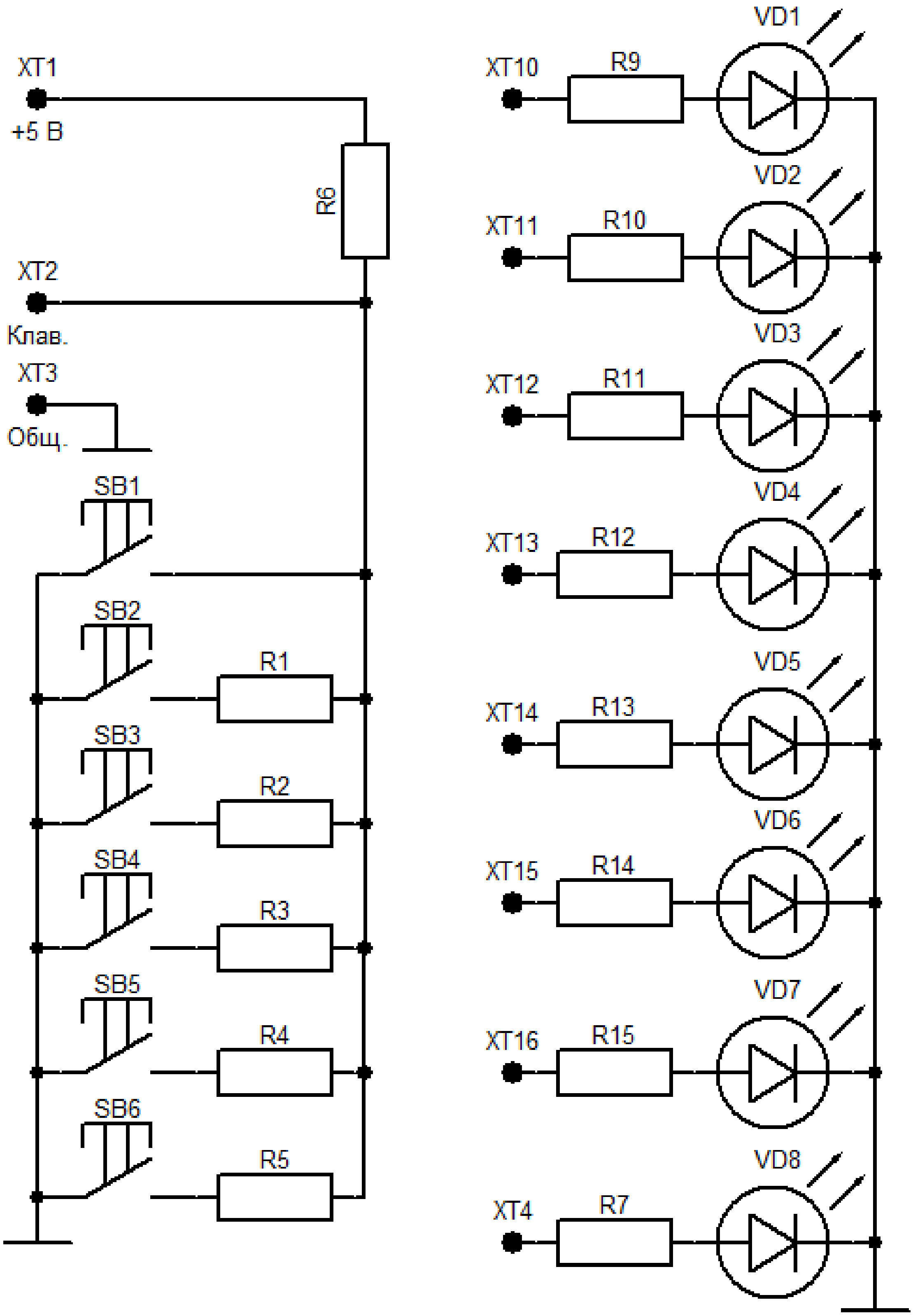


Figure 72 – Circuit 10 for problem 1

6.2 Problem 2

*Part 1.*Design an unregulated power supply using the data from Table 8.

Table 8 – Data for designing power supply

Option	Rectifier type	Current frequency, Hz	Ripple voltage, mv
1	Bridge	50	1210
2	Bridge	60	1040
3	full-wave	50	730
4	half-wave	50	1330
5	full-wave	60	310
6	full-wave	50	910
7	half-wave	50	280
8	half-wave	60	1020
9	Bridge	50	1460
10	Bridge	60	1100
11	full-wave	50	1260
12	half-wave	50	590
13	bridge	60	630
14	full-wave	50	1010
15	full-wave	60	1200

*Part 2.*Design a Zener diode voltage regulator using the data from Table 9

Table 9 – Data for designing Zener diode regulator

Option	U in min, V	U in max	I L min, mA	I L max, mA
1	15	17	15	38
2	17	19	23	41
3	16	18	27	35
4	15	17	14	18
5	16	18	14	42
6	16	18	27	37
7	16	18	12	30
8	17	19	21	41
9	16	18	14	34
10	16	18	14	25
11	16	18	20	24
12	16	18	13	46
13	17	19	29	33
14	16	18	26	45
15	15	17	23	43

Iz min=5 mA; Iz max=70 mA; Uz=12V

For every problem the solution should include full circuit drawing, equations and calculation.

6.3 Problem 3

Design a common emitter amplifier using the data from Table 10.

Table 10 – Data for problem 3

Option	G	Up, V	R_L, Ohm	β
1	5	12	900	50
2	7	10	1000	60
3	6	9	1100	70
4	10	7	1200	80
5	12	15	1300	90
6	6	18	1400	100
7	11	8	1500	50
8	14	11	1600	60
9	18	13	1700	70
10	8	14	1800	80
11	9	12	1900	90
12	16	9	2000	100
13	4	13	2100	110
14	3	14	2200	120
15	12	5	2300	130

6.4 Problem 4

Calculate the truth table for one of the following circuits:

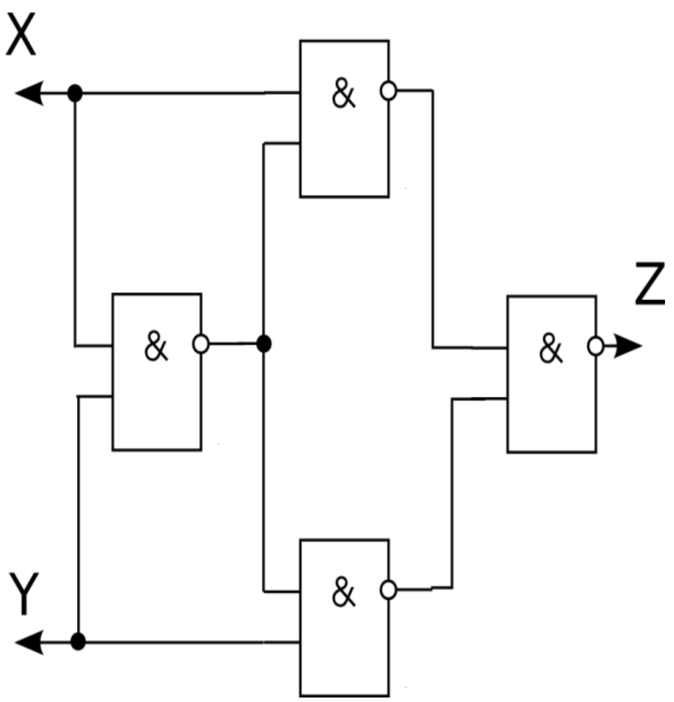


Figure 73 – Circuit 1 for problem 4

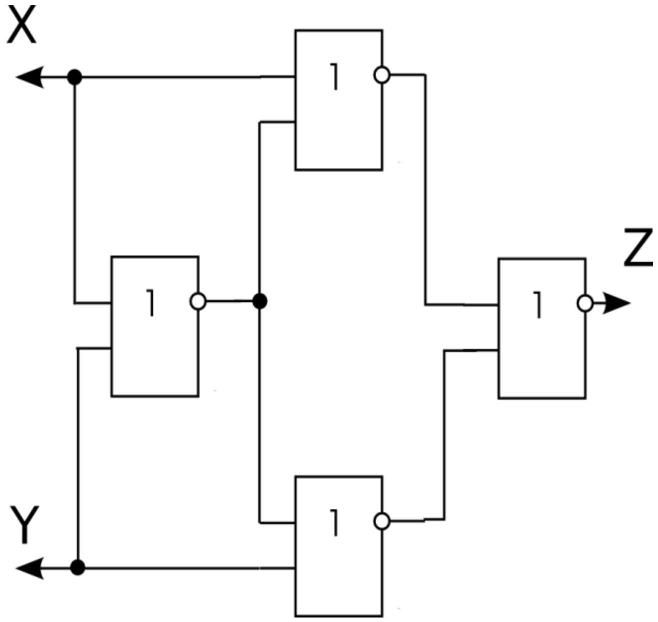


Figure 74 – Circuit 2 for problem 4

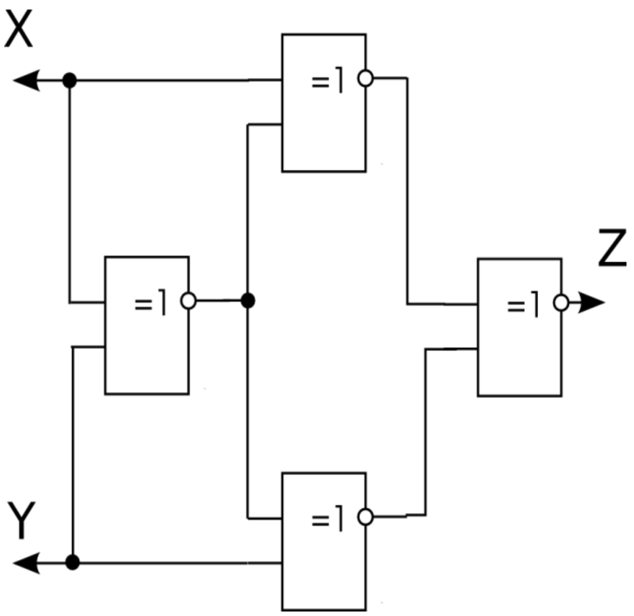


Figure 75 – Circuit 3 for problem 4

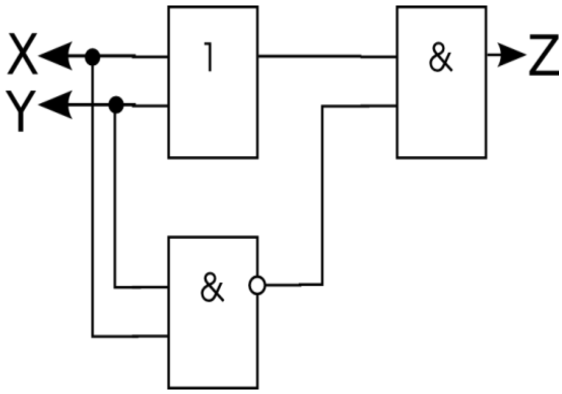


Figure 76 – Circuit 4 for problem 4

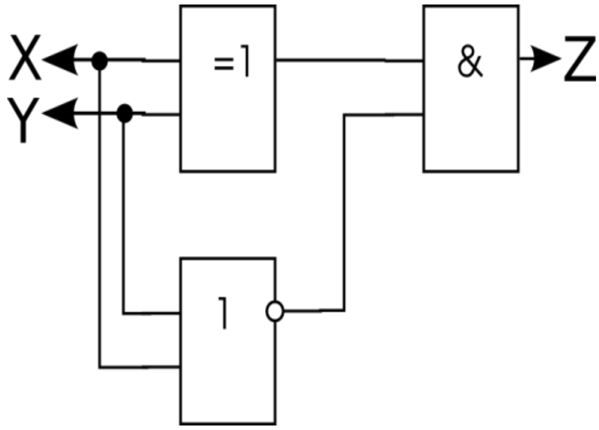


Figure 77 – Circuit 5 for problem 4

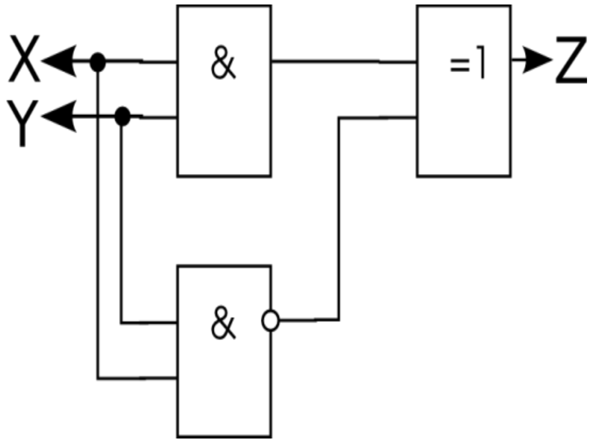


Figure 78 – Circuit 6 for problem 4

Conclusion

This manual addressed the main issues relating to the calculation and design of power supplies, amplifiers, signal generators and digital devices. One of the goals that the authors put forward during the development of the manual is to eliminate "white spots" in the presentation of the material accepted in the traditional literature, therefore, this manual contains sufficiently detailed conclusions of the basic formulas that can rarely be found even in the specialized electronics literature, although in educational literature on other areas of physics, the derivation of formulas is necessary.

This will allow students to learn the material in a more friendly form and not treat the calculation formulas as a kind of secret knowledge. Nevertheless, modern electronics covers a much larger number of areas that it is almost impossible to set out in the scope of this learning manual. In this regard, the authors recommend students not to neglect the literature recommended for studying and to perceive the whole range of information sources on the discipline in a comprehensive manner, while developing skills for searching and systematizing knowledge, which is one of the most important competencies of a modern specialist in any field.

References

1. Paul Horowitz and Winfield Hill, The Art of Electronics, Cambridge University Press, 2016 1220 c.
2. Williams Barry W. Principles and Elements of Power Electronics. Devices, Drivers, Applications, and Passive Components O'Reilly, 2014 1432 p.
3. Richard C. Dorf, Electronics, Power Electronics, Optoelectronics, Microwaves, CRC Press Taylor, 2008 502 p.
4. Sueker, Keith H. Power Electronics Design, McGraw Hill, 2005 272 p.
5. Қазақ тілі терминдерінің салалық ғылыми түсіндірме сөздігі : Электроника, радиотехника байланыс - Алматы : Мектеп, 2007. - 232 б.
6. М. С. Тясто Современный русско-английский словарь по радиоэлектронике - Ростов н/Д : Феникс, 2009. - 377 с.
7. R. Jablonski, T. Brezina. Advanced Mechatronics Solutios . Vol. 393 - Switzerland : Springer, 2016. - 668 p
8. K. Reif. Automotive Mechatronics. Automotive Networking, Driving Stability Systems, Electronics - Wiesbaden : Springer Vieweg, 2015. - 538 p
9. Zaman, N. Automotive Electronics Design Fundamentals - New York : Springer International Publishing Switzerland, 2015. - 262 p.
10. Нефедов, В. И. Основы радиоэлектроники и связи М. : Высшая школа, 2002. - 510 с.
11. Жұрынтаев, Ж. З. Сұлбатехника . - Алматы : ҚазҰТУ : Дәуір, 2011. - 288 б.