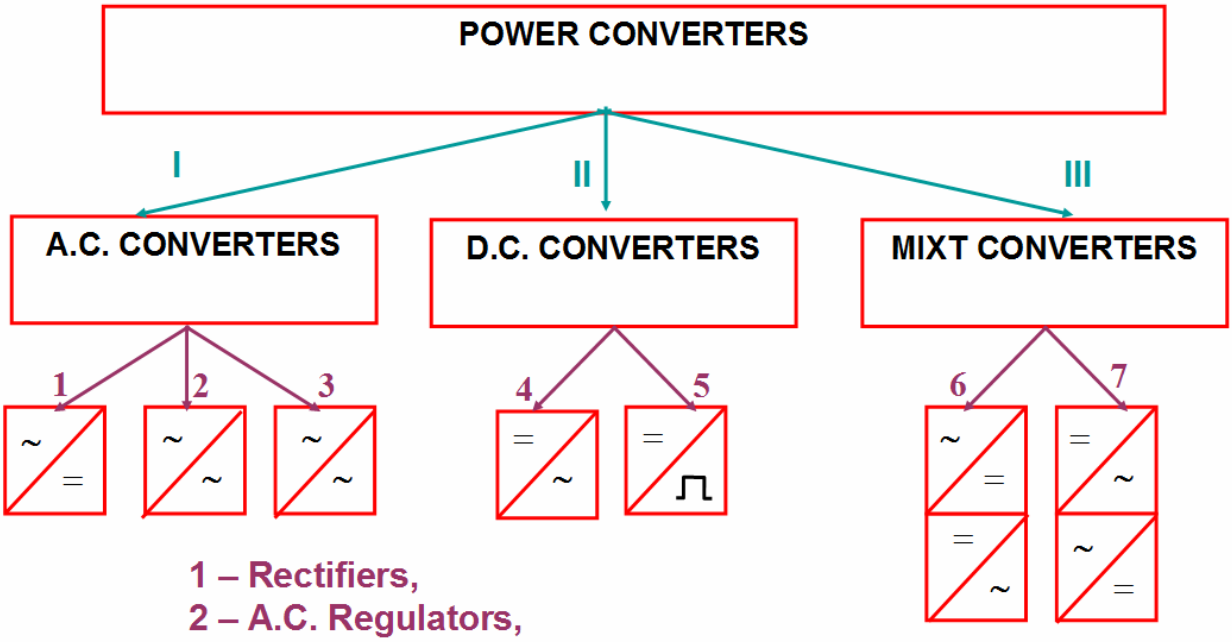


POWER CONVERTERS

A.C. CONVERTERS

D.C. CONVERTERS

MIXT CONVERTERS

1 – Rectifiers,
2 – A.C. Regulators,
3 – Cycloconverters,
4 – Inverters,
5 – Choppers,
6 – Frequency Converters,
7 – D.C. Regulators

UNCONTROLLED SINGLE PHASE RECTIFIERS

1.1. General notions

Rectifier is the converter that converts the alternating current (c.a.) into DC (c.c.).

The block diagram of the rectifier is shown in Fig. 1.1. The main elements of the rectifier are:

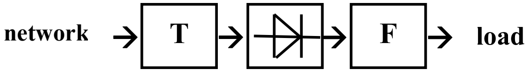


Fig.1.1.The block schema of the rectifier

✓Power transformer (**T**),
✓Group of valves and
✓Smoothing filter (**F**).

Also, the rectifier can be equipped with additional elements or circuits, which serve to:

- adjusting the rectified voltage,
- connect - disconnect,
- protection,
- for measurements of input, output and intermediate quantities (magnitude), etc.

Rectifiers can be <u>classified</u>:

➩ according to (by) the number of phases**:**
  ➢ single phase,
  ➢ multiphase (2 phases, 3 phases etc.);
➩ By type of valves**:**
  ➢ uncontrolled,
  ➢ controlled, ordered,
  ➢ half-controlled;
➩ by the form of waves on the load**:**
  ➢ Half-wave,
  ➢ Double alternation;
➩ according the connection of the valves**:**
  ➢ with neutral wire;
  ➢ bridge rectifier,
  ➢ with multiplication;

The main parameters (characteristics) of the rectifiers are:

✓ rectified voltage $\mathbf{U_d}$,
✓ rectified current $\mathbf{I_d}$,
✓ rectified power $\mathbf{P_d}$,
✓ efficiency η
✓ pulse factor:

$$k_p = \frac{\sum_{i=1}^{\infty} U_{im}}{U_d}, \qquad (1.1)$$

where the $\mathbf{U}_{im}$ is *i*-th order harmonic amplitude of the output voltage.

1.2. Half-wave single phase rectifier

During the analysis of the operation of the rectifiers, in the first approximation, we will consider the valve and transformer ideal, the load resistive, and the voltage in the network u_1 (therefore and u_2) will be sinusoidal:

$$u_1 = U_{1m} \sin \omega t, \tag{1.2a}$$

$$u_2 = U_{2m} \sin \omega t. \tag{1.2b}$$

The schema and waveforms of the half-wave single phase rectifier are represented in fig.1.2. During the positive alternation (half-wave) of voltage u_2 the valve **VD** is polarized directly and the voltage drop on the valve will be null and whole secondary voltage of the transformer u_2 falls (drops) on the load, and through the valve and the load flows current i_d.

During the negative alternation (half-wave) of voltage u_2, the diode is blocked, the current through it is null and whole voltage u_2 falls (drops) on the diode, and the current through the load and the voltage on it will be null. Therefore, average rectified voltage (on the load) will be:

$$U_d = \frac{1}{2\pi}\int_0^{\pi} U_2 d(\omega t) = \frac{1}{2\pi}\int_0^{\pi} U_{2m} \sin(\omega t) d(\omega t) = \frac{U_{2m}}{\pi} = \frac{\sqrt{2}}{\pi} U_2 . \tag{1.3}$$

Therefore, to get the voltage U_d on the load it is necessary to have:

$$U_2 = \frac{\pi}{\sqrt{2}} U_d . \tag{1.4}$$

The maximum voltage on the valve will be determined by the amplitude of the secondary voltage:

$$U_{RRM} = U_{2m} = \sqrt{2} U_2 = \frac{\pi}{2} U_d . \tag{1.5}$$

Pulse factor is **k_p=1,57.**

The frequency of the waves coincides with the frequency of the a.c. from the network $f_p = f_r$.

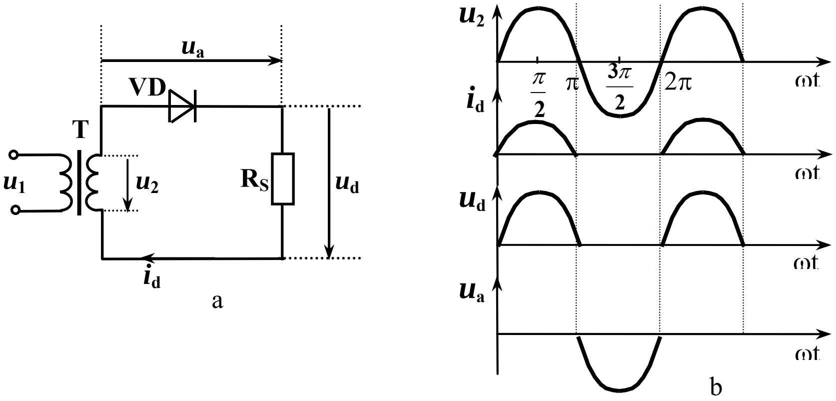


Fig.1.2. The scheme of the half-wave rectifier (a)
and the waveforms of voltages and current (b)

1.3. Double alternation single phase rectifier with neutral wire

The scheme and the waveforms of voltages and currents of double alternation single phase rectifier with neutral wire are represented in fig. 1.3. Secondary tensions are in anti-phase (Secondary tensions are in opposed phases):

$$u_{1-0} = -u_{2-0} = u_2. \qquad (1.6.)$$

During the positive alternation (half-wave) of voltage u_2 (ωt=0÷π) the valve **VD$_1$** is polarized directly and the diode **VD$_2$** is blocked. The voltage drop on the valve **VD$_1$** will be null and voltage u_2 falls (drops) on the load, and on **VD$_2$** falls double voltage **2u_2**. Through the valve **VD$_1$** and the load flows current $i_1 = i_d$.

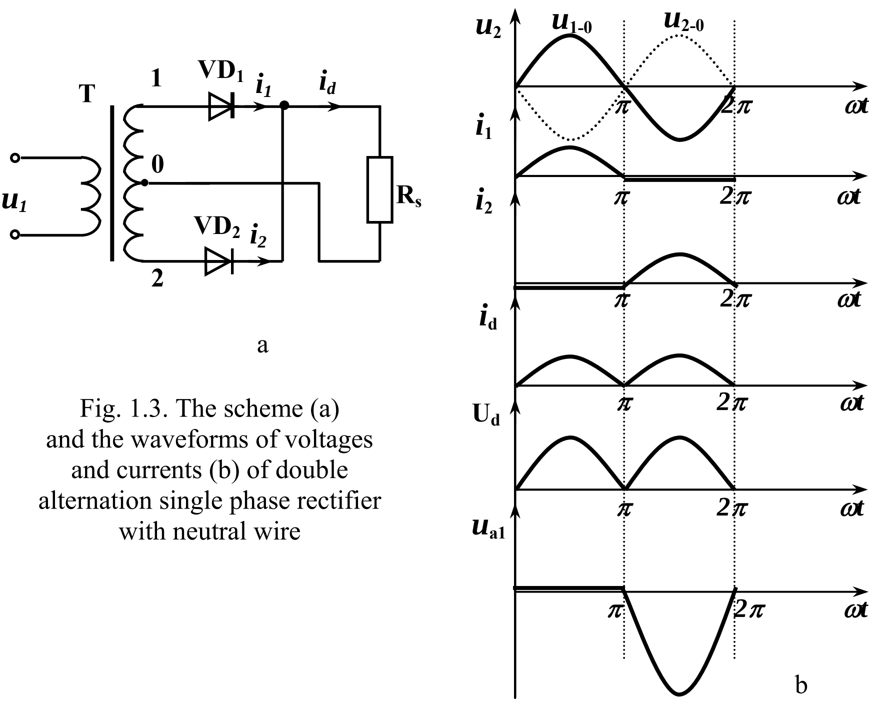
During the next (negative) alternation (half-wave) (ωt=π÷2π) the voltages u_{1-0} and u_{2-0} change polarities. The valve **VD$_2$** is polarized directly and the diode **VD$_1$** is blocked. The voltage drop on the valve **VD$_2$** will be null and voltage u_2 falls (drops) on the load, and on **VD$_1$** falls double voltage **2u_2**. Through the valve **VD$_2$** and the load flows current $i_2 = i_d$.

Therefore, average rectified voltage (on the load) will be:

$$U_d = \frac{1}{\pi}\int_0^{\pi} U_{2m}\sin(\omega t)d(\omega t) = \frac{2U_{2m}}{\pi} = 2\frac{\sqrt{2}}{\pi}U_2. \qquad (1.7)$$

Therefore, to get the voltage **U**$_d$ on the load it is necessary to have:

$$U_2 = \frac{\pi}{2\sqrt{2}}U_d. \qquad (1.8)$$



a

Fig. 1.3. The scheme (a) and the waveforms of voltages and currents (b) of double alternation single phase rectifier with neutral wire

b

The maximum voltage on the valve will be determined by double amplitude of the secondary voltage:

$$\mathbf{U_{RRM} = 2U_{2m} = 2\sqrt{2}U_2 = \pi U_d}. \qquad (1.19)$$

Pulse factor is $k_p=0,67$, and the frequency of the waves is double frequency of the a.c. from the network $f_p=2f_r$. Since the valves are identical, the average flow through the valve will be:

$$\mathbf{I_a=I_d/2}. \qquad (1.20)$$

1.4. Double alternation single phase bridge rectifier

The scheme and the waveforms of voltages and currents of bridge single phase rectifier are represented in fig. 1.4.

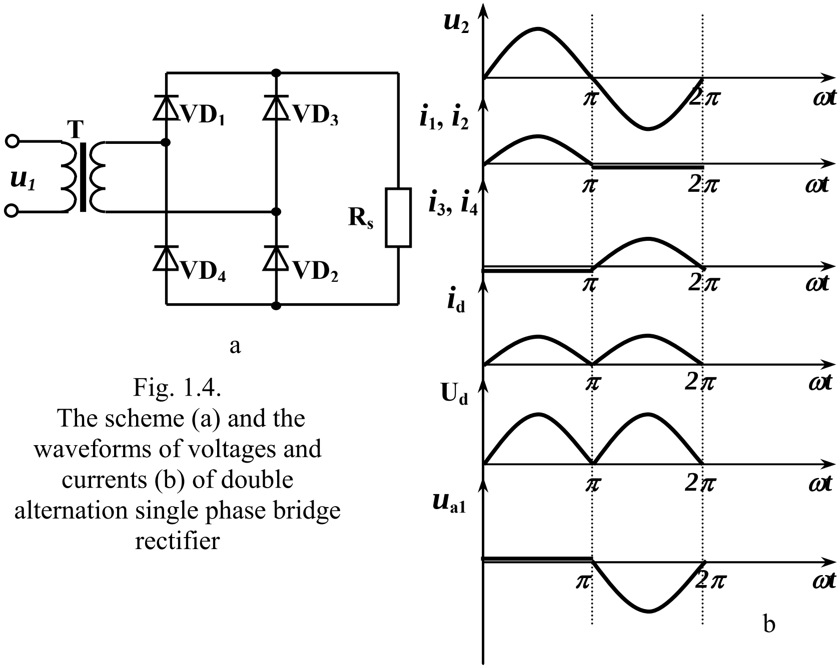


Fig. 1.4.
The scheme (a) and the waveforms of voltages and currents (b) of double alternation single phase bridge rectifier

During the positive alternation (half-wave) of voltage u_2 ($\omega t=0 \div \pi$) the valves VD_1 and VD_2 are polarized directly and the diodes VD_3 and VD_4 are blocked. The voltage drop on the valve VD_1 will be null and voltage u_2 falls (drops) on the load, and on each valves VD_3 and VD_4 falls voltage u_2. Through the valve VD_1, the load and the valve VD_2 flows current $i_1=i_2=i_d$.

During the next (negative) alternation (half-wave) ($\omega t=\pi \div 2\pi$) the polarity of the secondary voltage u_2 is changed. The valves VD_3 and VD_4 are polarized directly and the diodes VD_1 and VD_2 are blocked. The voltage drops on the valves VD_3 and VD_4 will be null and voltage u_2 falls (drops) on the load, and on each valves VD_1 and VD_2 falls voltage u_2. Through the valve VD_3, the load and the valve VD_4 flows current $i_3=i_4=i_d$.

All formulas obtained for single phase rectifier with neutral wire will be available for bridge rectifier without formula (1.19), because voltage drop on the valve isn’t double:

$$U_{RRM} = U_{2m} = \sqrt{2}U_2 = \frac{\pi}{2}U_d, \qquad (1.21)$$

1.5. Smoothing filters

Since the rectified voltage contains alternate components (harmonics), the ***smoothing filters*** are used to improve the quality of the rectified voltage or current. Smoothing filters are formed on the basis of reactive elements (capacitors or coils (inductors)). These elements have resistance in c.c. (capacitor - high and coil - small), completely contrary to its reactance (small and large, respectively). These properties of the reactive elements are used to form the smoothing filters - the capacitor is connected in parallel and the drosel - in series to the load (fig. 1.5).

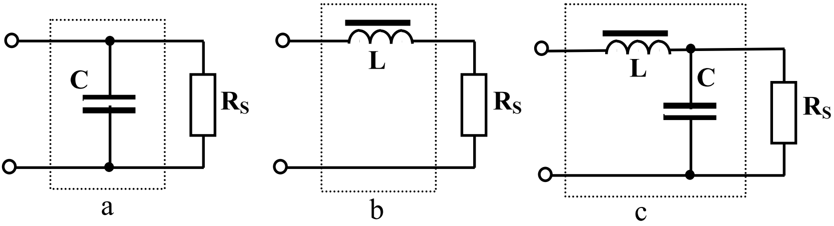


Fig.1.5.The schemes of elemental smoothing filters
a – capacitive, b – inductive, c – mixed

The capacitive filter shunts (shortens) the alternate component and, for this purpose (order), the capacity must be chosen from the condition:

$$x_C << R_S,\ \text{i.e.}\ \frac{1}{\omega_f C} << R_S \quad \text{and} \quad C >> \frac{1}{\omega_f R_S}, \qquad (1.22)$$

where ω_f is the fundamental harmonic of pulsations.

Capacitive filters are used for high- resistance loads and small currents in order to smooth out pulsations of the rectified voltage.

The inductive filter is formed to form conditions when the c.a. falls mainly on drosel, and the c.c. - on the load. For this purpose the inductance must be chosen from the condition:

$$x_L >> R_S,\ \text{i.e.}\ \omega_f L >> R_S \quad \text{and} \quad L >> \frac{R_S}{\omega_f}. \qquad (1.23)$$

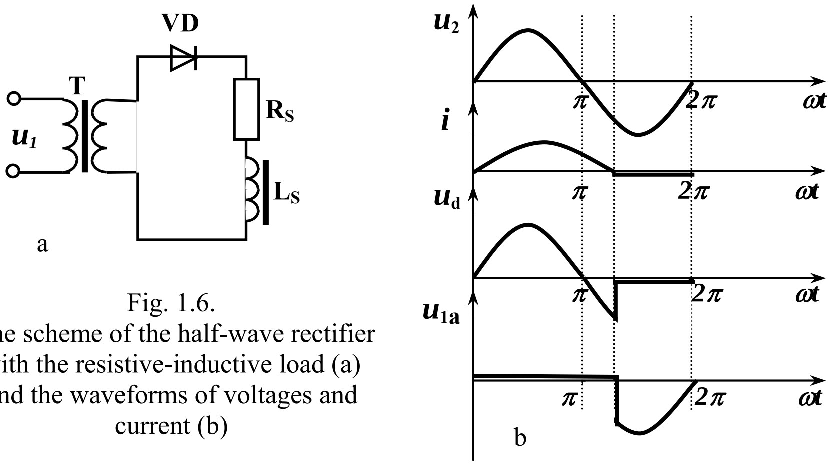
Inductive filters are used for low-resistance loads and large currents to smooth the pulsations of the rectified current.

1.6. Operation of single-phase rectifiers with inductive load

If at the rectifier output we will have a DC machine, relay, electromagnet, etc., the load will be inductive. Due to the energy storage processes in the inductance, i.e. the delay of the current against the voltage, in cases where the load is inductive or resistive-inductive, the rectifier's operation is influenced by this phenomenon.

1.6.1. Half-wave rectifier

The schema and waveforms of the voltages and currents for this case are represented in fig.1.6. During the increasing of the voltage ($\omega t=0\div\pi/2$), the energy is stored in the inductance and the current increases more slowly, while the voltage decreases ($\omega t=\pi/2\div\pi$) the current continues to increase. The current increases and decreases more slowly than the voltage, and when the voltage goes through zero the current still has a positive value. The valve steal remains in the conduction state as long as the current flows through the load and the voltage on the load is negative during this time.



a

b

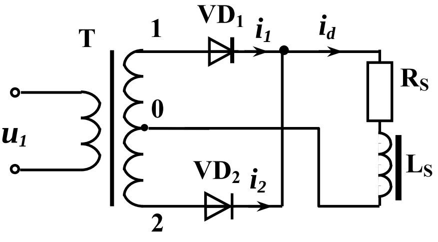
Fig. 1.6.
The scheme of the half-wave rectifier with the resistive-inductive load (a) and the waveforms of voltages and current (b)

1.6.2. Double alternation rectifier

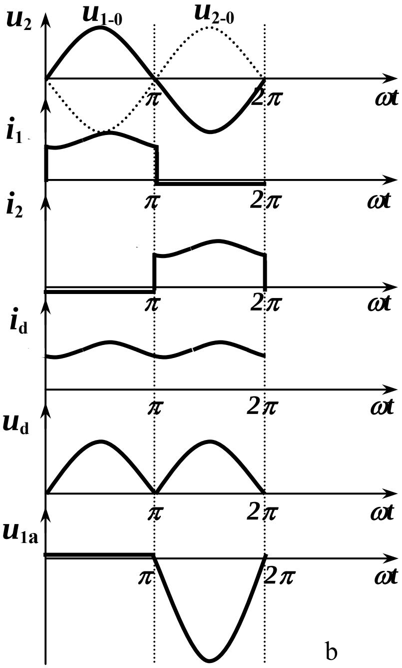
The schema and waveforms for this case are represented in fig.1.7. Since the inductance is not in valve circuit, the switching of the load current from one diode to the other takes place at the moments of passing the secondary voltage through zero. The waveforms of the currents through the valves repeat the shape of current through load in the respective ranges, and the voltage on the valves does not change its shape (compared to the case of the resistive load). The pulsations of the rectified current are substantially reduced, and when:

$$\boldsymbol{\omega_f L_S \geq (10 \div 12)\, R_S}, \qquad (1.24)$$

($L_S \to \infty$) the current through load can be considered constant, and the waveforms of the currents through the valves will take the form of rectangular pulses.



a



b

Fig. 1.7.The scheme (a) and the waveforms of voltages and currents (b) of double alternation single phase rectifier neutral wire with the resistive-inductive load

1.7. External characteristics of single-phase rectifiers

If it is taken into account that the rectifier circuit elements (transformer, valves, etc.) are not ideal and some parte of voltage drops on them, the rectified voltage will be less, the higher the current through the load. Dependence of the mean rectified voltage by the rectified current is called ***the external characteristic*** $U_d=f(I_d)$.

- *In the case of* **rectifier without filter** in the idle mode (regime) $(I_d=0)$ $U_{d0}\cong 0.9U_2$ (see expression (1.8)) the voltage drop on the circuit elements ΔU_d increases with the increase of the rectified current and the rectified voltage decreases linearly (see fig.1.8 curve 1):

$$U_d = U_{d0} - \Delta U_d. \qquad (1.25)$$

The slope of the external feature is predominantly determined by the transformer: if the winding resistances are high, the slope of the external characteristic will also be higher.

- *In the case* of **rectifier with capacitive filter** the output voltage (U_d) in the idle mode will be determined by the amplitude of the voltage on the secondary winding of the transformer because the capacitor manages to charge up to the maximum voltage and does not discharge in the absence of current through the load:

$$U_{d0}=U_{2m}=\sqrt{2}\,U_2\,. \qquad (1.26)$$

Upon the increase of the I_d ($I_d>0$) U_d stream it decreases for two reasons:

La creşterea curentului I_d ($I_d>0$) U_d se micşorează din două cauze:

- ✓ voltage drops on circuit elements and
- ✓ due to the fact that the capacitor is discharged by load.

When the filter capacity increases, the slope of the external characteristic decreases (see figure 1.8 curves 2 and 3).

- *In the case of* **rectifier with mixed filter** (inductive-capacitive) the external characteristic will have two domains (see fig.1.8 curve 4):
  - ✓ in the first field at the very low values of current the external characteristic is steep,
  - ✓ in the second field at the high values of current the external characteristic is slow.

In the second field, the slope of the external characteristic will, however, be higher than in the case of a non-filter, due to the additional voltage drop on the ohmic resistance of the filter drosel.

In the first field ($I_d<I_{d.cr}$) the broken (intermittent, discontinuous) current mode apears in the operation of the load. The inductance **L** becomes an element of the capacitor charging circuit from the secondary winding of the transformer and capacitor voltage increases as in (analogously to) the capacitive filter case.

! This is **important** to avoid overvoltage on the load: ***at low currents the voltage will increase 1.5 times the case without the filter.***

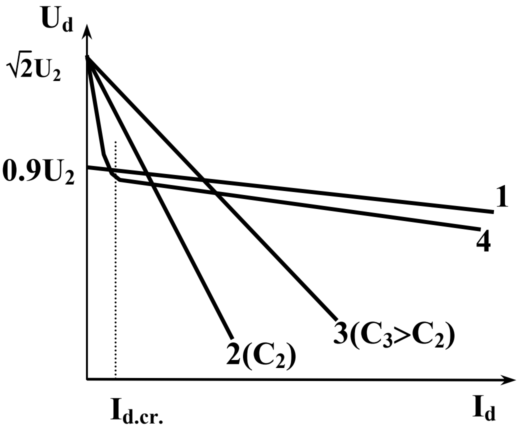


Fig.1.8.The external characteristics

1.8. Multiplicators of voltage

When it is necessary to obtain a high rectified voltage and it is not possible to use the lifting transformer for this purpose, the rectifier circuits with voltage multiplication are used. Voltage capacitors are used as temporary voltage sources in multipliers.

The schema of half-wave rectifier circuit with doubling voltage is represented in fig.1.9.

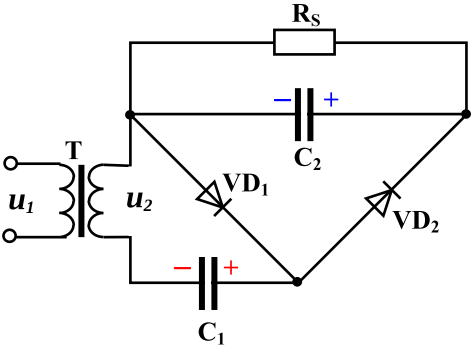


Fig. 1.9. The schema of half-wave rectifier circuit with doubling voltage

Operation:

During the positive alternation of voltage on the transformer secondary, the **VD_1** is in conduction and the **VD_2** is blocked. Capacitor **C_1** is charged from transformer secondary by **VD_1** up to **U_{2m}** with the polarity shown on the diagram.

During the negative alternation of voltage on the transformer secondary, the **VD_2** is in conduction and the **VD_1** is blocked. Capacitor **C_2** is charged from the transformer secondary and the voltage on the capacitor plates **C_1** through **VD_2** up to the voltage 2**U_{2m}** with the polarity shown on the diagram.

On the load **R_S** is applied the voltage from the plates of the capacitor **C_2**, ie the double voltage (2**U_{2m}**). Forwards, during positive alternations of voltage on the secondary of the transformer, the capacitor **C_1** restores its charge through the conduction valve **VD_1**, and during negative voltage alternations on the transformer secondary, the capacitor **C_2** restores its charge through the conduction valve **VD_2**.

The schema of double alternation rectifier circuit with doubling voltage is represented in fig.1.10.

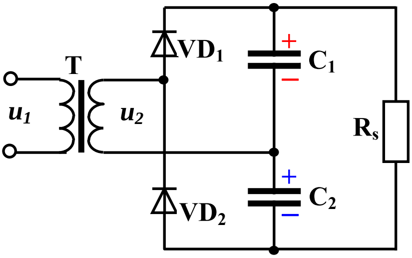


Fig. 1.10. The schema of double alternation rectifier circuit with doubling voltage

Operation:

During the positive alternation of voltage on the transformer secondary, the **VD_1** is in conduction and the **VD_2** is blocked. Capacitor **C_1** is charged from transformer secondary by **VD_1** up to **U_{2m}** with the polarity shown on the diagram.

During the negative alternation of voltage on the transformer secondary, the **VD_2** is in conduction and the **VD_1** is blocked. Capacitor **C_2** is charged from the transformer secondary through **VD_2** up to the voltage **U_{2m}** with the polarity shown on the diagram.

On the load **R_S** is applied total voltage (sum) from the plates of the capacitors **C_1** and **C_2**, ie the double voltage (2**U_{2m}**). Forwards, during positive alternations of voltage on the secondary of the transformer, the capacitor **C_1** restores its charge through the conduction valve **VD_1**, and during negative voltage alternations on the transformer secondary, the capacitor **C_2** restores its charge through the conduction valve **VD_2**.

The schema of half-wave rectifier circuit with tripled voltage is represented in fig.1.11. By adding a group consisting of a diode and a capacitor (**VD₃** and **C₃**) the voltage multiplication factor in the circuit is increased by one unit.

The rectifier circuits with voltage multiplication are used to apply high voltages on high resistance and low currents loads (low electrical loads), for example, to form high electrostatic voltages.

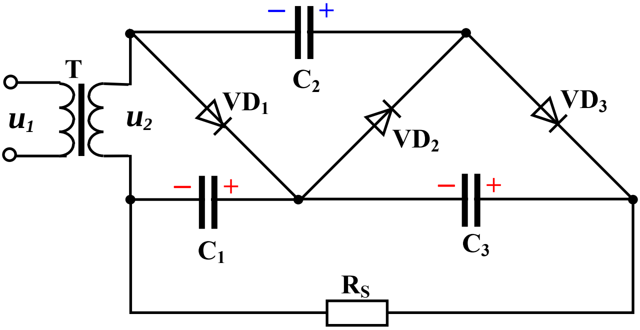


Fig. 1.11. The schema of half-wave rectifier circuit with tripled voltage

UNCONTROLLED THREE-PHASE RECTIFIERS

2.1. General notions

In the case of high required (consumed) power (over several kW), polyphase rectifiers are used, which have several **advantages** over the one-phase rectifiers **such as:**

- a more uniform load of the supply network, which is usually three-phase,
- the rectified voltage is of a higher quality (with low waves) and therefore the pulse factor is smaller, which leads to the possibility of using simpler and cheaper smooth filters;
- better use of power transformers for the same required power.

By connection of the valves, there are two types of three-phase rectifiers:

- ✓ with neutral wire,
- ✓ bridge rectifier.

2.2. Three-phase rectifier with neutral wire

The schema and waveforms of the uncontrolled three-phase rectifier with neutral wire are represented in fig. 2.1. In the case of the three-phase rectifier with neutral wire, the secondary windings of the transformer are star-connected. One of valve ($\mathbf{VD}_1$, $\mathbf{VD}_2$, $\mathbf{VD}_3$) is connected to each secondary phase circuit, and the load is connected to the neutral wire circuit.

At a considered time moment only one diode leads, that is, one that has the anode with the highest potential against the neutral wire, chosen as a reference.

Assuming the diode is ideal, in conduction being short-circuited, the cathodes of the other two diodes will be at higher potential in the circuit, being polarized back and blocked. The current condition is passed on diodes successively, so that the rectified voltage u_d represents the maximum phase of the secondary voltages of the transformer. The load current is formed by diode currents and always has the same direction. Thus:

$$i_d = i_{a1} + i_{a2} + i_{a3}. \qquad (2.1)$$

In the time interval t_1-t_2 the highest is the voltage on the phase **A** – u_{2A}. Therefore, the potential of the anode of diode $\mathbf{VD}_1$ is maximal in the rectifier circuit and $\mathbf{VD}_1$ is in conduction. The current flows through $\mathbf{VD}_1$ and load $\mathbf{R}_S$, and on the load is applied voltage u_{2A}. The other two valves are blocked, since the high voltage u_{2A} is applied to their cathodes, and on each of them the line voltage is applied: on $\mathbf{VD}_2$ – u_{2BA}, and on $\mathbf{VD}_3$ – u_{2CA}.

In the time interval t_2-t_3 the highest is the voltage on the phase **B** – u_{2B}. Therefore, the potential of the anode of diode $\mathbf{VD}_2$ is maximal in the rectifier circuit and $\mathbf{VD}_2$ is in conduction. The current flows through $\mathbf{VD}_2$ and load $\mathbf{R}_S$, and on the load is applied voltage u_{2B}. The other two valves are blocked, since the high voltage u_{2B} is applied to their cathodes, and on each of them the line voltage is applied: on $\mathbf{VD}_1$ – u_{2AB}, and on $\mathbf{VD}_3$ – u_{2CB}.

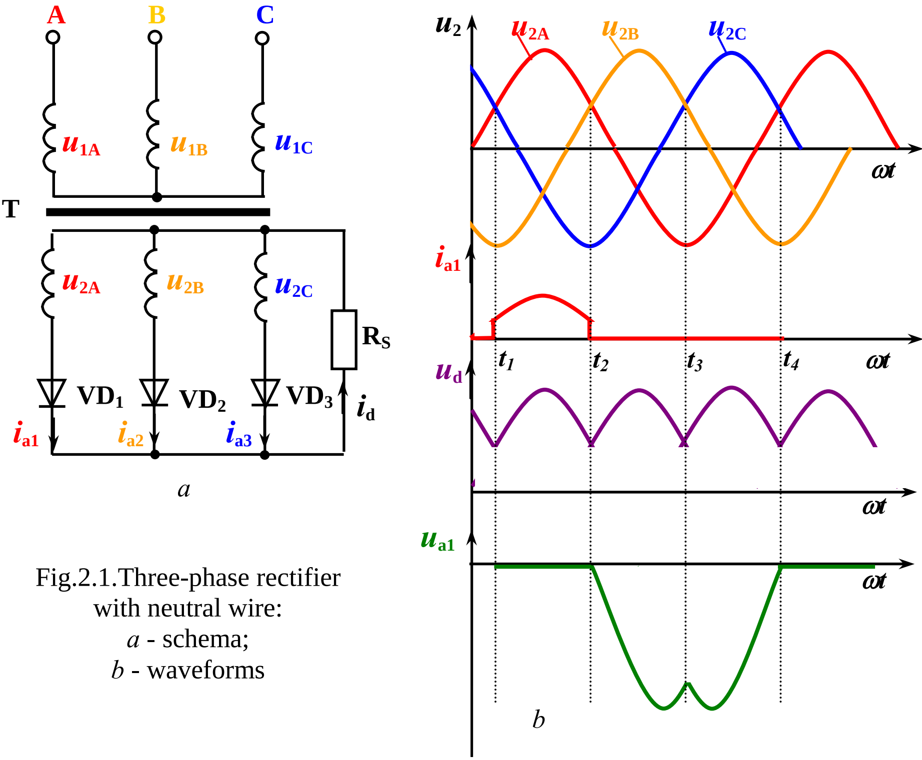


Fig.2.1.Three-phase rectifier
with neutral wire:
a - schema;
b - waveforms

In the time interval t_3-t_4 the highest is the voltage on the phase **C** – u_{2C}. Therefore, the potential of the anode of diode **VD$_3$** is maximal in the rectifier circuit and **VD$_3$** is in conduction. The current flows through **VD$_3$** and load **R$_S$**, and on the load is applied voltage u_{2C}. The other two valves are blocked, since the high voltage u_{2C} is applied to their cathodes, and on each of them the line voltage is applied: on **VD$_1$** – u_{2AC}, and on **VD$_2$** – u_{2BC}.

Moments t_1, t_2, t_3, etc. are called moments of natural commutation (switching).

The mean (average) value of the rectified voltage is:

$$U_d = \frac{2}{\frac{2\pi}{3}} \int_0^{\frac{\pi}{3}} U_{2m} \cos(\omega t) d(\omega t) = U_{2m} \frac{\sin\frac{\pi}{3}}{\frac{\pi}{3}} = \frac{3\sqrt{3}}{\sqrt{2}\pi} U_2 \approx 1{,}17 U_2 . \qquad (2.2)$$

The reverse repetitive maximum voltage on the valve will be determined by the amplitude of the line voltage:

$$U_{RRM} = \sqrt{3}\sqrt{2}U_2 = \sqrt{6}U_2 , \qquad (2.3)$$

The pulse factor of rectified voltage and current is $k_p=0.25$, and the frequency of waves is three times higher than the frequency of a.c. in the supply network $f_p=3f_r$.

2.3. Three-phase bridge rectifier

The schema and waveforms of the uncontrolled three-phase bridge rectifier are represented in fig. 2.2. In the case of the three-phase bridge rectifier, the secondary windings of the transformer can be connected both star-wise and in a triangle. The three-phase bridge rectifier circuit consists of two groups of valves: ***the anode group*** and ***the cathode group***. In the cathode group are included the valves, which have cathodes bound together: **VD$_1$**, **VD$_3$** and **VD$_5$**; and in the anode group are included the valves, which have the anodes connected together: **VD$_2$**, **VD$_4$** and **VD$_6$**. The load is connected between these two points, which form respectively ***the positive terminal*** of the load, i.e. the common point of the cathode group, and ***the negative terminal*** of the load, i.e. the common point of the anode group.

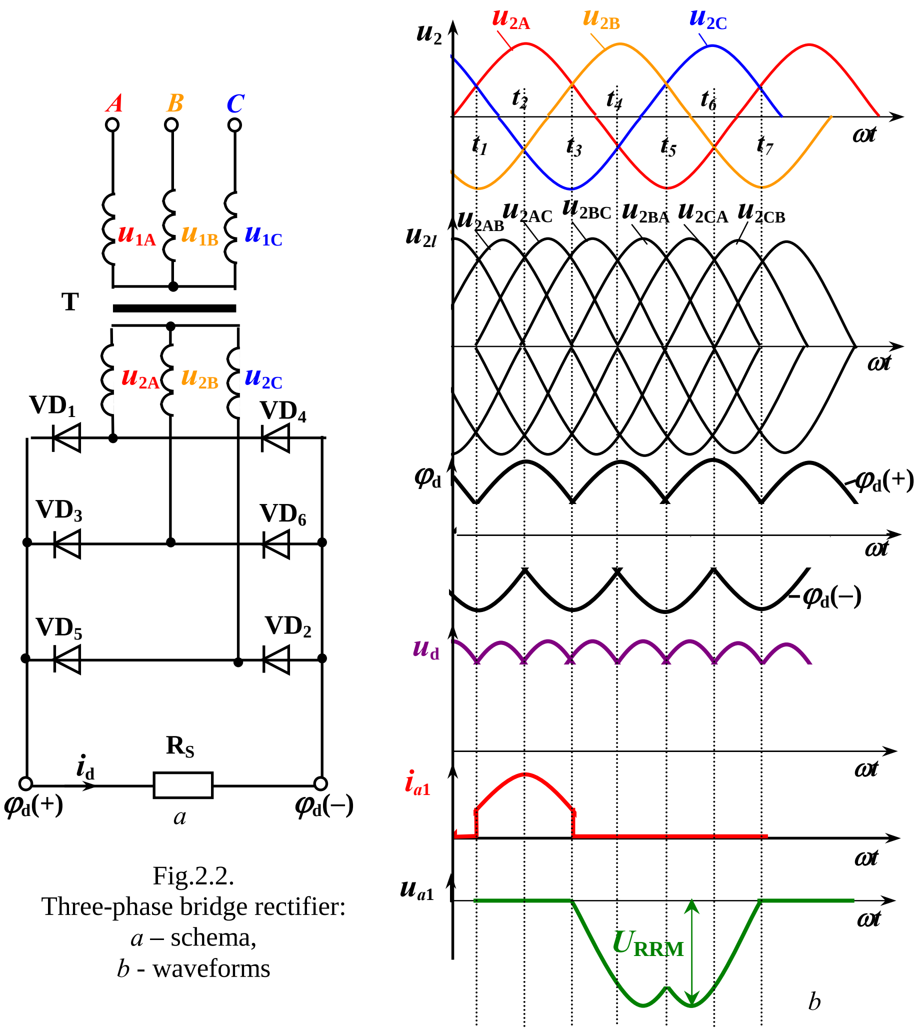


Fig.2.2.
Three-phase bridge rectifier:
a – schema,
b - waveforms

At any given time, only one diode in each group of valves is in conduction. In the cathodic group, is in conduction the valve, which currently has the highest potential on the anode, and in the anodic group is in conduction the valve, which currently has the cathode with the smallest potential.

Assuming the diode is ideal, the conduction being shorted, the cathodes of the other two diodes in the group will be at higher potential in the circuit, being polarized back and blocked. Therefore, the potential of the positive terminal of the load $\varphi_d(+)$ will be determined by the maximum portions of the phase voltages of the secondary windings of the transformer and the potential of the negative terminal of the load $\varphi_d(-)$ will be determined by the minimum portions of the phase voltages of the secondary windings of the transformer.

Rectified tension is the difference of these potentials:

$$u_{\mathrm{d}}=\varphi_d(+)-\varphi_d(-)\,, \qquad (2.4)$$

and represents the maximum portions of line tensions.

In the time interval t_1-t_2 is the phase voltage **A** – $u_{2\mathrm{A}}$ becomes higest, and the is the phase voltage **B** – $u_{2\mathrm{B}}$ is minimum. Therefore, the potential of the anode of the valve $\mathbf{VD_1}$ is maximal in the cathode group and $\mathbf{VD_1}$ pass in conduction, and the potential of cathode of the valve $\mathbf{VD_6}$ is minimal in the anode group and the $\mathbf{VD_6}$ is in conduction. Current flows through $\mathbf{VD_1}$, load $\mathbf{R_S}$ and $\mathbf{VD_6}$. Potential of the positive terminal of the load $\varphi_d(+)$ is determined by the voltage $u_{2\mathrm{A}}$, and the potential of the negative terminal of the load $\varphi_d(-)$ is determined by the voltage $u_{2\mathrm{B}}$. On the load is applied line voltage $u_{2\mathrm{AB}}$. The other two valves in the cathode group are blocked since the high voltage $u_{2\mathrm{A}}$ is applied to their cathodes, and on each of them is applied the line voltage: on $\mathbf{VD_3}$ – $u_{2\mathrm{BA}}$, and on $\mathbf{VD_5}$ – $u_{2\mathrm{CA}}$. Two other valves in the anode group are blocked because the negative voltage $u_{2\mathrm{B}}$ is applied to their anodes, and on each of them is applied the line voltage: on $\mathbf{VD_2}$ – $u_{2\mathrm{BC}}$, and on $\mathbf{VD_4}$ – $u_{2\mathrm{BA}}$.

In phase time t_2-t_3 the phase voltage **A** – $u_{2\mathrm{A}}$ remains higest, and the phase voltage **C** – $u_{2\mathrm{C}}$ becomes minimal. Therefore, the potential of the valve anode $\mathbf{VD_1}$ is maximal in the cathode group and the $\mathbf{VD_1}$ is still in conduction, and cathodic potential of the valve $\mathbf{VD_2}$ is minimal in the anode group and the diode $\mathbf{VD_2}$ is in conduction. Current flows through $\mathbf{VD_1}$, load $\mathbf{R_S}$ and $\mathbf{VD_2}$. The potential of the positive terminal of the load $\varphi_d(+)$ is determined by the voltage $u_{2\mathrm{A}}$, and the potential of the negative terminal of the load $\varphi_d(-)$ is determined by the voltage $u_{2\mathrm{C}}$. On the load is applied line voltage $u_{2\mathrm{AC}}$. The other two valves in the cathode group are blocked since the high voltage $u_{2\mathrm{A}}$ is applied to their cathodes, and on each of them a line voltage is applied: on $\mathbf{VD_3}$ – $u_{2\mathrm{BA}}$, and on $\mathbf{VD_5}$ – $u_{2\mathrm{CA}}$. Two other valves in the anode group are blocked because to their anodes is applied negative voltage $u_{2\mathrm{C}}$ and to each of them is applied negative line voltage: $\mathbf{VD_4}$ – $u_{2\mathrm{CA}}$ and $\mathbf{VD_6}$ – $u_{2\mathrm{CB}}$.

The rectifier's operation can be monitored analogously in the following time intervals: t_3-t_4, t_4-t_5, t_5-t_6, t_6-t_7 etc.

The moments $t_1, t_2, t_3, t_4, t_5, t_3,$ etc. are called moments of natural switching.

The mean value of the rectified voltage is:

$$\mathbf{U_d} = \frac{2}{\frac{\pi}{3}} \int_0^{\frac{\pi}{6}} \mathbf{U}_{\mathbf{2ml}} \cos(\omega t) d(\omega t) = \mathbf{U}_{\mathbf{2ml}} \frac{\sin\frac{\pi}{6}}{\frac{\pi}{6}} = \frac{3\sqrt{6}}{\pi} \mathbf{U}_{\mathbf{2}} \approx 2{,}34\mathbf{U}_{\mathbf{2}}. \quad (2.5)$$

The maximum voltage on the valve will be determined by the amplitude of the line voltage:

$$\mathbf{U_{RRM}} = \sqrt{\mathbf{3}}\sqrt{\mathbf{2}}\mathbf{U_2} = \sqrt{\mathbf{6}}\mathbf{U_2}. \qquad (2.6)$$

The pulse factor of rectified voltage and current is $\boldsymbol{k_p}\mathbf{=0.057}$, and pulse frequency is six times higher than the frequency of the a.c. in the supply network $\boldsymbol{f_p=6f_r}$.

2.4. Connections of rectifiers

In cases of required power greater than the nominal (maximum accepted) power of available rectifiers, two or more series- or parallel- connected rectifiers are used. Also, the connection of controlled rectifiers is used for reversible converters and cyclo converters. The series connection is used in case of higher voltages, because the voltage on the load is formed by the sum of the voltages of the rectifiers, and the parallel connection is used in the case of higher currents because the load current is formed by the sum of the rectifier currents.

The scheme of series connection of null wire rectifiers is shown in fig. 2.3, and in fig. 2.4 is represented the scheme of parallel connection of the null wire rectifiers.

The scheme of series connection of bridge rectifiers is shown in fig. 2.5, and in fig. 2.7 is represented the scheme of parallel connection bridge rectifiers.

To improve the quality of the rectified voltage, the scheme represented in fig. 2.6 can be used, where the secondary windings of a rectifier are star-connected, and the secondary windings of another rectifier are triangle-connected. In this case, the secondary voltages in the two rectifiers are mutually offset by 30^0 and therefore the rectified voltage obtained on the load as the sum of the voltages rectified by the two rectifiers will have the twelve-fold wave frequency as the alternating current frequency in the supply network and the quality is much higher than for each separate rectifier (see figure 2.8).

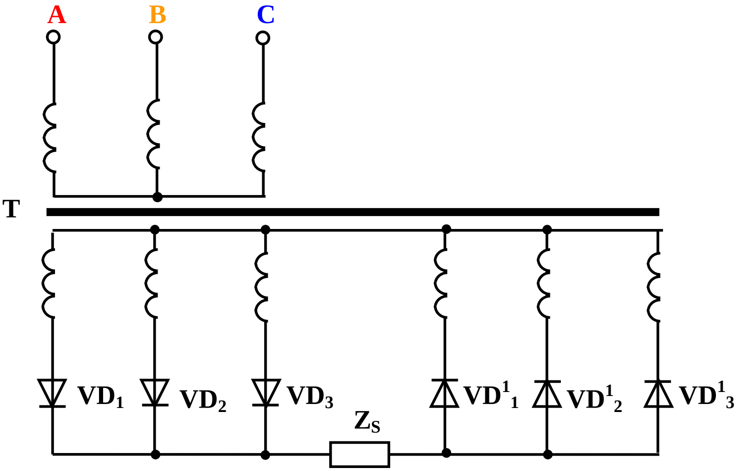


Fig.2.3. The scheme of series connection of null wire rectifiers

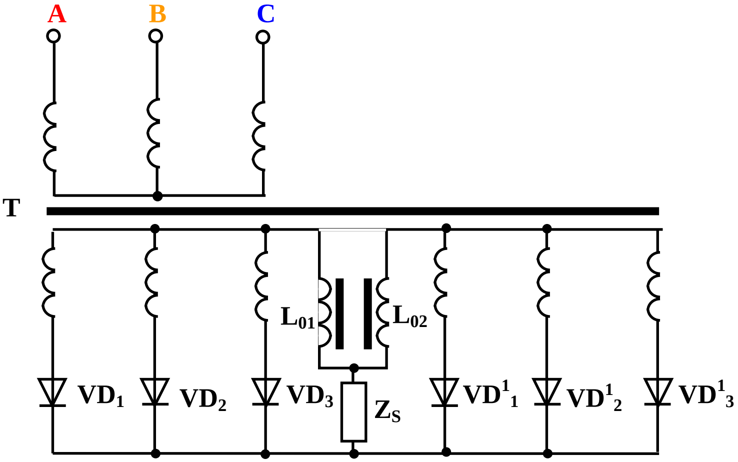


Fig.2.4. The scheme of parallel connection of the null wire rectifiers

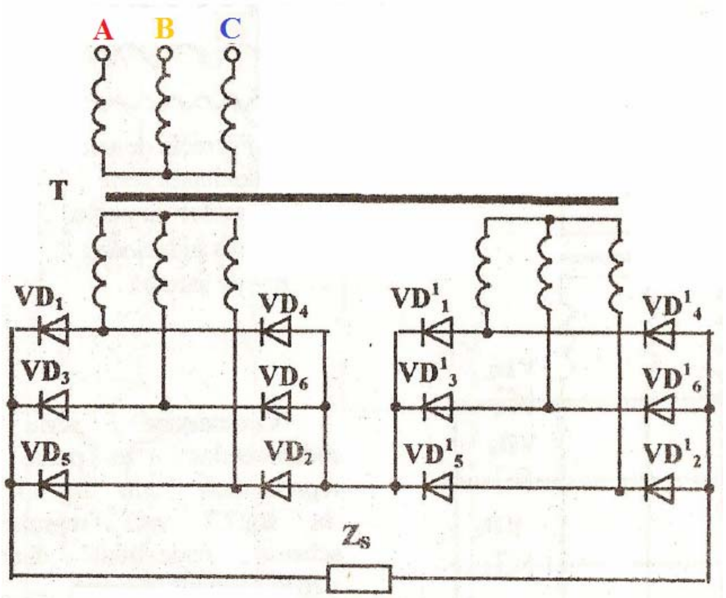


Fig.2.5.The scheme of series connection of bridge rectifiers

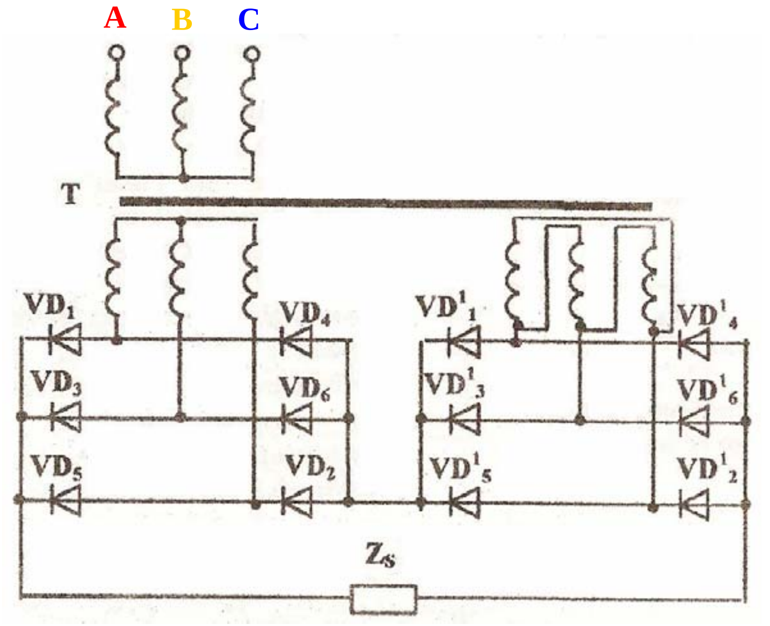


Fig.2.6. The scheme of series conection of bridge rectifiers

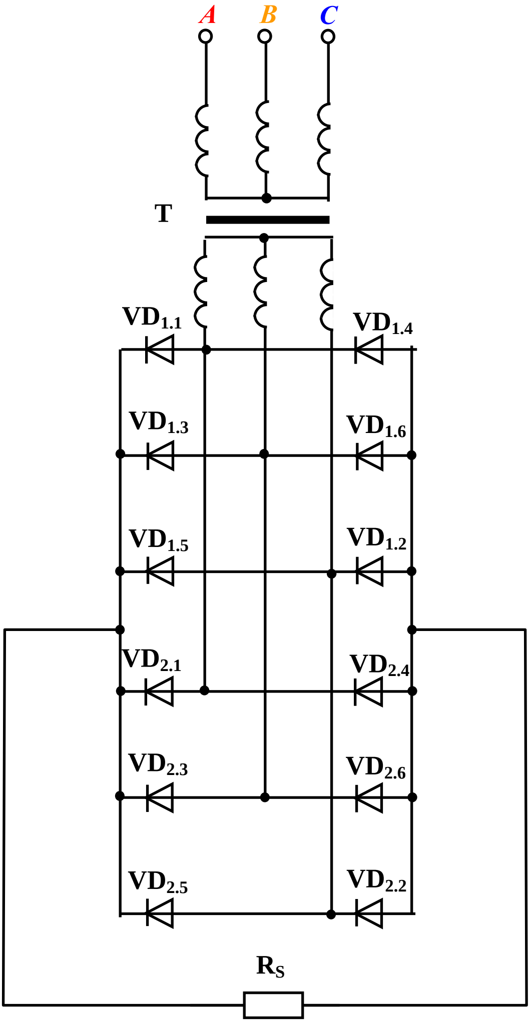


Fig.2.7.The scheme of parallel connection of bridge rectifiers

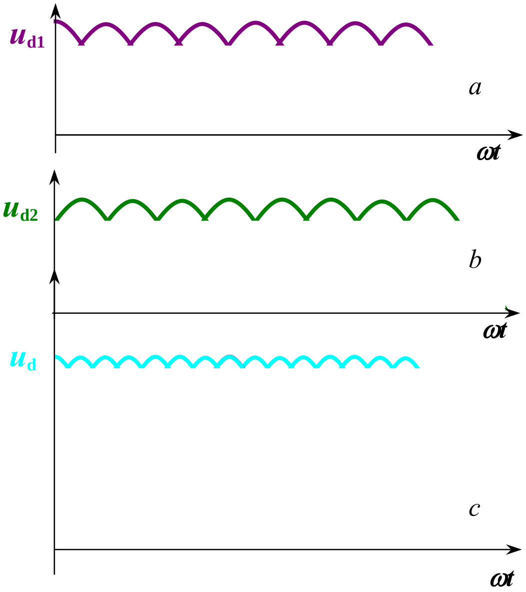


Fig.2.8. Waveforms of rectified voltages in series star-triangle connection of bridge rectifiers: *a*, *b* – from each bridge, *c* – on load

CONTROLLED SINGLE PHASE RECTIFIERS

3.1. General notions

To adjust the value of the rectified voltage U_d in the controled and semi-controled rectifiers, the impulse-phase control method is used, which implies the unlocking of the valves with a delay from the natural switching moments. The length of the delay is determined by the control angle α. For this purpose, thyristors are used in controled rectifiers as valves.

3.2. Double alternation single phase controled rectifier with neutral wire

3.2.1. Resistive load

The scheme and the waveforms of voltages and currents of double alternation single phase controled rectifier with neutral wire are represented in fig.3.1. Secondary tensions are in anti-phase (secondary tensions are in opposed phases):

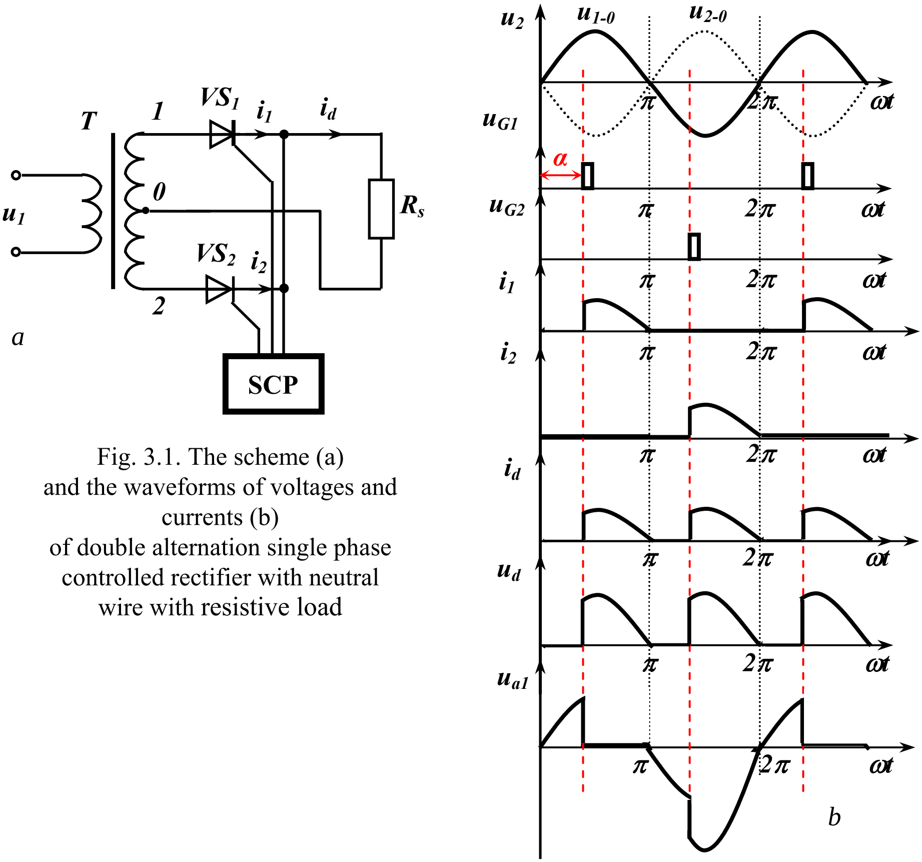


Fig. 3.1. The scheme (a) and the waveforms of voltages and currents (b) of double alternation single phase controlled rectifier with neutral wire with resistive load

During the positive alternation of voltage u_2 ($\omega t=0\div\pi$) the valve **VS$_1$** is polarized directly, and the valve **VS$_2$** is polarized in reverse. In the time interval $\omega t=0\div\alpha$ both valves remain locked, the currents through the valves and the load and the voltage on the load are null. Assuming the impedances of the locked valves under positive and negative voltage equal, we will have voltage of the same value on both valves.

At the moment $\omega t=\alpha$ from the control system **(SC)** on the gate of the thyristor **VS$_1$**, a control pulse is applied, which unlocks the thyristor **VS$_1$**. The voltage drop on the valve **VS$_1$** will be zero and the (positive) voltage falls on the load, and on the **VS$_2$** falls double voltage $2u_2$. Through **VS$_1$** and load flows the current $i_1=i_d$. At the moment $\omega t=\pi$ the voltage on the secondary winding of the transformer $u_{1\text{-}0}$ becomes negative and the thyristor **VS$_1$** is blocked and the load current and the voltage on the load become null.

At the moment $\omega t=\pi+\alpha$ from the control system **(SC)** on the gate of the thyristor **VS$_2$** a control pulse is applied, which unlocks the thyristor **VS$_2$**. The voltage drop on the valve **VS$_2$** will be zero and the voltage $u_{2\text{-}0}$ (positive) falls on the load, and on **VS$_1$** falls double voltage $2u_2$. Through **VS$_2$** and load flows the current $i_2=i_d$. At the moment $\omega t=2\pi$ secondary voltage $u_{2\text{-}0}$ becomes negative and the thyristor **VS$_2$** is blocked, and the load current and the voltage on the load become null.

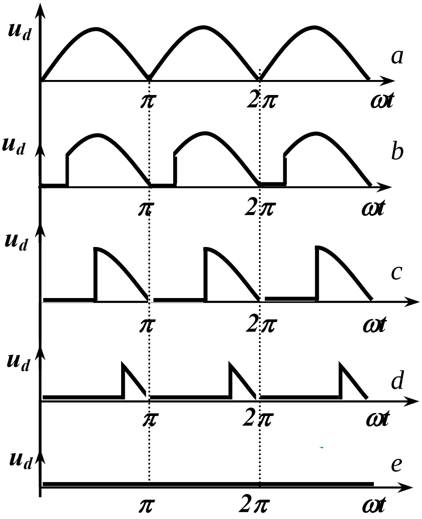


Fig. 3.2. Waveforms of rectified voltage for:
$a - \alpha=0$, $b - 0<\alpha<\pi/2$,
$c - \alpha=\pi/2$, $d - \pi/2<\alpha<\pi$,
$e - \alpha=\pi$

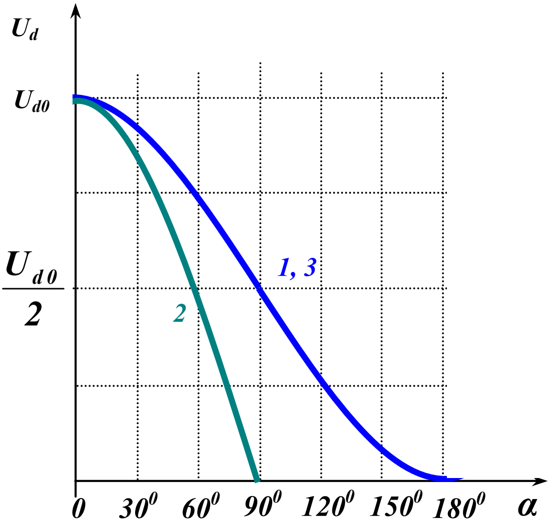


Fig.3.3. The control characteristics of controled rectifier for:
1 – resistive load ($L_d=0$),
2 – inductive load ($L_d\to\infty$),
3 – inductive load ($L_d\to\infty$) with escape diode

As mentioned above, the main feature of controlled rectifier is the ability to adjust the mean value of the rectified voltage. As shown in Fig.3.2, at the control angle $\alpha = 0$ (see fig.3.2.a) the rectified voltage form is identical to the case of the uncontrolled rectifier and its mean value is maximum:

$$\mathbf{U_{d0} = 2\frac{\sqrt{2}}{\pi}U_2 \cong 0{,}9U_2}. \tag{3.2}$$

At the control angle $\alpha=\pi$ (see fig.3.2.e) the shape of the rectified voltage is reduced to a horizontal line and its mean value is null (minimal).

Therefore, when the value of the control angle changing from 0 to π the average value of the rectified voltage will vary from ***0,9U₂*** to ***0***.

Depending of average value of the rectified voltage vs the value of the command angle α $U_d = f(a)$ is called ***the control characteristic*** of the controlled rectifier:

$$\mathbf{U_d = \frac{1}{\pi}\int_{\alpha}^{\pi} U_{2m}\sin(\omega t)d(\omega t) = U_{d0}\frac{1+\cos\alpha}{2}}, \tag{3.3}$$

and its shape, drawn according to the expression (3.3), is shown in figure 3.3 (curve 1).

3.2.2. Resistive-inductive load

The scheme and the waveforms of voltages and currents of double alternation single phase controled rectifier with neutral wire with resistive-inductive load are represented in fig.3.4. The inductive nature of the load changes the waveforms of the load current $i_d=f(\omega t)$, which does not repeat the voltage form yet, unlike the resistive load. After the time of unlocking of the thyristor, the current i_d increases slowly due to the energy storage in the inductance. At the decrease of load current energie is returned and the current continues to flow after the polarity change (from positive in negative) of secondary voltage and the respective valve remains in conduction, until the energy is exhausted and the current decreases to zero. This phenomenon brings to appearance of negative portions on the waveform of of the rectified voltage $u_d=f(\omega t)$.

The time intervals corresponding to the negative voltages on load increase proportionally to the ratio $\tau=L_s/R_s$. Thus these time intervals increase at increasing of load inductance and at a certain value of the inductance L_s, the negative voltage portions extend over the entire range of values of α and the load current becomes uninterrupted, i.e. the interrupted mode of load current disappears. At the same time, the negative portions of voltage on load reduce the average rectified voltage U_d.

Increasing the time of conducting of valves results in apeareance and increase of the time intervals in which the voltage on the blocked valve is positive.

The waveforms of voltages and currents of double alternation single phase controled rectifier with neutral wire with very inductive load ($L_s \to \infty$) are represented in fig.3.5. This case is very common in practice (for example, in electric drives with a DC machine).

This operating mode of the rectifier is characterized by the fact that the negative portions of the load voltage extend over the entire range of values of α, i.e. up to unlocking time of the next thyristor, and by the fact that the load current i_d is completely smoothed and has the temporal diagram as a horizontal straight line. Therefore, the waveforms of the currents through the valves will take the form of rectangular pulses with a duration and a pause equal to π and with amplitude I_d, the average value of the current through the valve will be:

$$I_d = I_d/2. \qquad (3.4)$$

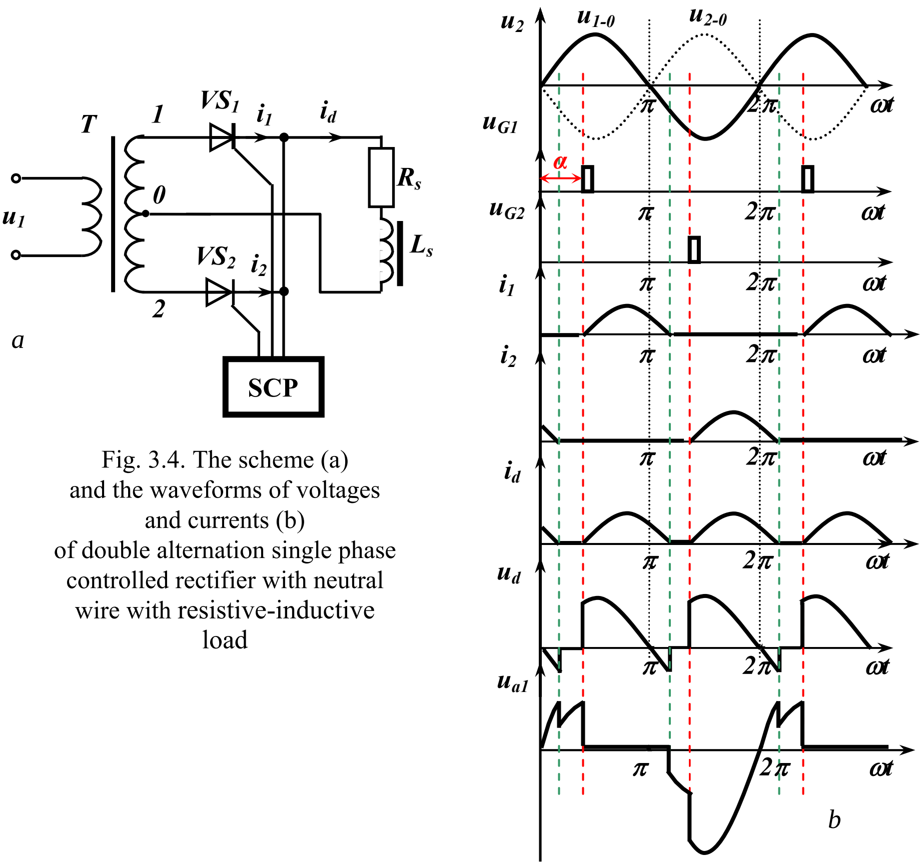


Fig. 3.4. The scheme (a) and the waveforms of voltages and currents (b) of double alternation single phase controlled rectifier with neutral wire with resistive-inductive load

The waveforms of voltage on the valves consist portions of double voltage ($u_{2\text{-}1}=2u_2$), and the maximum value of the positive U_{DRM} (for control angles greater than 90^0 $\alpha \geq 90^0$) and negative U_{RRM} (for control angles less than 90^0 $\alpha \leq 90^0$) is $2\sqrt{2}U_2$.

The presence of negative portions on load voltage waveforms leads to changing in the rectifier's control characteristic. For example, in the case of inductive load ($L_s \rightarrow \infty$) at the value of command angle $\alpha = 90^0$, the areas of the negative and positive portions of the load voltage become equal and therefore the average value of the rectified voltage is zero $U_d = 0$.

The control characteristic $U_d = f(\alpha)$ of controlled rectifier with inductive load ($L_s \to \infty$) can be represented analytically:

$$U_d = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} U_{2m}\sin(\omega t)d(\omega t) = U_{d0}\cos\alpha, \tag{3.5}$$

Therefore, the analytical expression of control characteristic in the case of inductive load ($L_s \to \infty$) is:

$$U_d = U_{d0}\cos\alpha, \tag{3.5a}$$

and is represented in fig.3.3 (curve 2).

As shown in fig. 3.5, the current consumed from the power supply network, which is the current through the primary winding of the transformer i_1, has the form of alternative rectangular pulses and has the fundamental harmonic i_1^1 delayed to the voltage in the network with an angle $\varphi = \alpha$. Therefore, we can mention two disadvantages of the operation of the controlled rectifier:

- ✓ introducing higher harmonics into the power supply, represented by the harmonic factor,
- ✓ inductive reactive power consumption, which is represented by a power factor lower than unit $\cos\varphi < 1$.

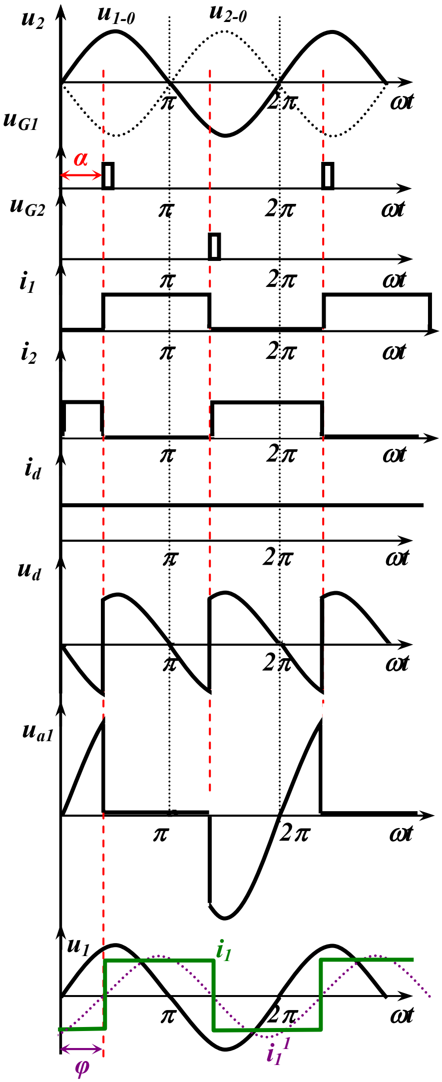
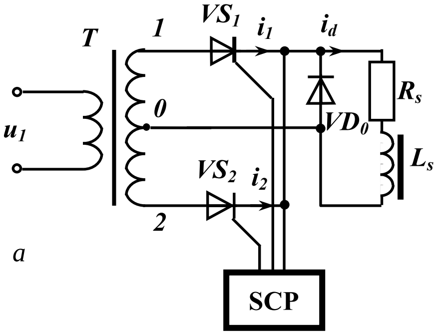


Fig. 3.5. Waveforms of voltages and currents of double alternation single phase controlled rectifier with neutral wire with inductive load ($L_s \to \infty$)

To increase the power factor of the rectifier and to reduce the rectified voltage pulses in the case of inductive load, ***the escape diode*** is used, which is connected in parallel with the load in such a way that the negative voltages on the load disappear. The scheme and the waveforms of voltages and currents of double alternation single phase controlled rectifier with neutral wire with inductive load (***Ls*** →∞) and with escape diode (***VD_0***) are represented in fig.3.6.



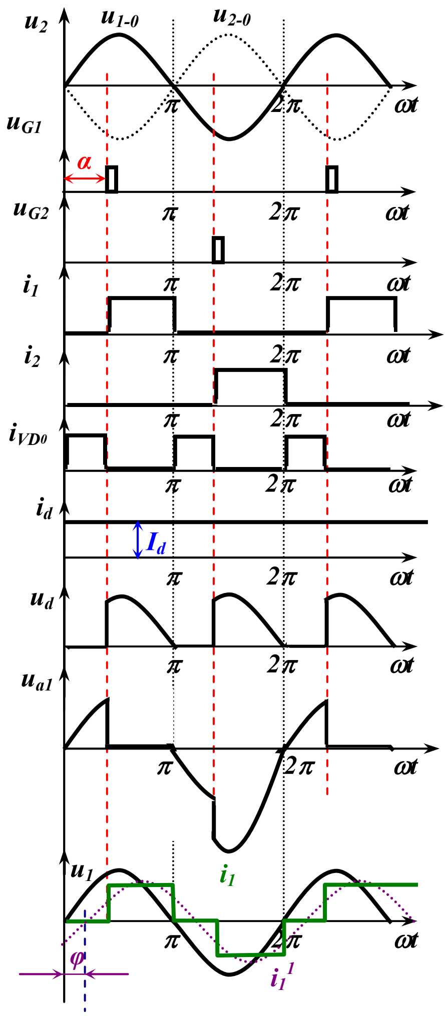


Fig. 3.6. . The scheme (a)
and the waveforms of voltages and currents (b)
of double alternation single phase controlled
rectifier with neutral wire with inductive load
(L_s→∞) with escape diode

In time ranges $0 \div \alpha$ the load current is maintained by the energy stored in the load inductance. In the absence of escape diode, the load current is closed by one of the valves and the secondary winding of the transformer, voltage on which is momentarily negative. The escape diode VD_0 shunts this circuit and the load current is closed by the escape diode and the valve is blocked by the negative voltage on the transformer's secondary. Due to the shunting of the load through the diode, the negative voltage portions on the load disappear and the shape of the control characteristic will be analogous to the resistive load case (see fig.3.3, curve 3), and the length (conduction angle) of the valves will decrease with α and the angle of the current delay to the voltage in the network will decrease to $\varphi=\alpha/2$.

CONTROLLED THREE-PHASE RECTIFIERS

Controlled three-phase bridge rectifier

The widest application in power converters has found the three-phase rectifier bridge.

The scheme of the controled three-phase rectifier is shown in figure 4.1. The peculiarities of operation of the controled three-phase rectifier consist in the delay with the angle α of the moments of unlock of the next valves related to the natural switching moments. This method of control is accomplished by delaying the angle of the control pulses provided by the control system. The operation of the three-phase bridge rectifier for the value of the command angle $\alpha=30^0$ is illustrated by the waveforms of voltages and currents in figure 4.2.

Since for the flow of the load current and therefore for the operation of the converter the conduction of one valve from each valve group is necessary, for provision of starting conditions of controled three-phase rectifier’s force circuit doubling of control pulses are made. For this purpose each control pulse is simultaneously applied and to the gate of the valve with the previous order number. In fig. 4.1 for doubling the control pulses, the pulse transformers (T_1-T_6) (through which the control pulses from the control system channels are applied) have two secondary windings.

In the case of inductive load ($L_s \to \infty$), the blocking of the valves is also delayed with the same angle α. The rectified voltage waveform contains negative voltage portions that reduce the rectified voltage average value. The waveforms of the rectified voltage for different control angular values are shown in fig. 4.3.

For the value range of the angle α from 0 to 60^0, the passing of the rectified voltage from one line voltage to another occurs at positive values of the line voltages and therefore the shape of the rectified voltage is analogous for both the resistive load and for the case of inductive load. The control characteristic $U_d=f(\alpha)$ differs for resistive or inductive load when the angle α has values greater than 60^0. Instead of the negative voltage portions (in the case of $L_s \to \infty$) on the waveforms of the rectified voltage when the load is resistive the voltage is null.

The control characteristic $U_d=f(\alpha)$ of the controled three-phase rectifier with inductive load ($L_s \to \infty$) can be found by finding the average value U_d on the interval $-\pi/3+\alpha \div +\pi/3+\alpha$ in the next mode:

$$U_d = \frac{1}{\frac{\pi}{3}} \int_{-\frac{\pi}{6}+\alpha}^{\frac{\pi}{6}+\alpha} \sqrt{6} U_2 \sin(\omega t) d(\omega t) = U_{d0} \cos\alpha ,$$

i.e. it has the analogous shape to the one-phase case (see fig.4.5.a).

In the case of $L_s=0$, the analytical expression for the control characteristic for the range of α: $60^0 \le \alpha \le 120^0$ is:

$$U_d = \frac{1}{\frac{\pi}{3}} \int_{-\frac{\pi}{3}+\alpha}^{\pi} \sqrt{6}U_2 \sin(\omega t)d(\omega t) = U_{d0}\left[1+\cos\left(60^0+\alpha\right)\right],$$

which is represented in fig.4.5.b.

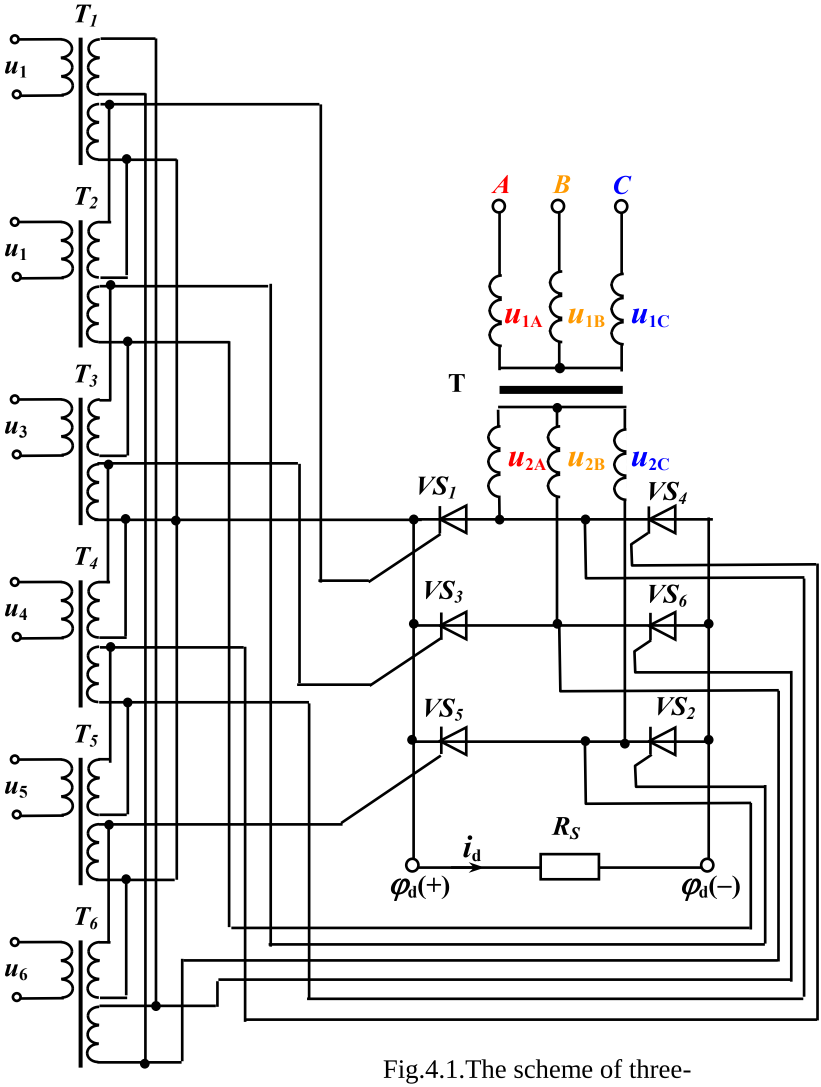


Fig.4.1.The scheme of three-phase controlled bridge rectifier

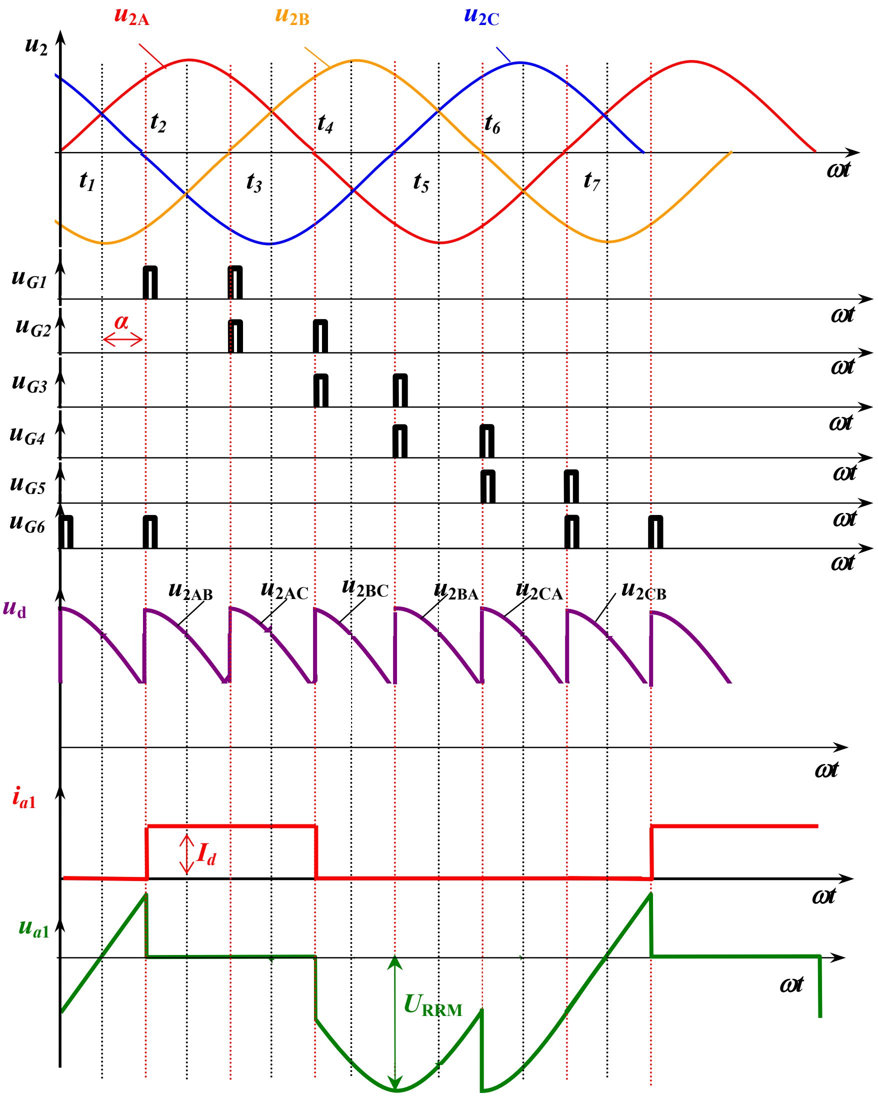


Fig. 4.2. The waveforms of voltages and currents of three-phase controlled rectifier: $\alpha=30^0$

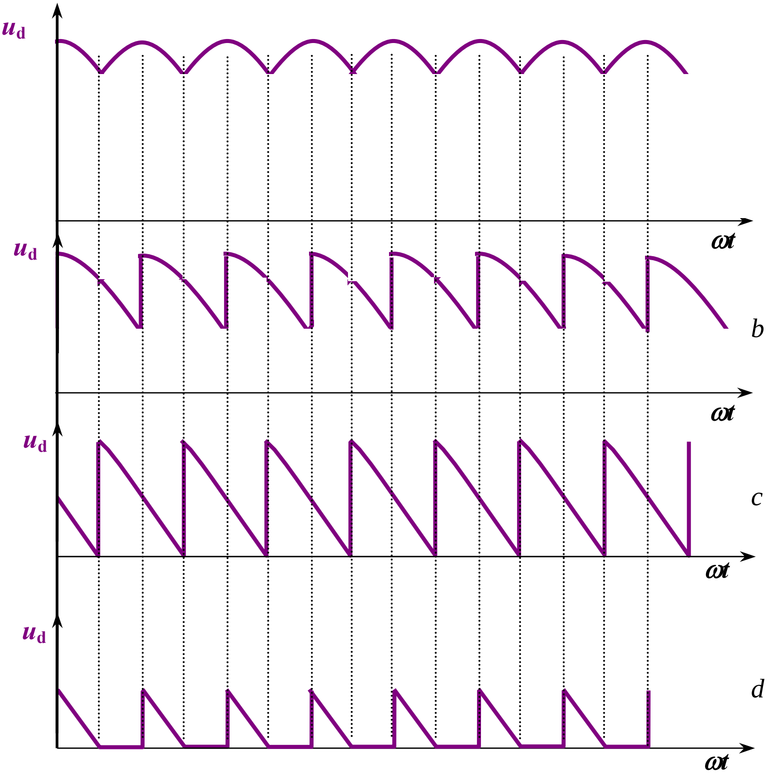


Fig. 4.3. The waveforms of rectified voltage
three-phase controlled rectifier with resistive load ($L_d = 0$):
a – $\alpha=0$, *b* – $\alpha=30^0$, *c* – $\alpha=60^0$, *d* – $\alpha=90^0$

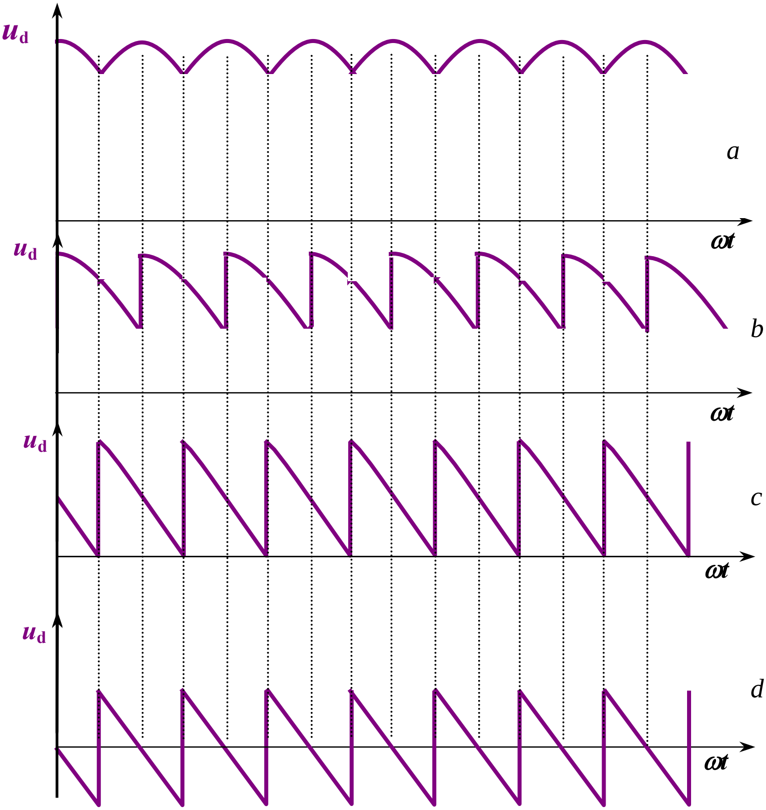


Fig. 4.4. The waveforms of rectified voltage
three-phase controlled rectifier with inductive load ($L_d \rightarrow \infty$):
$a - \alpha=0$, $b - \alpha=30^0$, $c - \alpha=60^0$, $d - \alpha=90^0$

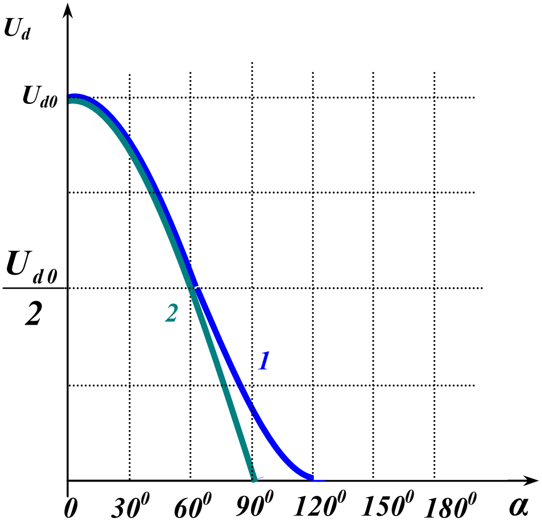


Fig.4.5. The control characteristics of thee-phase controled rectifier for:

a – resistive load ($L_d = 0$),

b – inductive load ($L_d \to \infty$)

GRID-TIE INVERTERS

Inverter mode is the process of converting energy from DC in the energy of AC. Grid-tie inverters convert the energy to the power supply network - the reverse process of rectifying. The grid-tie inverters are made on the same circuits as the controlled rectifiers. As a source of DC serves the DC machine operating in the generator mode. The reactor smoothens the waves of the input of the grid-tie inverter. In the rectifier mode, as the source, is the AC network.

Therefore, for $\alpha=0$, the phase of the current consumed in the network coincides with the supply voltage phase. In this case, the DC machine is consumer and operates in engine mode. In inverter mode, the DC machine is a generator and the AC network is a consumer. In this mode, for the preserved meaning of currents, determined by thyristors, the polarity of the E_d voltage is inverse. Changing the DC machine's polarity at the converter terminals is one of the switching conditions of the converter in the inverter mode. Therefore, in the inverter mode, the valves will be predominantly driven during negative alternations of the secondary voltages. In this mode, the secondary windings of the transformer are connected consecutively through the reactor L_d and the respective valves, to the source of DC E_d. In this way the transforming of the DC i_d in the AC i_1 is obtained. For this mode, the values of control angle α are between $\pi/2\div\pi$.

The blocking of the thyristor in the same time when the next thyristor is unbloked takes place under the action on the anode of the inverse voltage, created by the secondary voltage. Switching must, therefore, take place until the positive voltage occurs on the thyristor's anode. Otherwise, this thyristor will remain in conduction, and the short circuit mode, called the ***"inverter's upsetting"***, is formed in the converter circuit.

The angle of anticipation of natural switching moments $\beta=\pi-\alpha$ is called ***the inverter angle***.

In conclusion, the following conditions are required for switching the converter from rectifier to inverter mode:

1. *the polarity of the DC source* E_d *must be changed,*
2. *the flow of the current through the valves must be ensured, mainly during the negative polarity of the secondary voltages.*

5.1. *Single-phase gird-tie inverter with neutral wire*

The scheme and the waveforms of voltages and currents of double alternation single phase gird-tie inverter with neutral wire are represented in fig.5.1.

In the time interval from $\omega t=0$ to $\omega t=\alpha$, the conduction is the valve VS_2 and the current circulates through VS_2 and the secondary winding w_{2-0} due to electromotive tension E_d. In this way, the negative alternation of the voltage u_{2-0} determines the inverter voltage u_d. At the time $\omega t=\alpha$, a control pulse is applied to the gate of thyristor VS_1 and it is unblocked. The process of switching the current i_d from VS_2 to VS_1, which takes a time interval corresponding to the switching angle γ, is triggered.

During the switching process, the voltage on the inverter is null, the current i_{a1} increases from zero to I_d, and i_{a1} decreases from I_d to zero. From this time the current flows through VS_1 and the inverter voltage is determined by u_{1-0}.

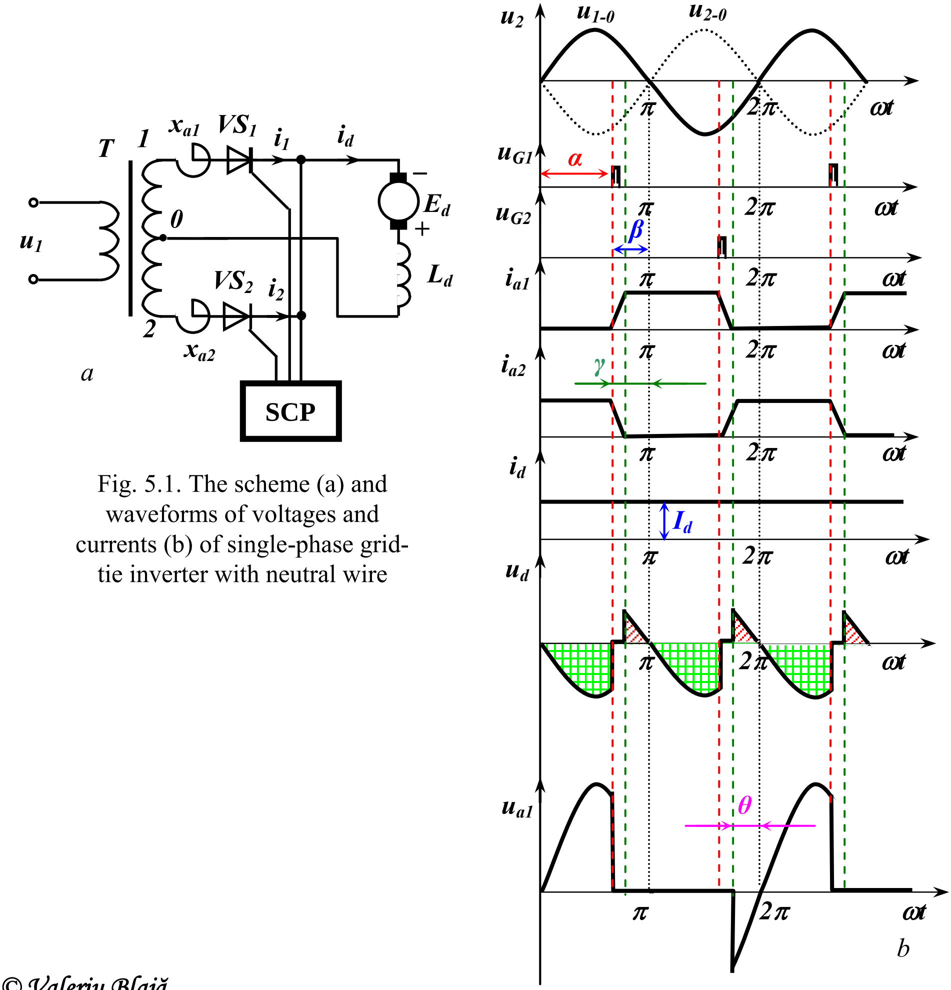


Fig. 5.1. The scheme (a) and waveforms of voltages and currents (b) of single-phase grid-tie inverter with neutral wire

In the time interval from $\omega t=\alpha+\pi+\gamma$ to $\omega t=2\pi$ the negative voltage is applied on VS_1. Also, in the range $\omega t=\alpha+\gamma$ to $\omega t=\pi$ the negative voltage is applied on VS_2, i.e. during this time interval $\theta=\beta-\gamma$, the negative voltage is applied to the valve and the valve restores its rectifier properties, due to the process of dissipating the charge carriers from the thyristor structure.

Since the areas of the negative voltage portions are larger than the areas of the positive voltage portions, the average inverter voltage is negative, which confirms that the transfer of energy to the supply network takes place. Tension on the valves are double the voltage of the inverter.

The minimum value of angle θ must be:

$$\theta_{min}=2\pi f t_{r.r.},$$

where: $t_{r.r.}$ is the thyristor's return time.

If $\theta< \theta_{min}$, ***"inverter's upsetting"*** occurs.

5.2. *Switching processes in single-phase gird-tie inverter with neutral wire*

The relations for the switching processes in the inverter driven by a single-phase gird-tie inverter can be obtained from the respective relations in the controlled rectifier, by replacing the control angle in the rectifier α with the inverter angle β. Therefore:

$$\beta=\pi-\alpha \text{ sau } \alpha=\pi-\beta.$$

Therefore, we will get:

$$i_{c.f.}=\frac{\sqrt{2}}{x_a}\cdot U_2\cdot \cos(\omega t-\beta), \tag{5.1}$$

$$i_{c.l.}=-\frac{\sqrt{2}}{x_a}\cdot U_2\cdot \cos\beta, \tag{5.2}$$

$$i_c=\frac{\sqrt{2}}{x_a}\cdot U_2\left[\cos(\omega t-\beta)-\cos\beta\right] \tag{5.3}$$

At the end of the switching process when $\omega t=\gamma$ the switching current will be $i_c=I_d$, and therefore:

$$I_d=\frac{\sqrt{2}}{x_a}\cdot U_2\left[\cos(\beta-\gamma)-\cos\beta\right]. \tag{5.4}$$

Therefore, for a concrete converter, when U_2 and x_a are set and for a concrete value of the angle β, the increase of the current I_d leads to the decrease of the angle θ, because with the increase of the current the energy stored in the dispersion reactants x_a and respectively the switching angle γ increases. In this way, as the current increases, the duration of applying the negative voltage on the valve decreases, which means that the angle θ is below the θ_{min} value. For this reason, the criterion for choosing the angle β is to provide the required value of the maximum current I_{dmax}, provided $\theta \geq \theta_{min}$.

Therefore, for the maximum current I_{dmax}, we will have:

$$I_{d\,max} = \frac{\sqrt{2}}{x_a} \cdot U_2 \left(\cos\theta_{min} - \cos\beta \right) \qquad (5.5)$$

From the expression (5.5) we get the value of the inverter angle β:

$$\beta = \arccos\left(\cos\theta_{min} - \frac{x_a}{\sqrt{2}} \cdot \frac{1}{U_2} \cdot I_{d\,max} \right) \qquad (5.6)$$

If we neglect the active resistance in the DC circuit, we can consider that electromotive tension E_d is balanced by the inverter voltage U_d.

In case of inverter mode, the switching process causes the voltage module $|U_d|$ to increase with $\Delta U_{d\gamma}$.

For $\gamma = 0$ we will have:

$$U_d = \left| \frac{1}{\pi} \int_{\pi-\beta}^{2\alpha-\beta} \sqrt{2} U_2 \sin(\omega t) \cdot (\omega t) \right|. \qquad (5.7)$$

Therefore:

$$U_d = \frac{2\sqrt{2}}{\pi} U_2 \cos\beta, \qquad (5.8)$$

or:

$$U_d = U_{do} \cos\beta, \qquad (5.8a)$$

where:

$$U_{do} = \frac{2\sqrt{2}}{5} U_2 \approx 0.9 U_2.$$

If we do not take into account the switching processes, the control characteristic is analogous to the rectifier's control characteristic, if we replace the angle α with the angle β. On the whole, the control characteristic comprising both converter modes is shown in fig.5.2.

When the switching process are considering, the average voltage of the inverter decreases by $\Delta U_{d\gamma}$.

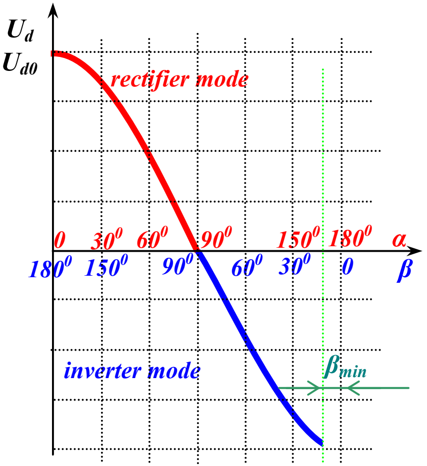


Fig.5.2. The control characteristic of single-phase converter

$$\Delta U_{d\gamma} = \frac{1}{\pi}\int_{\pi-\beta}^{\pi-(\beta-\gamma)} \sqrt{2}U_2 \sin(\omega t)d(\omega t) = \frac{\sqrt{2}}{\pi}U_2[\cos(\beta-\gamma)-\cos\beta]. \tag{5.9}$$

Therefore:

$$\Delta U_{d\gamma} = \frac{U_{d0}}{2}(\cos(\beta-\gamma)-\cos\beta), \tag{5.10}$$

and

$$U_d = U_{d0}\cos\beta + \Delta U_{d\gamma}, \tag{5.11}$$

$$U_d = \frac{U_{d0}}{2}(\cos(\beta-\gamma)+\cos\beta). \tag{5.12}$$

The average value of the inverter voltage is opposite and equal to E_d. Increasing E_d leads to an increase in the I_d current, i.e. to the increase of the power delivered to the network. This leads to the increase of γ and consequently to the increase of the U_d voltage.

The E_d growth limit is stopped by decreasing the β-γ difference to θ_{min}.

Therefore:

$$E_{d\,max} = U_{d\,max} = \frac{U_{do}}{2}(\cos\theta_{min} + \cos\beta). \tag{5.13}$$

*The E_d vs I_d dependence is called **the input characteristic of the inverter**.*

From the expressions (5.9) and (5.4) we find $\Delta U_{d\gamma}$:

$$\Delta U_{d\gamma} = \frac{x_a}{\pi}I_d. \tag{5.14}$$

By replacing (5.14) into (5.11) we get the expression for the input characteristic of the converter:

$$E_d = U_d = U_{do}\cos\beta + \frac{x_a}{\pi}I_d. \tag{5.15}$$

Unlike the rectifier case, the angle β is used here, and the switching voltage is greater than zero. When the current reaches the maximum value, angle θ becomes $\theta = \theta_{min}$. For larger values of the DC current, the inverter upsetts. As the angle β decreases, the limit value of the maximum current decreases. This value is found in ***the inverter limitation characteristic***. To find it, we will expose the $\cos\beta$ by θ_{min} from the expression (5.5):

$$\cos\beta = \cos\theta_{min} - \frac{x_a}{\sqrt{2}U_2}I_{d\,max}. \tag{5.16}$$

We replace the expression (5.16) in the expression for the input characteristic of the inverter and we obtain:

$$E_{d\,max} = U_{d\,max} = U_{do}\cos\theta_{min} - \frac{x_a}{\pi}I_{d\,max}. \tag{5.17}$$

We notice that the slope of the limitation characteristic is equal in value but has the opposite direction to the slope of the input characteristic.

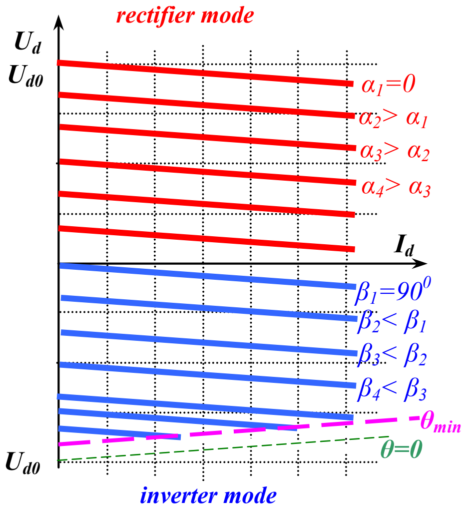


Fig.5.3. The external characteristics of single-phase converter

CONVERTERS FOR DC ELECTRICAL DRIVES

The control of the DC machine speeds can be done by three methods:

1. armature voltage regulation,
2. regulation of the current in the field winding,
3. combined method.

The voltage or current is regulated in controlled rectifiers, of which the rectifiers in mono- or tri-phase bridges are used more frequently. For the first method, a high power rectifier is used for armature voltage regulation, and the current in the field winding $I_{exc.}$ is provided by an uncontrolled low-power rectifier.

For the second method, the armature (inductor) voltage can be provided by an uncontrolled power rectifier and an controlled low power rectifier that regulates $I_{exc.}$. Athough the first method is more expensive, it is widely used due to good dynamic characteristics, while in the second method the system can operate at a lower speed.

The third method is used in more special cases. In most automatic DC electric drives it is also necessary to revert the direction of the drive of the DC machine.

Another problem is related to the formation of the recuperative braking regime. In a simpler version, is used a converter, which can operate in the rectifier mode at startup and inverter mode at braking, and to change the speed direction, the armature voltage polarity is changed with a mechanical switch.

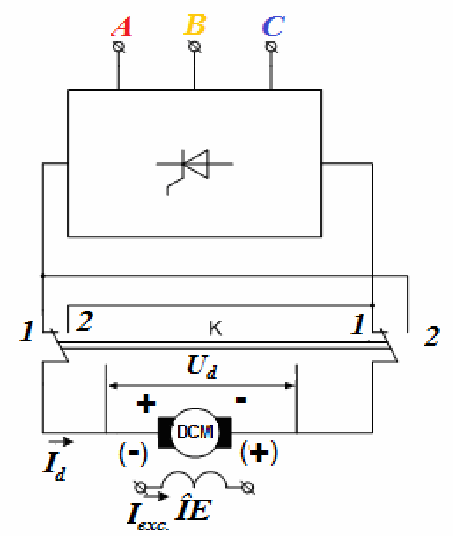


Fig.6.1. The scheme of irreversible converter

If we take into account the nonlinearities in the low-current area because of the interrupted current, the external characteristics $U_d=f(I_d)$ of the converter can be homologated with the mechanical characteristics $n=f(M)$ of the electromechanical system, since the machine rotations n are in direct relation with the armature voltage U_d, and the current consumed by the armature is directly dependent on the mechanical torque on the shaft. When switch **K** is set to position **1**, the armature voltage U_d with polarity + – is applied to the armature. A command angle $\alpha=\alpha_1$ is formed from the control system and applied to gate and according to the characteristic for an unchanged mechanical load torque and current decreases and rises rotations n and armature voltage U_d.

Not reaching the identified value it is created another command angle α_2 and is passed horizontally on other characteristic (corresponding to the angle α_2) at the same speed and therefore suddenly increases the current and torque, and then according to this characteristic decreases the current and the torque, increases the speed. Starting the DC motor and reaching the nominal speed (required) with those speed is done by zigzag movement on the external characteristics.

The speed of the increase in the rotations of the DC motor is limited by the maximum value of the current of the armature. For this purpose, a current transducer is installed in the circuit of the armature, which signals through the feedback loop to the control system.

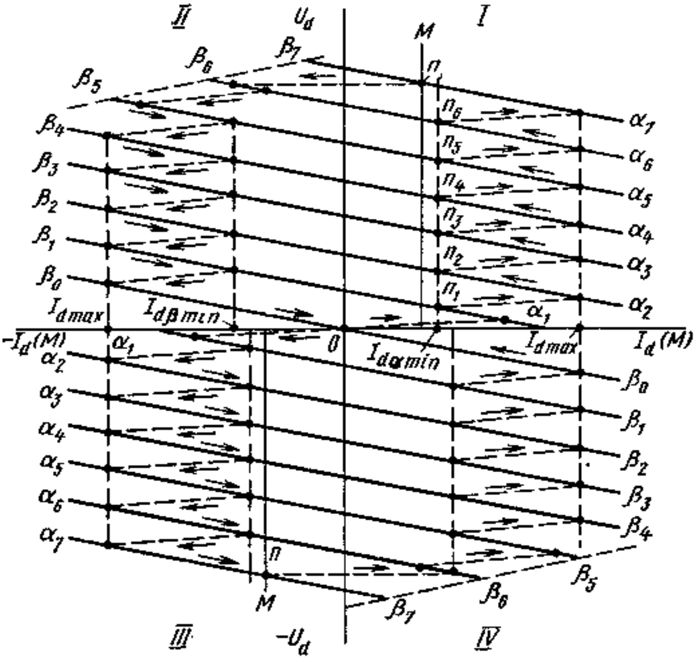


Fig.6.2. Combined external characteristics
of the reversible DC converter

The starting process is carried out at the required speed, i.e. at the start by a tachometer reaction signal applied to the automatic adjustment system. Thus, in the quadrant ***I*** the converter operates in a rectifier mode with $\alpha<90^0$, and the DC mashine operates in the engine (consumer) mode and the power is transmitted from supply power network via the converter to the DC motor.

For machine braking, switch ***K*** is set to position ***2***, and the polarity of electromotive tension E_d from the armature of electric motor is changed to the DC terminals of the converter. In this way, the converter switches to inverter mode, and the DC mashine switches to the generator mode.

During the process of turning over of the energy to the grid the converter operates on the characteristic corresponding to the angle β_1 which varies within the limits $0^0<\beta<90^0$. The speed decreases not reaching to I_{dmin}, the angle β of the inverter is increased to β_2 and from the horizontal it passes on the inverter characteristic corresponding to the angle β_2. In the same way, the machine speed is decreased, operation takes place in quadrant ***II***, where recuperative braking is performed.

If the position of the switch is not changed and the command angle α is further diminished ($\alpha<90^0$), for example up to α_1, operation of the electromechanical system is switched to the quadrant ***III***, where the DC drive starts in the opposite direction to the previous speed, and by changing the position of the switch ***K*** from position ***2*** to position ***1***, the operation in quadrant ***IV*** will pass, where regenerative braking is achieved in this sense of speed.

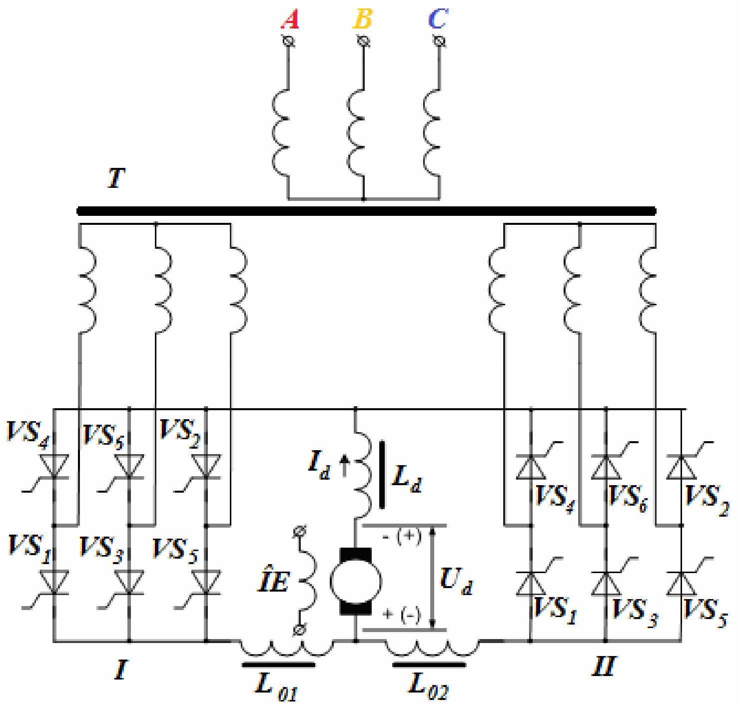


Fig.6.3. The scheme of crossed connection
of two three-phase rectifier bridges

The operation of this electromechanical system depends greatly on the faithful operation of the mechanical switch ***K***. This disadvantage can be overcome by using reversible converters in which two sets of thyristors (rectifier bridges) in other words two irreversible converters, are connected. Connections of these more commonly used thyristor sets are:

- ***crossed*** (see fig.6.3) and
- ***anti-parallel*** (see fig.6.4).

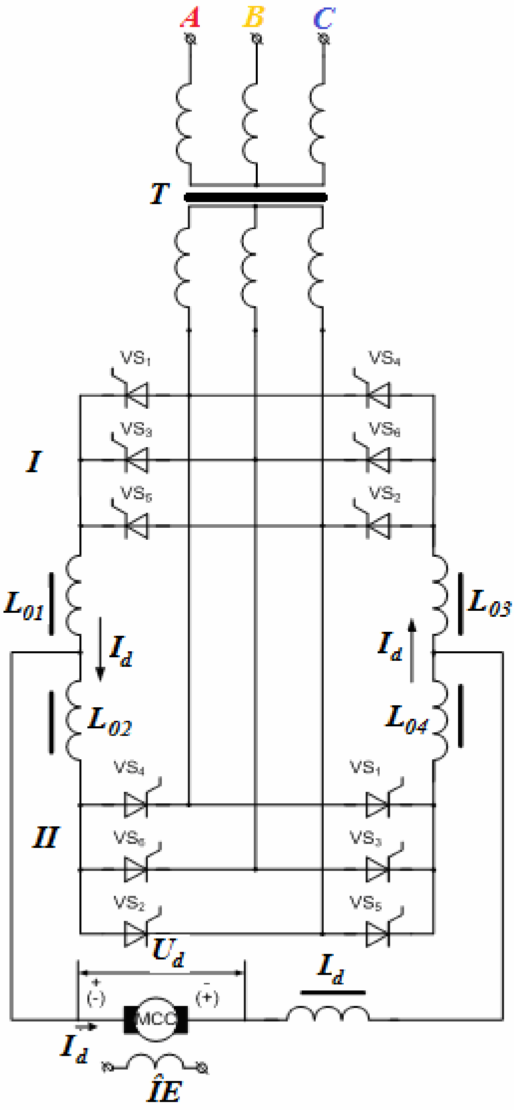


Fig.6.4. The scheme of anti-parallel connection of two three-phase rectifier bridges

Wider practical application found the anti-parallel connection of two three-phase bridges. In order to ensure the operation of the electromechanical system in both directions of the DC machine, but also in both directions of the energy flow between the AC power supply and the DC machine in the reversible converter, both bridges can operate, both in the rectifier mode, and inverter mode.

The bridges's control can be done in two ways: ***common*** and ***separate***.

In the case of a ***common control***, the control pulses are applied at the same time to the thyristors's gates of the in both sets so that one set operates in the rectifier mode and the other in the inverter mode. The respective $U_{d\alpha I}$ and $U_{d\beta II}$ voltages correspond to the polarity of the operation of the DC machine. For example, in quadrant ***I***, where set ***I*** operates in rectifier mode, and set ***II*** works in inverter mode:

$$U_{d\alpha I} = U_{d\beta II}.$$

Respectivly: $U_{doI} \cos \alpha_I = -U_{doII} \cos \alpha_{II}$.

Being powered by the same secondary voltage: $U_{doI} = U_{doII}$,

and, therefore: $\cos \alpha_I + \cos \alpha_{II} = 0.$

In this way we get the common's command condition that is: $\alpha_I + \alpha_{II} = 180^0$.

Therefore, if the set ***II*** works in inverter mode we will have:

$$\beta_{II} = 180^0 - \alpha_{II}, \qquad \beta_{II} = \alpha_I.$$

That is, the inverter angle in set ***II*** is equal to the value of the command angle in set ***I.***

If the direct direction of the DC motor rotations corresponds to the voltage's U_d polarity indicated on the scheme, then in the quadrant ***I***, the first set acts as a rectifier and the machine works as a motor, the armature current flows from left to right. During this time the set ***II*** can act as an inverter, but it is inactive (the current through the thyristors of this set does not flow).

In order to move into the quadrant ***II***, the command angle α decreases and the inverter angle increases in the set ***II*** in such a way that the recuperative braking is imposed, and the armature current through the converter will reverse.

Further the command angle β_{II} increases up to 90^0 and operation takes place in the quadrant ***II***. Moving from one characteristic to another, the speed decreases if necessary up to zero. At this time, the command angle in set ***I*** – α_I increases to 90^0.

When the command angle in set ***II*** – α_{II} will be further reduced, operation goes into quadrant ***III*** for the same direction of current it is necessary to start the machine in the opposite direction. For this purpose the set ***II*** works (active as a rectifier), respectively, α_{II} will be less than 90^0, i.e. $\alpha_I > 90^0$, that is the set ***I*** is ready to act as an inverter.

If the electromotive tension E_d on the armature, which now has the polarity (– +), is quite high and the angle α_{II} will increase to 90^0 and the angle α_I will decrease to 90^0 (β_I increases to 90^0) in this case the current it changes its meaning and circulates through the thiristors of the set ***I***, therefore by switching the switch ***K*** to position ***1*** it goes into the quadrant ***IV***, where recuperative braking of this speed direction occurs.

The main disadvantage of the common control method is the presence of ***equalizing tension*** and ***circulation currents*** between sets of thyristors. The *equalizing voltage* is the difference in instantaneous voltage values on the two sets of braking.

Circulation currents formed by this equalizing voltage circulate through the internal contours of the converter formed by the thyristors in conduction on the same side of the two sets but from different phases and respective phase voltages.

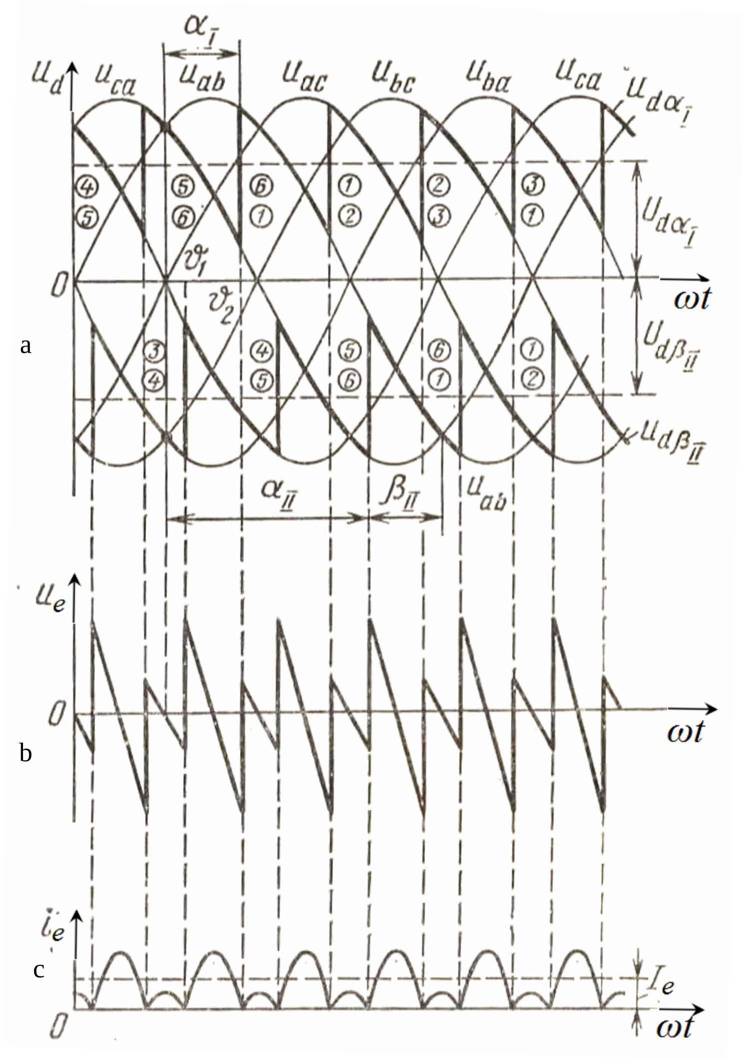


Fig.6.5. The waveforms of output (a) and equalizing (b) voltages and circulation current (c) in reversible converter with common control

Since the resistences in the internal circuits of the converter are small, the circulation currents can reach very high values and may exceed the admissible values for thyristors, the current limiters L_{01}, L_{02}, L_{03}, L_{04} are required to prevent the breakdown of thyristors from the internal circuits of the converter. If the reactors are saturated, two of them, for example L_{01} and L_{03}, are saturated by the load current, and two others, for example L_{02} and L_{04}, serve to limit the circulation currents. If the reactors are unsaturated, only two L_{01} and L_{04} or L_{02} and L_{03} can be used. The inductances of these reactors are usually chosen so that the circulation currents do not exceed $0,1I_d$.

Separate command

At the separate command, the need for current limiting reactors disappears because the control pulses are applied to the thyristor’s gates of one set (required) and in the other set thyristors remain locked, therefore there is no equalization voltage and circulation currents. However, in the separate control, the dynamic characteristics of electromechanical system are worse, because switching from one set of valves to another requires a break to lower the current to zero and firmly lock the thyristors.

7. AC REGULATOR

7.1. General notions

The alternating current (voltage) *(AC)* ***regulators*** *are static converters, which transforms AC from the source (from the power supply network) in the AC of the same frequency, but with the possibility of adjusting the effective voltage on the load (receiver, requester, consumer). Therefore, the AC regulator regulates the flow of energy from the source to the consumer.*

The basic element of the AC regulator is the static circuit breaker, having the role of connecting/disconnecting a receiver to/from the AC. The static circuit breakers can be used for simple connection/disconnection of the receiver to/from the source and (especially) to vary the alternative voltage applied to the receiver (implying the possibility of continuous regulation and with a very good power efficiency of the receiver on the power supply network).

AC regulators can be used:

- in electric AC drives to regulate the speeds of the asynchronous motors,
- AC welding equipment,
- adjustable power supply to high voltage installations,
- adjustable supply of electric furnaces,
- adjustable electric lighting etc.

AC regulators can be:

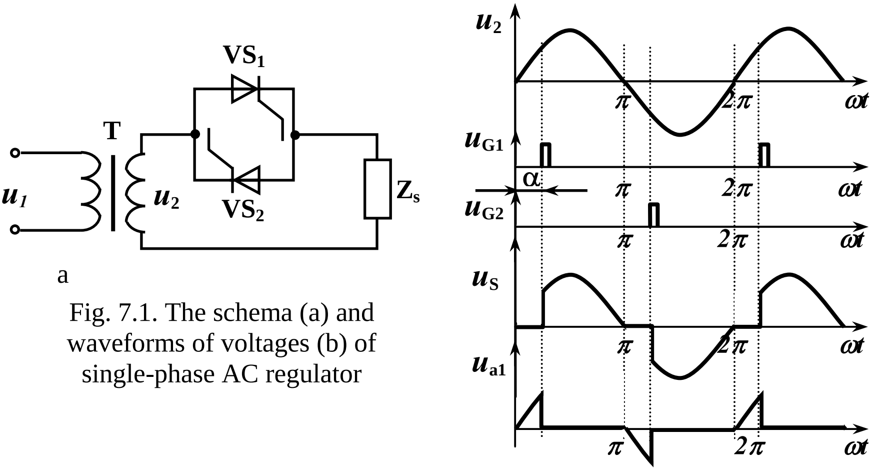
- single phase and
- three phase;
    - symmetrical and
    - asymmetrical;
        - reversible and
        - irreversible.

By the control method AC regulators can be:

- phase angle control,
- step by step,
- PWM.

7.2. Single-phase AC regulator

Since the alternating current given to load changes its direction twice over one period, a single phase static circuit breaker generally contains either a pair of antiparallel electrical valves or a bi-directional semiconductor device (triac). The schema of single-phase AC regulator is represented in Fig.7.1.a. The connection/disconnection of the load to the secondary winding of the power transformer **T** (at source) during the positive alternation (half-wave) of voltage u_2 is performed by the thyristor **VS$_1$** and during the negative alternation of voltage u_2 by the thyristor **VS$_2$** This variator has the simplest power circuit, but it involves a more complicated control device (the cathodes of the thyristors are not connected together), because between the channels of the control system the high anode voltage will be present.



a

b

Fig. 7.1. The schema (a) and waveforms of voltages (b) of single-phase AC regulator

This disadvantage is excluded in AC regulator with the power circuit formed by a semicomanded bridge (see fig. 7.2.a). The scheme involves a higher voltage drop on the circuit breaker (on a thyristor and a diode). During the positive alternation the current flows through the thyristor **VS$_1$** and the diode **VD$_2$**, and during the negative alternation the current flows through the thyristor **VS$_2$** and the diode **VD$_1$**.

A more economical AC regulator is represented in fig.7.2.b. Here the circuit breaker function has a thyristor, connected in the continuous voltage diagonal of an uncontrolled rectifier bridge, operating at each alternation, controlling the average value of the alternating current through load.

The role of thyristors, connected in the antiphase, (the circuit breaker) can realize a triac (see fig. 7.2.c). In order to realize the galvanic separation between the control system and the power circuit, phototransistor optocouplers can be used (see fig. 7.2.d).

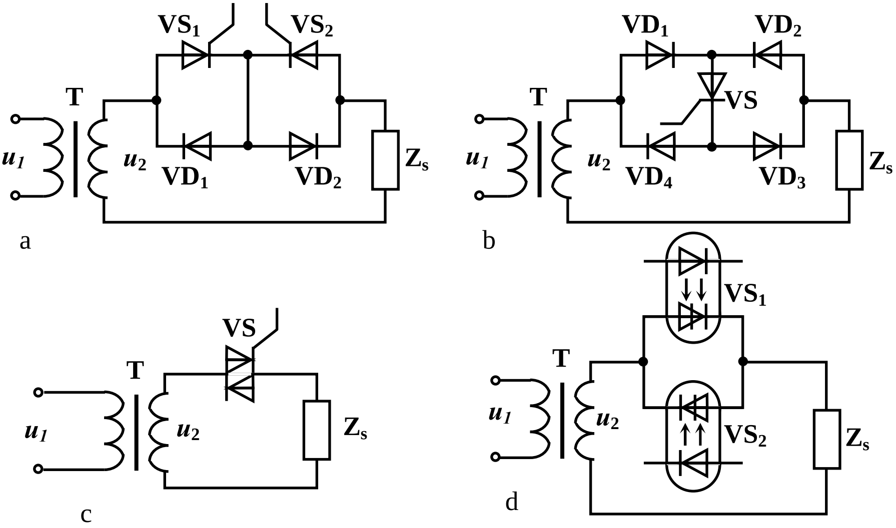


Fig. 7.2. The schems of single-phase AC regulator with:
a – semicomanded bridge,
b – thyristor in diode's bridge,
c – triac,
d – optocouplers

The phase angle control is analogous to the controlled rectifiers command. In case of phase angle control, the static circuit breaker periodically connects the receiver (at each alternation) with a certain adjustable delay α (control angle) to the moments of natural zero crossing of voltage. Operation of the AC regulator with antiparallel thyristors (fig.7.1.a) is illustrated by the waveforms of the voltages in the circuit, shown in Fig.7.1.b. The effective value of voltage on load depends on thyristor's conduction time.

Therefore, the effective value of the voltage (current) in the receiver (load) can be varied by adjusting the control angle α (by means of the gate control system) from a maximum value obtained at $\alpha=0$, to zero – for $\alpha=180^0$. The dependence of the effective voltage value on the load vs the control angle α is represented by the ***control characteristic***, which has the analytical form represented by the expression:

$$U_S = \sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi}\left(\sqrt{2}U_2\right)^2 \sin^2(\omega t)\,d(\omega t)}, \qquad (7.1)$$

and the graphic is represented in fig.7.3.

In high voltage controlled rectifiers, the rectifier in the secondary winding circuit is made by an uncontrolled (diode's) rectifier, and an AC regulator is connected to the primary winding circuit. This makes it a much cheaper version.

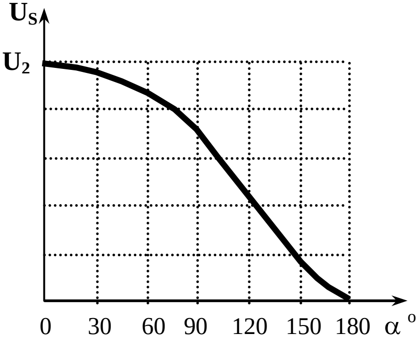


Fig.7.3. The control characteristic of AC regulator

7.3. Three-phase AC regulator

In the case of high-power receivers, when supplying is realized from the three-phase power network, three-phase AC regulator variants are required. The main solutions consist in connecting in each phase of a single-phase two-thyristor coupler in antiparallel connection (or one of the variants represented in fig. 7.2). The schemes of the most widespread variants of three phase AC regulators are represented in fig. 7.4: for connection with neutral wire (a), star connection (b) and triangle connection (c) of single-phase AC regulators. The supply of each single-phase AC regulators is made with one of the phase voltages (fig.7.4.a and b) or a line voltage (fig.7.4.c). The operation of each phase AC regulator is identical to the single-phase case and does not depend on the processes in other phases.

The connection of the 3 pairs of thyristors (or other type of circuit breaker) is absolutely necessary for the three-phase receivers with null conductor. In the absence of this, in one phase the phases regulator can be give up (see fig. 7.4.d) or semi-controlled static circuit breakers (thyristor connected anti-parallel with diode) can be used on each phase (see fig. 7.4.e). Unlike the variants presented above (fig.7.4.a, b and c), which are ***symmetrical***, these variants are called ***asymmetric***. In the case of asymmetric three-phase AC regulators analysis of the phase operation is done taking into account the other phases by the expression:

$$i_R + i_S + i_T = 0 . \qquad (7.2)$$

For reversible AC electric drives, three-phase AC regulators of the type represented in fig. 7.5 can be used. For one direction of rotations of the asynchronous machine, the thyristors of the couples 2,4 and 5 are commanded, and for the inverse direction of the rotations the thyristors of the couples 1,3 and 5 are commanded, two phases on the load are changed each with other.

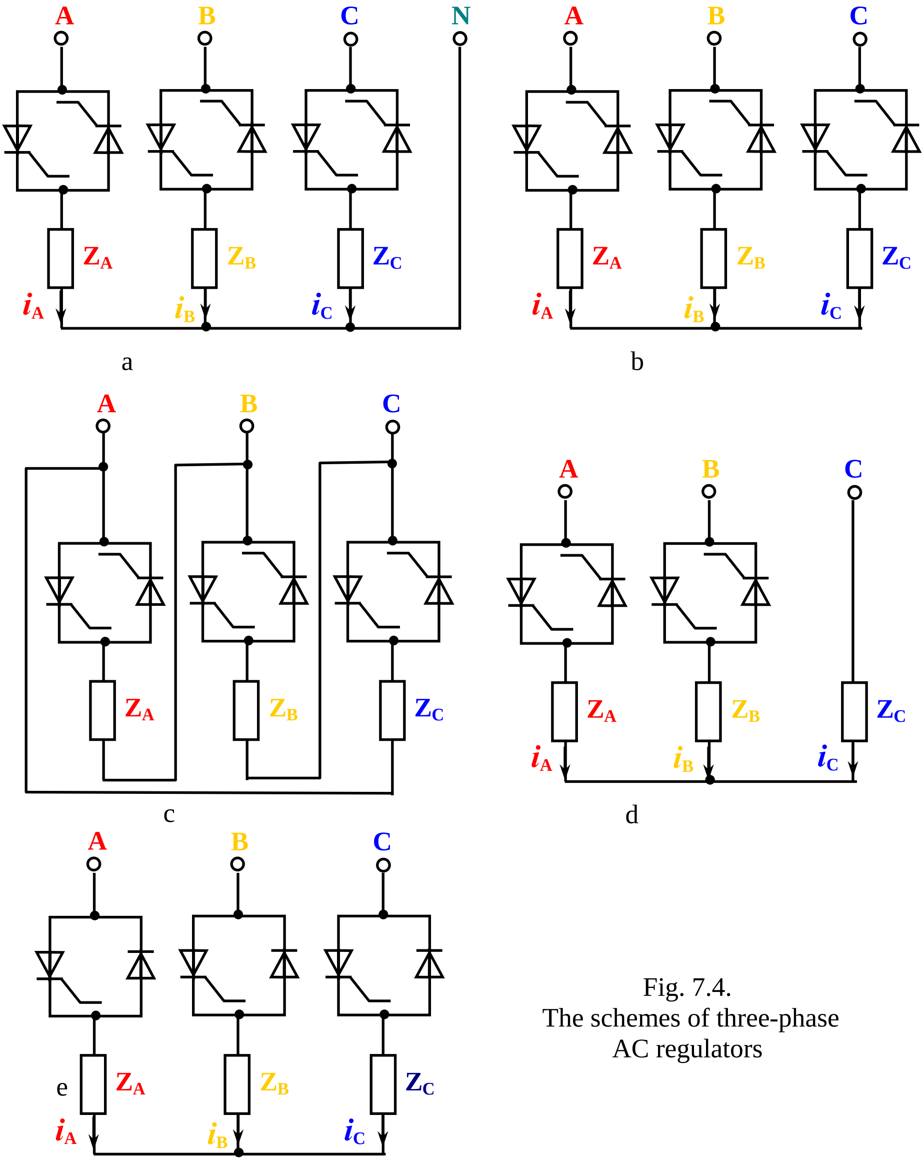


Fig. 7.4.
The schemes of three-phase
AC regulators

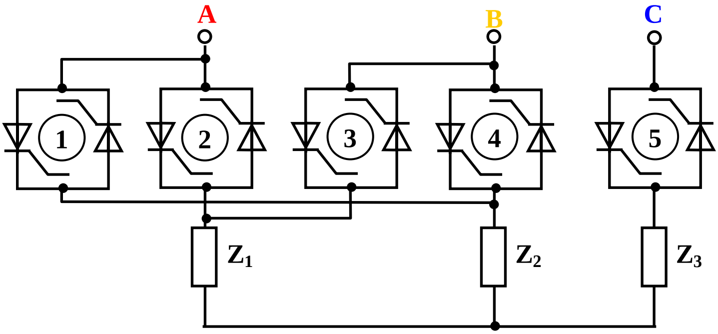


Fig. 7.5. The scheme of reversible three-phase AC regulator

8. CHOPPERS

8.1. General notions

Converters with time duration modulation (CTDM) are switches that operate on the principle of a circuit breaker and serve to adjust the voltage or current on the receiver, and in general: control the power flow between the source and the receiver. CTDM connects/disconnects the DC source to the receiver (load) and can therefore be called DC regulator (which are also called ***chopper***). Consequently, voltage pulses are formed at the chopper's output.

In order to control the energy flow oriented from the source to the load (in some cases and vice versa) the duration (t_i) or period (T) of the pulses can be adjusted and we will have respectively:

- ***time modulation converters,***
  when the duration of the pulses is variable and the period (frequency) is constant:
  $t_i = var,\ T = const.$
- ***frequency modulation converters,***
  when the frequency (period) is variable and the pulse duration is constant:
  $T = var,\ t_i = const.$
- ***time and frequency modulation converters,***
  when and pulse duration and frequency (period) are variable:
  $t_i = var,\ T = var.$

More common are time modulation converters.

Depending on the elements with which the converters are equipped, they differ:

- a converters with semi-controlled valve (conventional thyristors),
- a converters with fully-ordered devices such as:
  - ✓ **PTB** (power bipolar transistors),
  - ✓ **FET** (field effect transistors),
  - ✓ **GTO** (gate turn-off thyristors)
  - ✓ **IGBT** (insulated gate bipolar transistors).

Depending on the polarity and the method of output voltage regulation CTDM can be:

- ***irreversible*** and
- ***reversible***.

In the irreversible CTDM, the output voltage has unchanged amplitude and polarity, and the command is realized by variing the pulse duration. The irreversible CTDM works in one or two quadrants.

The output voltage of reversible CTDM can get both polarities. The output voltage of reversible CTDM is alternate and the alternating amplitude is varied or the voltage is alternate and the alternation duration is varied. The reversible CTDM, as a rule, have the bridge circuit and operate in four quadrants.

For CTDM we can mention the following ***advantages***:

- *high efficiency* because the losses on the controlled device (valve) are minimal;
- *low sensitivity to temperature variables*, because the adjusted parameter is time;
- small gauge and mass and permanently are ready for operation.

and ***disadvantages***:

- the pulsating regime is accompanied by the appearance of higher harmonics and therefore it is necessary to use filters, which worsen dynamic performance;
- disturbance due to the high current switching speed.

8.2. Irreversible chopper with fully-ordered devices

In the chopper schemes for fully ordered devices (which, as mentioned above, can be: PBT, FET, GTO, IGBT), we will use the GTO symbol.

The force scheme (a) and voltage and current time-diagrams for the resistive-inductive load case (b) in the circuit of the irreversible chopper in one quadrant with fully controlled devices are reprezented in figure 8.1. We will analyze two different cases of load.

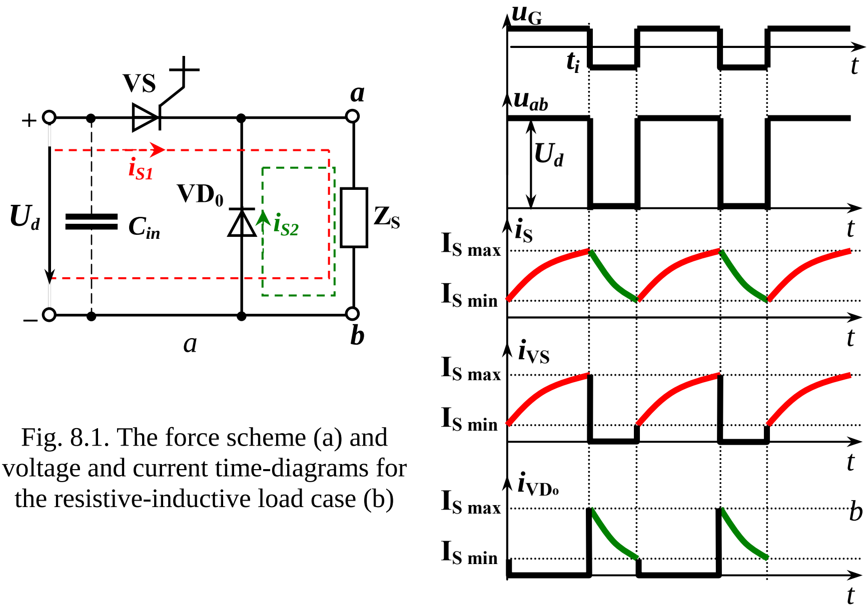


Fig. 8.1. The force scheme (a) and voltage and current time-diagrams for the resistive-inductive load case (b)

8.2.1. Active-inductive load

In the time interval from ***0*** to t_i, the device ***VS*** is in conduction and the load current (see i_{S1} in fig.8.1.a) flows through ***VS***, and to the load terminals (see in fig.8.1.a terminals *a* and *b*) is applied the voltage U_d. During this time the load consumes energy from source (part of it is stored in load inductance) and load current increases exponentially from I_{smin} to I_{smax}.

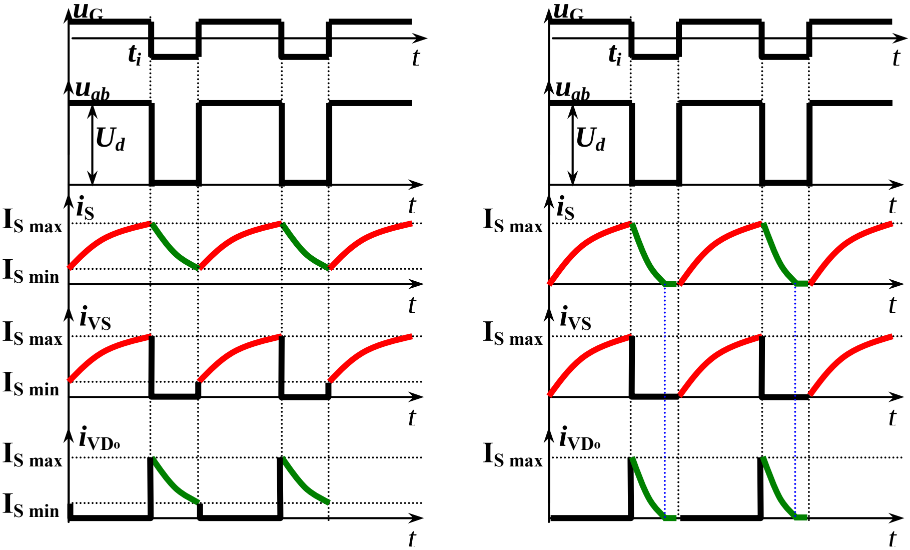
In the time interval from t_i to ***T***, the device ***VS*** is blocked and the load current (see i_{S2} in fig. 8.1.a) flows through the run-off diode VD_0 and is maintained in the same direction by the auto-induction electromotive force ***EMF***. At load terminals (*a* and *b*) the voltage is zero. The energy stored in the load inductance is consumed on the load resistance and the resistance of the run-off diode VD_0. The load current decreases exponentially from I_{smax} to I_{smin}.

As a rule, a filter (C_{in}) for the overvoltage protection of circuit's devices is mounted at the entrance of the choppers.

8.2.2. Load with EMF

When the chopper's load is a DC machine (DCM) (for example, machine's armature), there will be an electromotive force ***EMF*** in the output circuit that will change the operation of the chopper cardinally and two operation modes will be possible:

- uninterrupted current's mode,
- interrupted current's mode.



a *b*

Fig. 8.2.Time-diagrams of voltages and currents in the force circuit of irreversible in one quadrant chopper for load with EMF at:

a – uninterrupted current's mode,
b – interrupted current's mode

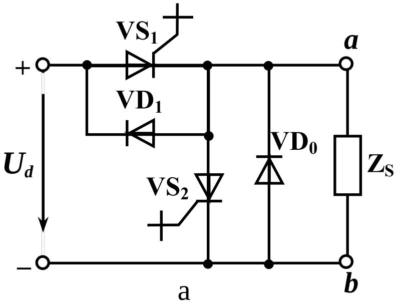
If the load current in uninterrupted current's mode has its minimum value I_{smin} higher than zero and through the armature permanently flows current, then in the interrupted current mode the load current will drop to zero and there will be time intervals in which the load current will be null. Uninterrupted current mode is preferred, and interrupted current mode is inadmissible for DCM. Time-diagrams of voltages and currents in the irreversible in one quadrant chopper circuit for these two regimes are represented in fig. 8.2.a and fig. 8.2.b, respectively.

The amplitude of the pulses of the current depends on the duration of the pulses t_i and the frequency of the commutations: for the constant frequency (period) with the increasing of the duration increases and the amplitude of the pulses of the current; and for a constant duration with the frequency increasing the pulse amplitude also increases.

Interrupted current's mode can occur at low load when pulse duration t_i is very close to the load time constant, or when the electromotive voltage in the load circuit is high.

8.3. Irreversible chopper in two quadrants

The scheme (a) and the voltage and current time-diagrames (b) in the force circuit of the irreversible chopper with two fully-ordered valves are represented in figure 8.3.. In this chopper, due to the presence of yet another fully commanded device VS_2 and a diode VD_1 that shunts the device VS_1, it is possible to reverse the flow of energy when the energy in the load circuit is recovered to the source. That means that besides the already known mode, we will have the recuperative braking mode. The devices VS_1 and VS_2 are ordered in antiphase.



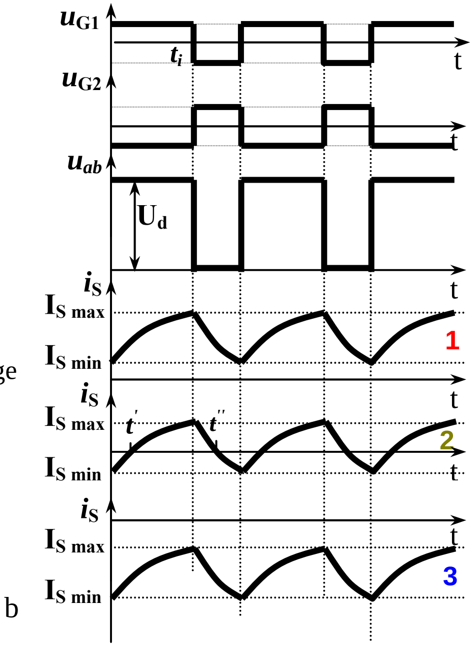


Fig. 8.3. The scheme (a) and the voltage and current time-diagrames (b) of irreversible chopper in two quadrants

Depending on the ratio between the value of the electromotive voltage (*EMV*) **E** in the load circuit and the value of average voltage imposed by the source to the load terminals (*a* and *b*), $\gamma\ \mathbf{U_d}$, where γ is the impulse filling factor (the conduction factor):

$$\gamma = \frac{\mathbf{t}_i}{\mathbf{T}}, \qquad (8.1)$$

three operating modes are possible:

1. *Small EMV* $\mathbf{E < \gamma U_d}$

When the mechanical load is high and therefore the electromotive voltage *EMV* ***E*** is low, the energy flow is oriented from source to load (DCM). The load current has one meaning and is uninterrupted. Therefore, operation occurs in the first quadrant (positive voltage and positive current). The time-diagram of the circuit's current for this mode is curve **1** in fig.8.3.b. In the time range from ***0*** to $\boldsymbol{t_i}$ the current flows through $\boldsymbol{VS_1}$ and load, and in the time interval from $\boldsymbol{t_i}$ to ***T*** the current is closed by the run-off diode $\boldsymbol{VD_0}$;

2. *AC mode*

When the mechanical load decreases, the average load current decreases, the machine speed increases and *EMV* increases. The *EMV* value is close to the average voltage imposed by the source to the load terminals $\gamma\mathbf{U_d}$:

$$\mathbf{E} \sim \gamma\mathbf{U_d}$$

The energy flow as well as the load current will be alternative, that is, at different time points it will have different directions and therefore operation takes place in both quadrants (I and II). The time-diagram of the circuit current for this mode is curve **2** in figure 8.3.b.

In the time range from ***0*** to $\boldsymbol{t_i}$ $\boldsymbol{VS_1}$ is in conduction. From ***0*** to $\boldsymbol{t'}$ the energy stored in the load in previous period is recovered to the source and the current, which is negative, flows through the shunt diode $\boldsymbol{VD_1}$. At the moment $\boldsymbol{t'}$ the current changes its direction and continues to flow through the device $\boldsymbol{VS_1}$ until the moment when $\boldsymbol{VS_1}$ is blocked. Current increases exponentially. In the time range from $\boldsymbol{t'}$ to $\boldsymbol{t_i}$ the energy flow direction is oriented from source to load.

As soon as the $\boldsymbol{VS_1}$ device is blocked (moment $\boldsymbol{t_i}$), the load current is closed by the run-off diode $\boldsymbol{VD_0}$ and decreases exponentially until moment $\boldsymbol{t''}$, when it reaches zero and changes its direction. In the time interval from $\boldsymbol{t_i}$ to $\boldsymbol{t''}$ the energy stored in the load is consumed on the load resistance and on the resistance of the diode $\boldsymbol{VD_0}$. After changing its direction, the current will flow through the device $\boldsymbol{VS_2}$. During this time (from $\boldsymbol{t''}$ to ***T***) the energy stored in the load is consumed on the load resistance and on the resistance of the device $\boldsymbol{VS_2}$;

3. *High EMV*

$$E > \gamma U_d$$

If the mechanical load on the DCM decreases, the rpm (spead) increases and *EMV **E*** increases. The meaning of load current and energy flow is changing. The energy flow is oriented from the load (DCM) to the source. The load current has only one meaning (negative) and is uninterrupted. Therefore, operation occurs in the second quadrant (voltage and current with different senses). The time-diagram of the circuit current for this mode is curve **3** in figure 8.3.b.

In the time interval from ***0*** to t_i, the current flows through VD_1 and the energy from DCM is oriented to source, and in the time interval from t_i to ***T*** the current flows through the device VS_2 and the energy stored in the load is consumed on the load resistance and on the resistance of the device VS_2.

8.4. Reversible chopper with fully-ordered devices

In reversible choppers is possible to operating in four quadrants: both the voltage and the current, and hence the direction of the machine speed, and the sense of the energy flow can have both senses. Reversible choppers without electromechanical switch (or mechanic) usually are in bridge scheme. The scheme of a reversible bridge chopper with fully commanded devices is shown in figure 8.4. This chopper can be ordered in three ways:

- ***symmetrical control,***
- ***asymmetrical control,***
- ***alternate control.***

8.4.1. Symmetrical control

Time-diagrams of voltages and currents in the circuit of the reversible chopper with symmetric control are shown in fig. 8.5.

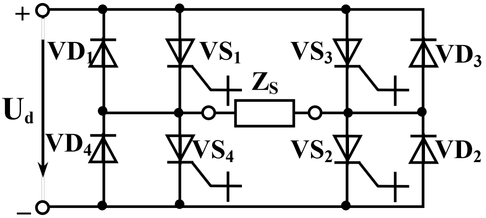


Fig. 8.4.The scheme of reversible chopper with fully-ordered devices

The devices are ordered in couples on diagonals: (VS_1 with VS_2) and (VS_3 with VS_4) in antiphase. In the time interval from ***0*** to t_i devices VS_1 and VS_2 are unlocked, and VS_3 and VS_4 are blocked. During this time, the load current flows through VS_1 and VS_2, and the voltage of the source U_d with polarity + – (which we will consider positive) is also applied to the load.

In the time interval from t_i to ***T*** the devices VS_1 and VS_2 are blocked, and devices VS_3 and VS_4 are unlocked. The voltage with negative polarity is applied to the load, and the load current continues to flow in the same direction (maintained by the energy stored in the load) and current circuit is closed through VD_3 and VD_4.

The average value of voltage on the load is:

$$U_s = U_d\,(2\gamma\text{-}1)\ . \qquad (8.2)$$

Therefore, when the fill factor is less than 0.5, the average value of voltage on the load will be negative: $\gamma<0{,}5 \Rightarrow U_s<0$, and when $\gamma>0{,}5 \Rightarrow U_s>0$.

For the symmetric command we can mention the following ***disadvantages:***

- voltage on the load is alternate (it changes the polarity in each period),
- the pulse factor gets high values.

These disadvantages make it used in low power equipment.

8.4.2. Asymmetrical control

Time-diagrams of voltages and currents in the reversible chopper circuit with asymmetric control are shown in fig. 8.6.

The devices (***VS₁*** and ***VS₄***) in one bridge shoulder (branch) are commanded in antiphase. In the other branch one device is permanently in conduction (***VS₂***), and another one (***VS₃***) - is permanently blocked. To change the direction of machine speed, the control on the branches will change with the place.

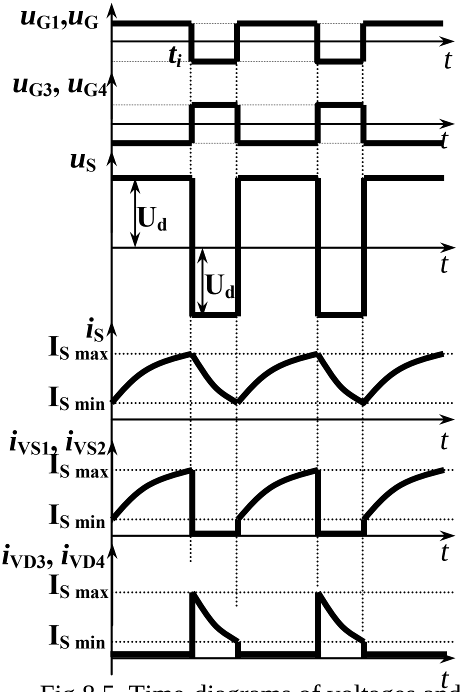


Fig.8.5. Time-diagrams of voltages and currents in the reversible chopper circuit with symmetrical control

If the load is resistive-inductive and does not contain *EMF*, the operation is as follows:

In the time interval from ***0*** to t_i the devices VS_1 and VS_2 are unlocked, and the devices VS_3 and VS_4 are blocked. During this time, the load current flows through VS_1 and VS_2 and the voltage U_d with positive polarity is applied to the load. The load current increases exponentially.

In the time interval from t_i to ***T*** the device VS_1 is blocked and the device VS_2 is in conduction. The voltage applied to the load is null and the load current continues to flow in the same direction (maintained by the stored energy in the load) and current cicuit is closed through the diode VD_4 and the device VS_2. The load current decreases exponentially. The time-diagram of current for this case is represented by curve **1** (fig.8.6).

If in the load circuit is present *EMT* (DCM) then three cases are possible depending on the ratio between values of ***E*** and γU_d:

1. when the values are:

$$\mathbf{E < \gamma U_d,}$$

chopper operation and time-diagram of current will be analogous to the above case (curve **1**);

2. if γ remains the same, and DCM's speed and *EMV* rises, we will have:

$$\mathbf{E \sim \gamma U_d},$$

i.e. mode of *alternating current*.

For this case the operation is in the following way: In the time interval from $\boldsymbol{0}$ to $\boldsymbol{t'}$ the load current is negative and flows through the diodes $\boldsymbol{VD_1}$ and $\boldsymbol{VD_2}$ and energy, stored in the load, is recuperated to the source. In the time interval $\boldsymbol{t'}$ to $\boldsymbol{t_i}$, the load current is positive (increases exponentially) and flows through the devices $\boldsymbol{VS_1}$ and $\boldsymbol{VS_2}$ and the energy flow is oriented from source to load. In the time interval from $\boldsymbol{t_i}$ to $\boldsymbol{t''}$ the load current is positive (decreases exponentially) and flows through the diode $\boldsymbol{VD_4}$ and the device $\boldsymbol{VS_2}$. In the time interval from $\boldsymbol{t''}$ to $\boldsymbol{T}$, the load current already has negative sense and flows through the device $\boldsymbol{VS_4}$ and the diode $\boldsymbol{VD_2}$. The time-diagram of current in this case has the shape represented by curve **2** in fig. 8.6;

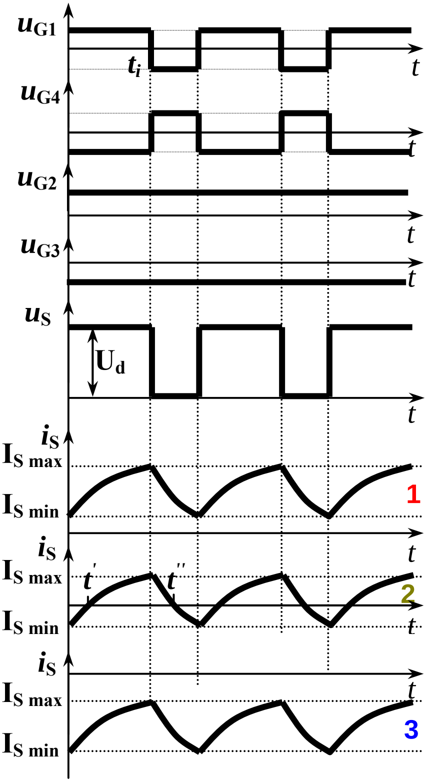


Fig. 8.6.
Time-diagrams of voltages and currents in the reversible chopper circuit with asymmetrical control

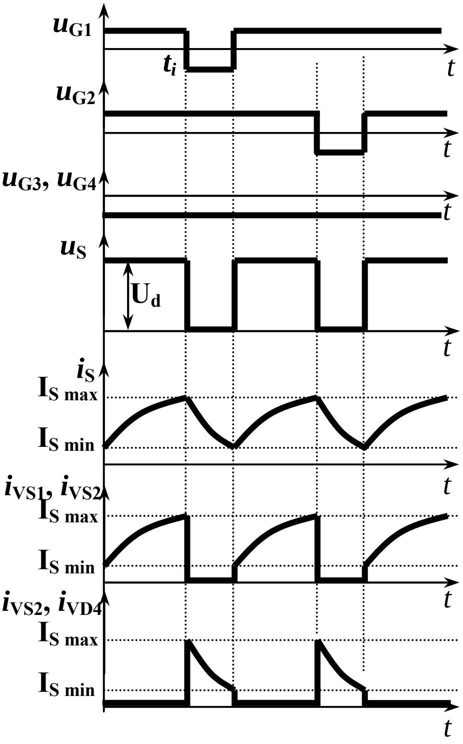


Fig. 8.7.
Time-diagrams of voltages and currents in the reversible chopper circuit with alternative control

3. if *EMV* continues to grow $\mathbf{E > \gamma U_d}$
we will have a *recuperative regime*.

The load current is permanently negative and the current's diagram is represented by curve **3** in fig. 5.7 and the energy flow is predominantly oriented from DCM (load) to the source. In the time interval from 0 to ti the load current flows through the diodes VD_1 and VD_2, and in the time interval from t_i to T – through the device VS_4 and the diode VD_2.

For this command mode (asymmetrical) we could mention such ***advantages*** as:

- the voltage on the load has a single polarity,
- pulses are smaller.

8.4.3. Alternative control

Time-diagrams of voltages and currents in the circuit of reversible chopper with alternative control are shown in fig. 8.7.

The devices VS_3 and VS_4 are permanently blocked, and the devices VS_1 and VS_2 are blocked in the time intervals from t_i to T in different successive periods (alternative). In order to change the direction of the machine's speed, the pairs order will change with the place.

In the time range from 0 to t_i the devices VS_1 and VS_2 are in conduction, positive voltage is applied on the load, and the load current flows through the devices VS_1 and VS_2. In the time interval from t_i to T the device VS_1 is blocked and the voltage on the load is zero and the load current flows through the device VS_2 and the diode VD_4. In the time interval from T to $T+t_i$, the devices VS_1 and VS_2 are in conduction, positive voltage is applied to the load and the load current flows through the devices VS_1 and VS_2. In the time interval from $T+t_i$ to $2T$ the device VS_2 is blocked and the voltage on the load is zero and the load current flows through the device VS_1 and the diode VD_3.

For the alternative control, we can mention ***the advantage***: the device switching frequency is two times lower.

9. INVERTORS

9.1. General notions

Inverters are converters that convert direct current to alternating current, i.e., DC–AC. Unlike grid-driven inverters, which serve to orientate the energy flow to the existing grid; autonomous inverters operate for a consumer (load, receiver, requester) autonomous from the power supply, and usually have as a source a battery, a solar battery, a DC machine. Also, unlike grid-driven inverters, which form AC with the determined frequency of the network; autonomous inverters form at output AC with a constant or adjustable frequency determined in the inverter circuit.

For autonomous inverters the following **areas of use** can be listed:

- powering the AC equipment in cases where only unique source of electricity is a battery, a solar battery, etc. (for example, under field conditions),
- powering the AC equipment in the event of an interruption in the AC supply network,
- powering the AC technology equipment of frequency other than standard frequency (induction heating, high frequency, etc.),
- electric drives or electric traction with AC machines (asynchronous or synchronous) frequency controlled.

Common requirements for autonomous inverters are:

- maximum efficiency,
- possibility of stabilizing the output frequency or adjusting it in wide limited,
- possibility of adjusting the output current,
- the stability of the output voltage to variations in the working mode of the load,
- the waveforms of output voltage and current as close as possible to the sinusoid,
- minimal energy consumption,
- the possibility of idling.

Autonomous inverters can be **classified:**

- by **the number of phases:**
  - mono-phase (single-phase),
  - polyphase (2 phases, 3 phases etc.);

- by **type of valves:**
    - with fully-ordered devices,
    - with conventional thyristors;

- by **connecting scheme** of the valves**:**
    - with neutral wire,
    - bridge scheme;

- depending on the electromagnetic processes that take place in the autonomous inverter circuit, they differ:

    - ***current's inverters,***
    - ***voltage's inverters,***
    - ***resonant's inverters.***

An inductor with a very high inductance ($L_d \to \infty$) is connected at entrance of *current's inverter* in series with the source so that the current of the source will be kept constant. That means that, the source works in the current generator mode.

A capacitive filter with a very high capacity is connected at entrance of *voltage's inverter* in parallel with the source so that the voltage of the source will be kept constant. That means that, the source works in the voltage generator mode.

The *resonance's inverters* have a force scheme analogous with the current's inverters, but the input inductance is not very high. It is chosen in such a way that together with the switching capacitor and taking into account the reactive nature of the load an oscillating circuit with the resonance frequency slightly higher than the output frequency is formed.

9.2. Single phase current's inverter in bridge with parallel switching capacitor

The schema of the single-phase current's inverter with conventional thyristors with parallel switching capacitor is represented in fig. 9.1.a, and the time-diagrams of voltages and currents in its circuit is represented in fig. 9.1.b. Thyristors are ordered in pairs (VS_1 with VS_2 and VS_3 with VS_4) in anti-phase. The inductor L_d with a very high inductance ($L_d \to \infty$) is connected in input circuit, that the input current is pulseless and has a constant value I_d, and the currents through the valves are in the form of rectangular pulses.

In the first half of the output period the valves VS_1 and VS_2 are unlocked and the valves VS_3 and VS_4 remain blocked. During this time the current I_d flows through VS_1 and VS_2 and the output current i_{out} is positive and has this value (I_d). The output current i_{out} is branched into the current i_C, which charges the switching capacitor C with the polarity + –, decreasing exponentially, and the load current i_S, which increases at the same rate because:

$$i_S + i_C = i_{out} = I_d. \qquad (9.1)$$

In the second half of the output period the valves ***VS₃*** and ***VS₄*** are unlocked and the switching capacitor becomes short-circuited by all the valves. The condenser discharge current flows in opposite direction to the current of the thyristor ***VS₁*** and ***VS₂***, reduces it very quickly to zero and causes the thyristors ***VS₁*** and ***VS₂*** to block. After this time, the switching capacitor ***C*** is recharged from the source via ***VS₃*** and ***VS₄*** with polarity (**–**) **(**+). We will mention that discharge of the condenser will also take place through the load. The load current changes its meaning in every half-period.

In order to limit the sudden increase of the current through the thyristor anodes, in series with the thyristors are mounted current limiting reactors.

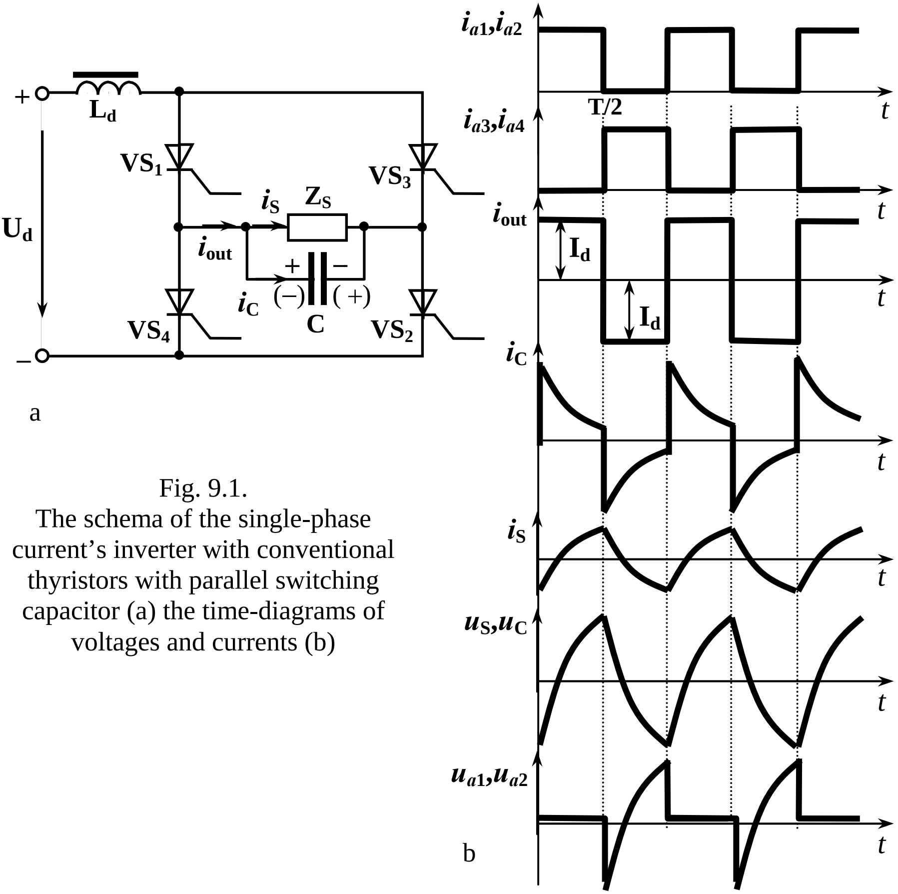


Fig. 9.1.
The schema of the single-phase current's inverter with conventional thyristors with parallel switching capacitor (a) the time-diagrams of voltages and currents (b)

9.3. Single phase current's inverter with neutral wire with parallel switching capacitor

The schema of the single-phase current's inverter with neutral wire with conventional thyristors with parallel switching capacitor is represented in fig. 9.2.a, and the time-diagrams of voltages and currents in its circuit is represented in fig. 9.2.b. The load is coupled through the transformer ***T*** with neutral wire. Thyristors VS_1 and VS_2 are ordered in anti-phase.

In the first half of the output period the valve VS_1 is unlocked and the valve VS_2 remains blocked. The capacitor is charged through the thyristor VS_1, the diode VD_2 and the primary winding $w_{1\text{-}2}$ of the transformer ***T*** with the polarity + –. Current through $w_{1\text{-}2}$ induces in secondary winding w_2 the output voltage.

In the second half of the output period the valve VS_2 is unlocked and the voltage on the capacitor plates ***C*** contributes to blocking the thyristor VS_1. Further the switching capacitor ***C*** is charged through VS_2, diode VD_1 and semi-winding $w_{1\text{-}1}$ with reverse polarity to the previous one (–) (+). The current through $w_{1\text{-}1}$ induces in w_2 the output voltage, which will now have the opposite polarity. The diodes VD_1 and VD_2 serve to separate switching capacitor ***C*** from load, in order to avoid discharge of capacitor through load.

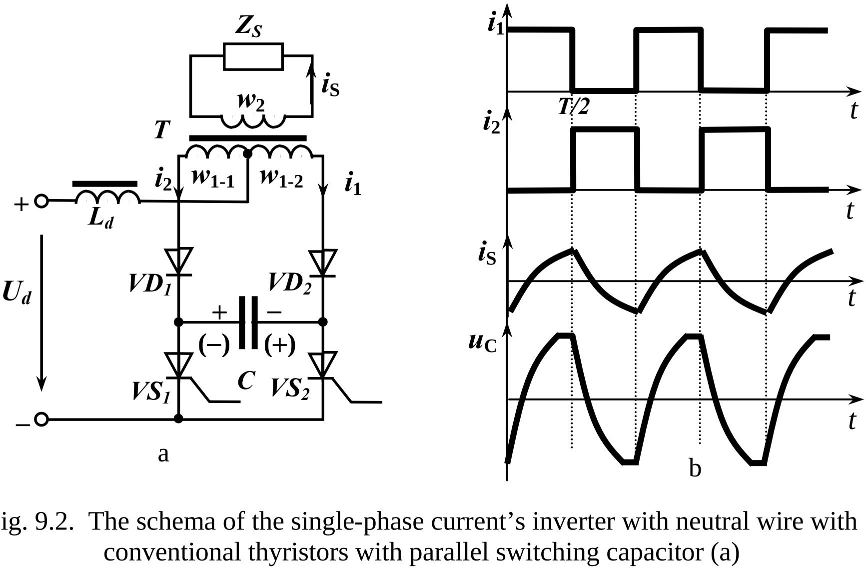


Fig. 9.2. The schema of the single-phase current's inverter with neutral wire with conventional thyristors with parallel switching capacitor (a) and the time-diagrams of voltages and currents (b)

9.4. Three-phase bridge current's inverter with parallel switching capacitor

The schema of the three-phase bridge current's inverter with conventional thyristors with parallel switching capacitors is represented in fig. 9.3.a, and the time-diagrams of voltages and currents in its circuit is represented in fig. 9.3.b.

The operating principle of the three-phase current's inverter is analogous to the principle of operation of single-phase inverters and is illustrated by the waveforms of voltages and currents in the inverter's circuit (see fig.9.3.b).

The order of the thyristors operation is as in the three-phase bridge rectifier:

VS_1 and VS_6, VS_1 and VS_2, VS_3 and VS_2,
VS_3 and VS_4, VS_5 and VS_4, VS_5 and VS_6,

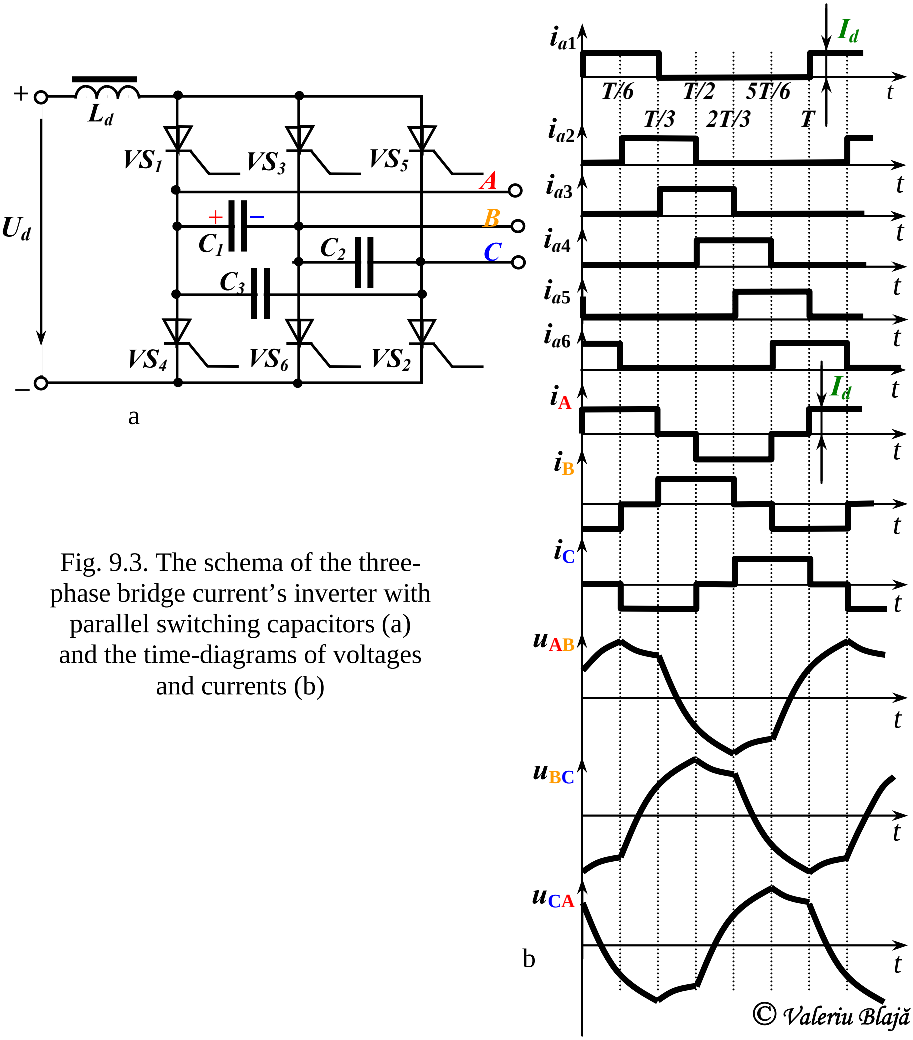


Fig. 9.3. The schema of the three-phase bridge current's inverter with parallel switching capacitors (a) and the time-diagrams of voltages and currents (b)

Because each thyristor conducts current in pair with a thyristor from another group for 1/6 of the period of output oscillations, then conducts current 1/6 of the period in pair with the next thyristor in the other group; the command of the thyristor is made, or with two short pulses with an interval of 1/6 of the period between them, or with a pulse duration of more than 1/6 of the period.

Switching of the thyristors takes place due to the switching capacitors C_1, C_2 and C_3, which can be connected "in the star" (see fig.9.3.a) or "in triangle" in the inverter circuit. Here occurs the switching between the valves: blocking of one thyristor takes place after the unblocking of the thyristor from the same valve group. For example: blocking the VS_1 thyristor will occur after the thyristor VS_3 is unblocked due to the voltage accumulated on the capacitor C_1 with polarity + – by VS_1 and VS_6 (when VS_1 was in conduction). On the anode of the thyristor VS_1, the reverse polarization voltage from C_1 is applied and he (VS_1) is blocked.

The shape of the output voltages is much closer to the sinusoidal shape, compared to the shape of the output voltage to the single-phase inverters (the waveforms for both the line voltages and the phase currents are represented in fig.9.3.b). Phase currents are alternate in character and are formed by rectangular pulses, and line voltages have waveforms formed by exponential portions caused by charge-discharge of switching capacitors.

In order to avoid discharging the switching capacitors through the load circuit, the capacitor-to-load separation diodes are used in the mode shown in figure 9.4. Here the diodes VD_1, VD_2, VD_3, VD_4, VD_5, VD_6 do not allow leakage currents to flow through the load and therefore we will already need two sets of switching capacitors: C_1, C_3, C_5 and C_2, C_4, C_6.

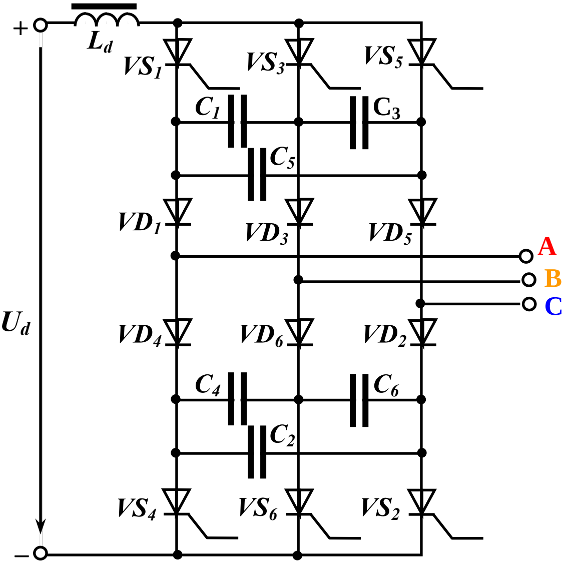


Fig.9.4.The schema of the three-phase bridge current's inverter with parallel switching capacitors and separation diodes

9.5. Single phase bridge voltage's inverter

Autonomous single-phase voltage's inverters are as usually formed on the basis of the bridge scheme, as shown in figure 9.5.a. A high capacity capacitor is included at the input of the inverter, which maintains the input voltage of the inverter U_d constant. The load is connected in diagonally of the bridge.

We will analyze the operation of the inverter with fully-controlled devices. In order to obtain a symmetrical and alternative form of the output voltage u_s, the devices are controlled in pairs (VS_1 with VS_2 and VS_3 with VS_4) in the anti-phase, so that the conduction time (conduction angle) of a device is a half-period ($T/2$) of the output oscillations. In the stationary mode, the shape of the current through inductive-resistive load i_s is symmetrical, alternate and consists of exponential parts with the time constant $\tau=L_s/R_s$ (see fig.9.5.b).

In the first half-period (from $t=0$ to $t=T/2$) VS_1 and VS_2 are in conduction. The voltage of source U_d with polarity + – (see fig.9.5.a), which is considered positive, is applied on load. The load current flows through VS_1 and VS_2 (positive sense) and increases exponentially.

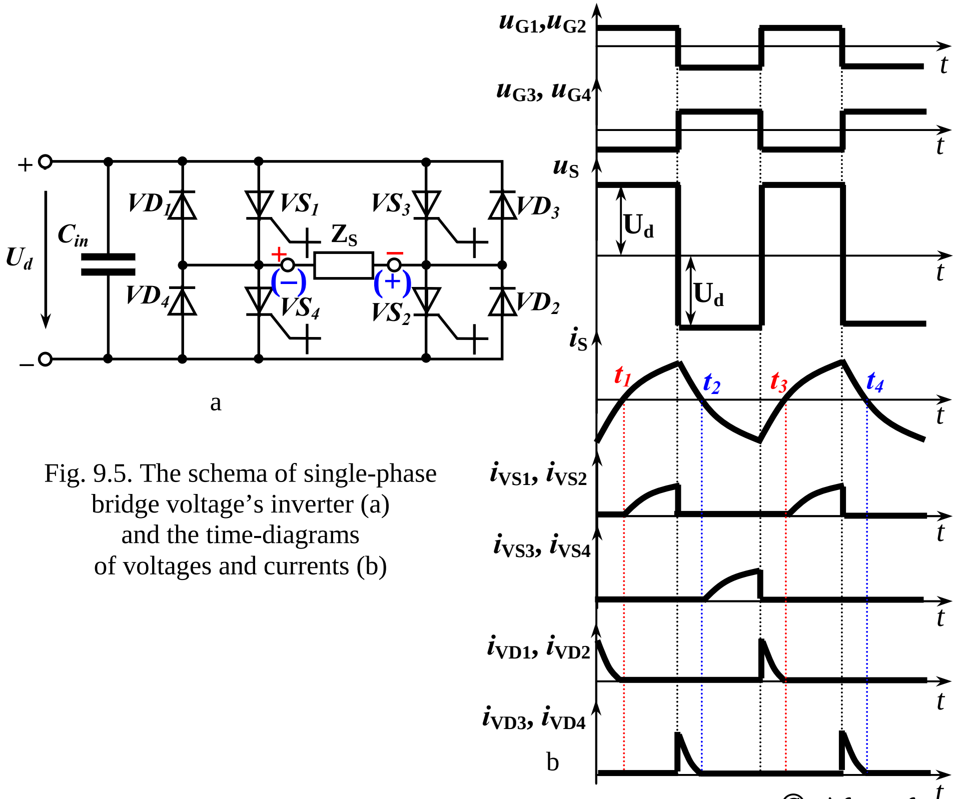


Fig. 9.5. The schema of single-phase bridge voltage's inverter (a) and the time-diagrams of voltages and currents (b)

In the second half-period (from ***t=T/2*** to ***t=T***) VS_3 and VS_4 are set in conduction and VS_1 and VS_2 are blocked. The voltage of source U_d with the polarity (-) (+) (see fig.9.5.a), which is considered negative, is applied on the load. Due to inductive load, the current will continue to flow in the same direction through load and will be closed through the diodes VD_1 and VD_2 until the moment t_2 when the current becomes zero. The energy stored in the load inductance is returned to the source. Therefore, the role of the diodes in the inverter circuit is to drive the reactive current of the load. After the moment t_2 the load current changes direction, increases exponentially and is closed through the devices VS_3 and VS_4.

9.6. Resonant’s inverters

Resonant’s inverters have a force circuit analogically as circuit of current’s inverters with inductance in the input circuit. Inductance of the input reactor is chosen from the condition that the switching capacitor charging takes place in an oscillating process (also taking into account the load reactant). The resonance frequency of the oscillating process must be slightly higher than the frequency of the alternating output current. Therefore, the valve current decreases to zero and the valve manages to block before the next valve is unblocked.

In resonant’s inverters, the shape of the output current is very close to the sinusoid, and this fact considerably reduces switching losses, eliminating the need for current limiting reactors in the valve circuit. All this makes the resonant inverters preferable for high frequency applications: very high speed AC motors, ultrasonic or electrothermia equipment, etc.

To illustrate the operation of resonant’s inverters, we will analyze the schema and waveforms of voltage and currents in the circuit of single-phase rezonant’s inverter with parallel switching capacitor shown in figure 9.6.

After unblocking the thyristors VS_1 and VS_2 the charging process of the capacitor ***C*** starts and the charging current first increases and then decreases sinusoidally. When the current i_{out} decreases to zero, in analogous mode are canceled the currents through the thyristors VS_1 and VS_2 (i_{a1}, i_{a2}), and the thyristors are blocked. During this time, the voltage on the capacitor is higher than the voltage of the power supply and therefore reverse voltage is applied on the devices VS_1 and VS_2. In the time interval from t_1 to t_2 any valve are not in conduction, the input current of the inverter is null and the thyristors VS_1 and VS_2 have the possibility to be blocked.

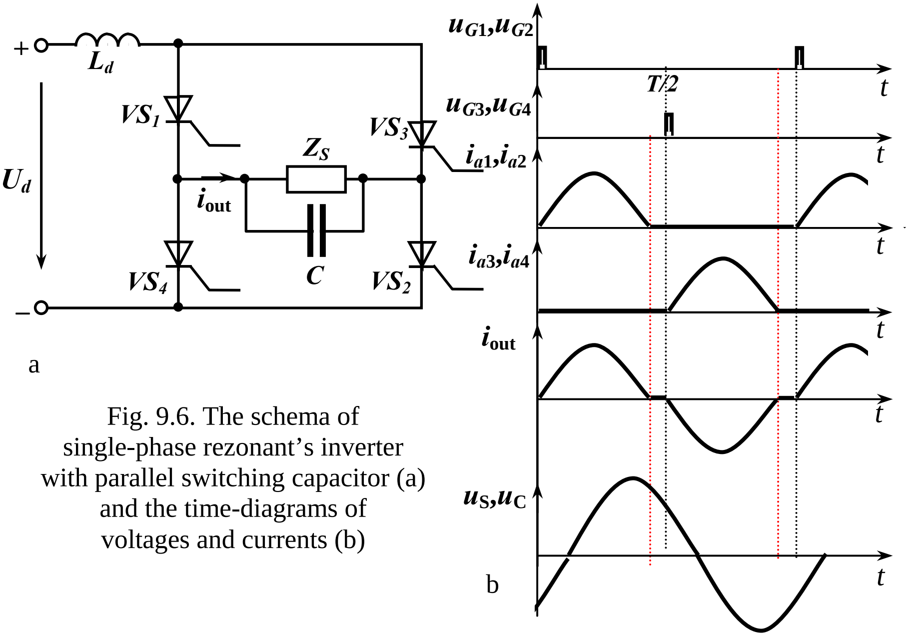


Fig. 9.6. The schema of single-phase rezonant's inverter with parallel switching capacitor (a) and the time-diagrams of voltages and currents (b)

10. FREQUENCY CONVERTERS

10.1. General notions

Frequency converters are power circuits that convert alternating current with voltage U_1 and frequency f_1 in alternating current with voltage U_2 and f_2 that can be adjusted. Frequency converters are used predominantly in modern AC drives with rotary or linear asynchronous or synchronous motors.

Frequency converters can be:

- direct frequency converters (cycloconverters),
- indirect frequency converters (frequency converters with DC intermediate circuit).

The cycloconverters can be:

- with natural switching,
- with forced switching.

10.2. Indirect frequency converters

In these converters the double conversion of the electric energy is done. The block schema is represented in fig.10.1.

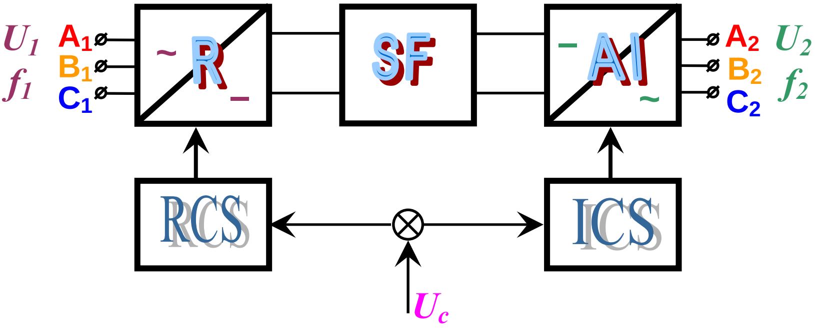


Fig.10.1.Block schema of the indirect frequency converter:

R – Rectifier,
SF – Smoothing Filter,
AI – Autonomous Inverter,
RCS – Rectifier's Control System,
ICS – Inverter's Control System

The rectifier can be controlled, uncontrolled or semi-controlled. The inverter can be of the current, of the voltage or of the resonance. When the inverter is of the current, the filter is inductive and the converter is called a *frequency converter with DC current intermediate circuit*. If the inverter is of the voltage, the filter is capacitive and the converter is called *frequency converter with DC voltage intermediate circuit*.

In this converter the alternating current is rectified in **R**ectifier, the waves are smoothed in the **S**moothing **F**ilter, and the **A**utonomous **I**nverter forms alternating current with any other frequency set in the **I**nverter's **C**ontrol **S**ystem.

The main disadvantage of these converters is in the double conversion mode, so their energetic efficiency is reduced. In order to achieve energy transfer in both directions, between the source and the consumer, we would need fully-controlled devices on both sides of the current.

At the moment, such devices do not exist, and for this reason valve groups can be used which, as a whole, can perform these functions. Some examples of such valve groups are represented in fig.10.2.

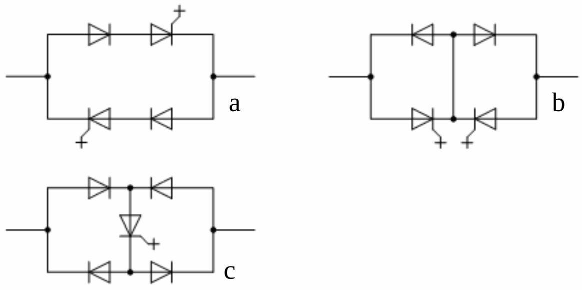


Fig.10.2. Fully-controlled on both directions of the current valve groups

In the indirect frequency converters, energy recovery can also be provided by other methods – by modifying the converter circuit. Let's look at, for example, a single phase frequency converter with continuous voltage intermediate circuit, in which energy recovery is realized.

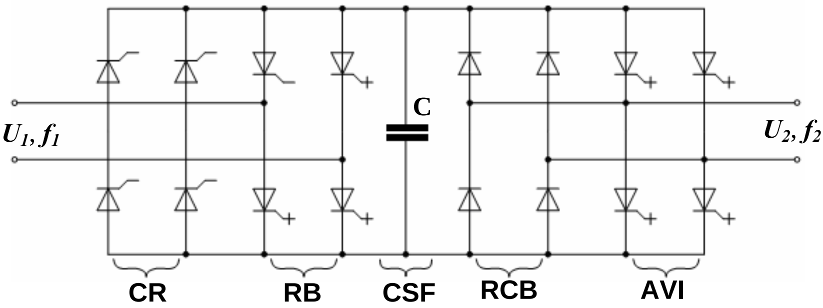


Fig.10.3.The schema of single phase frequency converter with continuous voltage intermediate circuit:

CR – **C**ontrolled **R**ectifier,
RB – **R**ecuperative **B**ridge,
CSF – Capacitive **S**moothing **F**ilter,
RCB – **R**everse **C**urrent **B**ridge,
AVI – **A**utonomous **V**oltage's **I**nverter

The transfer of energy from the source (***U_1, f_1***) to the consumer (***U_2, f_2***) is done via the **C**ontrolled **R**ectifier **CR** and the **A**utonomous **V**oltage's **I**nverter **AVI**. Recovery of energy to the power supply network is done by rectifying in the **R**everse **C**urrent **B**ridge **RCB** and converting into the **R**ecuperative **B**ridge **RB**. Last bridge exerts the grid-tie inverter function.

In the case of the frequency converter with DC current intermediate circuit, when the filter is inductive and the inverter is inverter of the current, the need for the reverse current diodes and the recovery bridge disappears, because the direction of the DC current through the intermediate circuit does not change in this case. The rectifier for the recovery mode is switched to grid-tie inverter mode.

If the consumer is not a reversible electric machine, the frequency converter's structure is simpler as it does not have to provide a bi-dimensional flow. In the case of low-power frequency converters, an uncontrolled rectifier is used and the voltage adjustment ***U_2*** is done with a Chopper interleaved in the DC intermediate circuit.

10.3. Direct frequency converters

The direct frequency converters (*the cycloconverters*) ensure that the cycle of conversion takes place in a single step from the alternating current with ***f_1*** in the alternating current with another frequency ***f_2*** less then ***f_1***. The cycloconverters operate on the principle of the successive cyclic connection-disconnection of the phases of the receiver directly to the phases of the network (source) by means of a static switching network (controlled or semi-controlled valves).

Cycloconverters are special by the following moments:

- high conversion efficiency, which is a great advantage for high power consumers,
- possibility of adjustment of output frequency and voltage,
- they are made exclusively on the basis of conventional thyristors,
- the complexity of the control circuit is proportional to the number of valves,
- the need to correct the input power factor and reduce the harmonics at the output by means of additional circuits.

At the base of the cycloconverter's operation are used the possibilities of reversible converter (double converter or four-quadrant converter) (see fig.10.4) that is able to achieve both the both polarity of the output voltage ***U_2*** and both directions of the output current ***I_2*** in the converter circuit. Such a converter is obtained by the anti-parallel connection of two converters, operating in two quadrants, each (converter-inverter mode) by controlling the phase of the unblocking impulses (control angles) ***α_1, α_2*** of the thyristors in relation to the input voltage phase can be obtained at the terminals of the receiver average rectified voltage continuously adjustable by both polarities (alternating voltage).

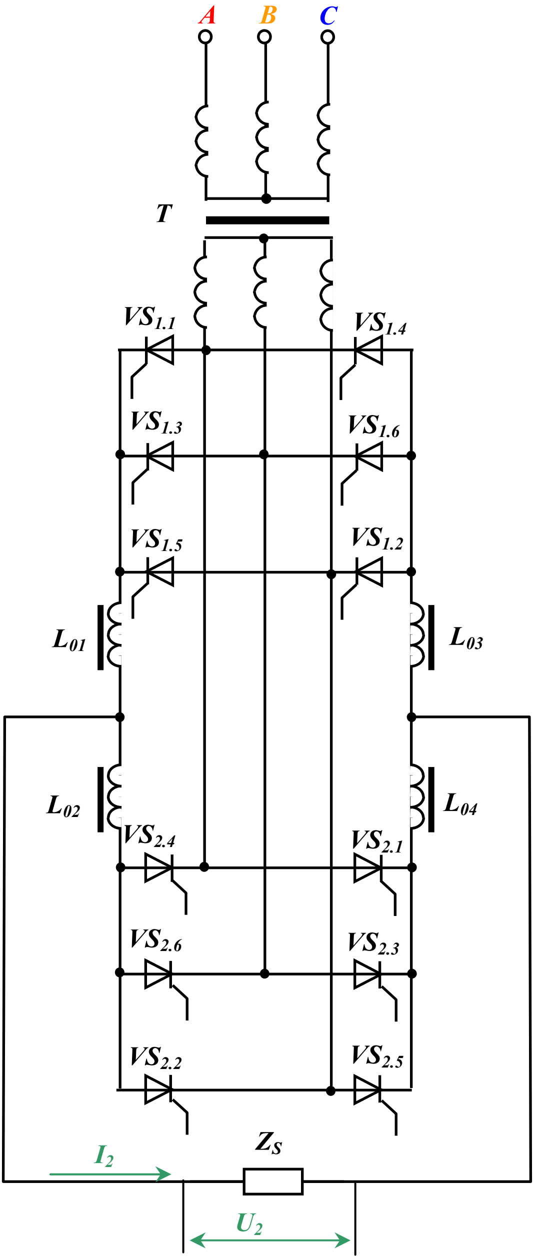


Fig.10.4.The scheme of
three-phase – single-phase cycloconverter

The waveform of the output voltage consists of portions of the network voltage formed by thyristors. For better quality, the three-phase network is used. Through an appropriate programming of all the angles of conversion, the cycloconvertor can synthesize the output voltage from the sine arcs belonging to the input voltage. So that the average value of output voltage varies periodically according to a sinusoidal or trapezoidal law, etc. Inevitably, the output voltage will have, besides the fundamental harmonic, a certain content of higher harmonics.

Operation of three-phase– single-phase cycloconverter:

The valves are unblocked, in each set of valves in the known order of the operation of the controlled three-phase bridge rectifier. The control angle is varied cyclically over time. Therefore, the output voltage is formed by portions of the network line voltage and has the fundamental harmonic $\boldsymbol{\omega_2}$. To form the positive alternation on load the first set of thyristors works in the rectifier mode, and the second set of thyristors is switched to inverter mode. In order to form the negative alternation, the set I is switched to inverter mode, and the set II operates in the rectifier mode. The output voltage of the cycloconverter can be represented as periodic variable average voltage rectified at the output of the controlled rectifier (see fig.10.5).

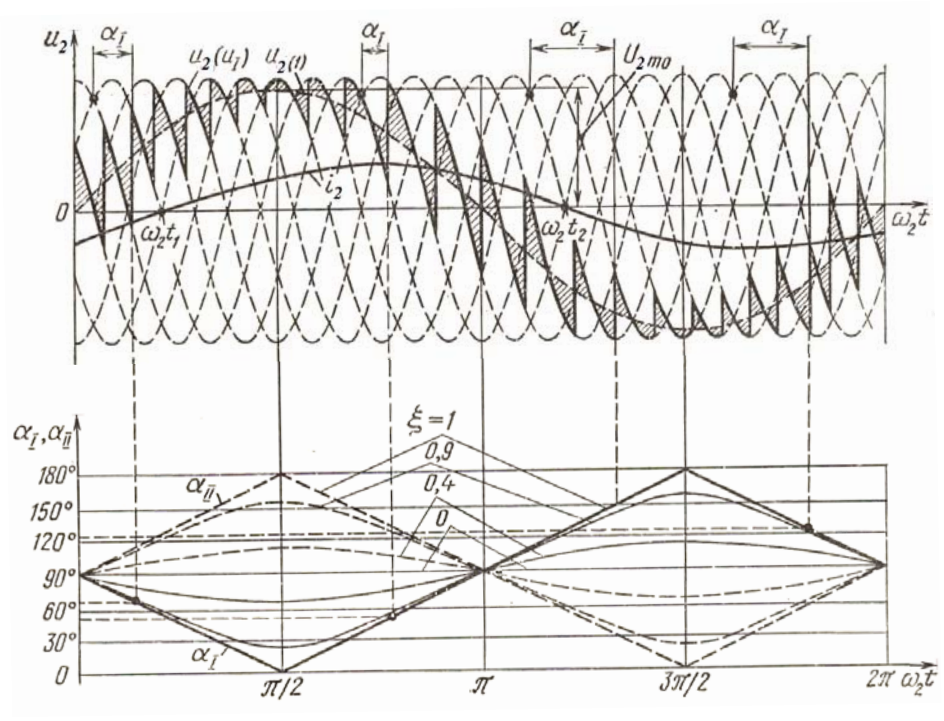


Fig.10.5.The waveforms of voltages in circuit
of three-phase– single-phase cycloconverter

For example, for the first set of thyristors it can be written:

$$u_s = U_{smo} \cos \alpha_I(t) \qquad (10.1)$$

where: U_{smo} is amplitude of output voltage or output voltage value for $\alpha_I = 0$ **.**

Therefore changing the control angle we can obtain the variable output voltage after a desired law.

From another point of view, if we neglect pulse output voltage for a sinusoidal law we can write:

$$u_s = U_{sm} \sin(\omega_2 t) \qquad (10.2)$$

where: U_{sm} is amplitude of voltage on load**.**

Therefore, in order to obtain a sinusoidal voltage with output frequency ω_2, the control angle must be varied over time according to the expression:

$$\alpha_I = \arccos(\xi \sin \omega_2 t) \qquad (10.3)$$

where:

$$\xi = \frac{u_{sm}}{u_{smo}} \qquad (10.4)$$

Analogously for second set of valves we can write:

$$\alpha_{II} = \arccos(-\xi \sin \omega_2 t). \qquad (10.5)$$

When $\xi = 1$, i.e. the amplitude of the U_{out} is the maximum, the control angle will vary over time:

to form **first quarter** of the output voltage period ($0 < \omega_2 t < \frac{\pi}{2}$), the angle α_I will linearly decrease from 90^0 to 0^0 and the angle α_{II} will increase from 90^0 to 180^0.

To form the **second quarter** of the output voltage period ($\frac{\pi}{2} < \omega_2 t < \pi$), α_I increases from 0^0 to 90^0, and α_{II} decreases from 180^0 to 90^0.

To form the **third quarter** of the output voltage period ($\pi < \omega_2 t < \frac{3\pi}{2}$), α_I rises from 90^0 to 180^0, and α_{II} decreases from 90^0 to 0^0.

To form the **fourth quarter** of the output voltage period ($\frac{3\pi}{2} < \omega_2 t < 2\pi$), α_I decreases from 180^0 to 90^0, and α_{II} rises from 0^0 to 90^0.

When $\xi < 1$, the control angle varies in narrower limits and non-linear over time. Because in this converter it works on the natural control the extreme values of the control angle are limited by the inverter's upsetting mode. In such way α can not be larger than $180^0 - (\gamma + \theta_{min})$ and α can not be less than $(\gamma + \theta_{min})$, where: γ is switching angle, $\theta_{min} = \frac{2\pi f_1}{t_{rr}}$, and t_{rr} is return time of valves.

The three-phase – three-phase cycloconverters are formed on the basis of three three-phase – single-phase cycloconverters controlled with a 120^0 phase shift of output voltages. In order to keep the harmonic content of the output voltage at an acceptable level, it is necessary to $f_2 \leq \frac{f_1}{3}$.

Therefore, cycloconverters can be used more advantageously in applications requiring low frequency AC.

The structure of the cycloconverter allows the reversibility of its operation. So the connection to the grid of the electric machines that will work, or as an electric motor including a recuperative braking reaction, or as a generator.

The performance of the cycloconverters allows them to be used mainly to regulate the speed of high-power and slow-speed motors with and without their inclusion in automatic speed stabilization loops.

Another direction of application of cycloconverters is to use them to stabilize the frequency of the voltage drop on an alternative generator driven by the axle of an internal combustion engine having variable speed.

The cycloconvertor converts the input variable frequency into a constant output frequency at an additional stabilized with the automatic adjustment loop.