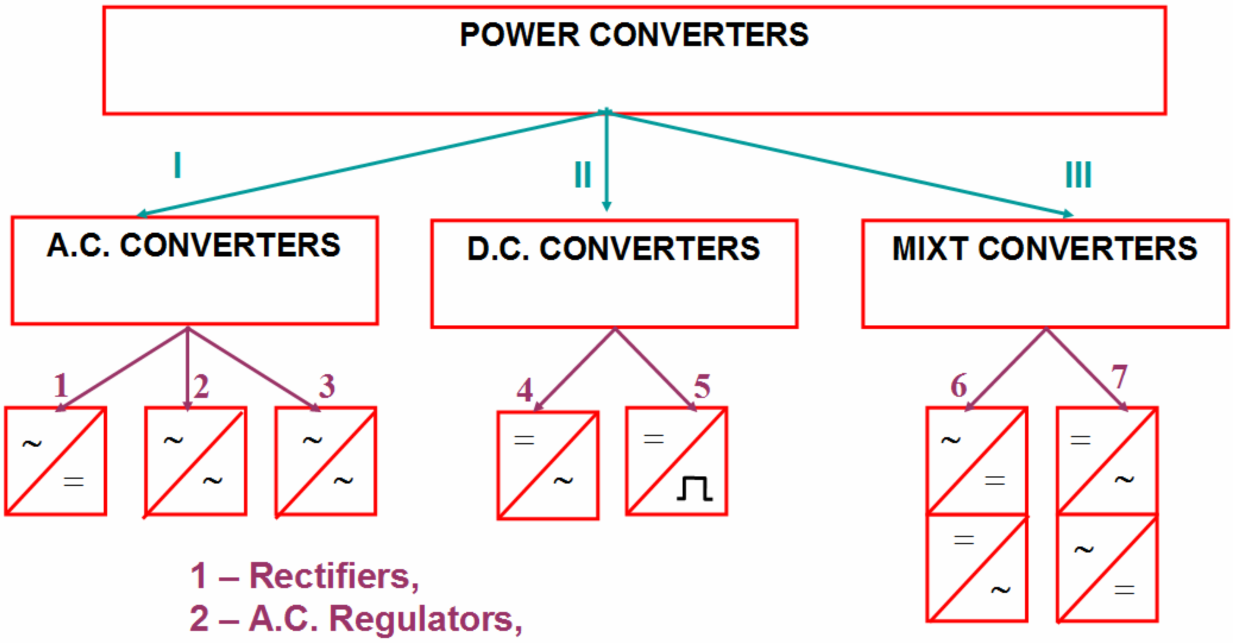


1 – Rectifiers,
2 – A.C. Regulators,
3 – Cycloconverters,
4 – Inverters,
5 – Choppers,
6 – Frequency Converters,
7 – D.C. Regulators

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:

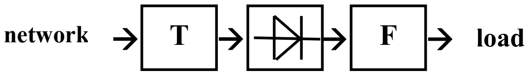


Fig.1.1.The block schema of the rectifier

✓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 classified:

- 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:

$$U_d=\frac{1}{2\pi}\int_0^{\pi}U_2d(\omega t)=\frac{1}{2\pi}\int_0^{\pi}U_{2m}\sin(\omega t)d(\omega t)=\frac{U_{2m}}{\pi}=\frac{\sqrt{2}}{\pi}U_2. \tag{1.3}$$

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 $\mathbf{k_p=1,57}$.

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

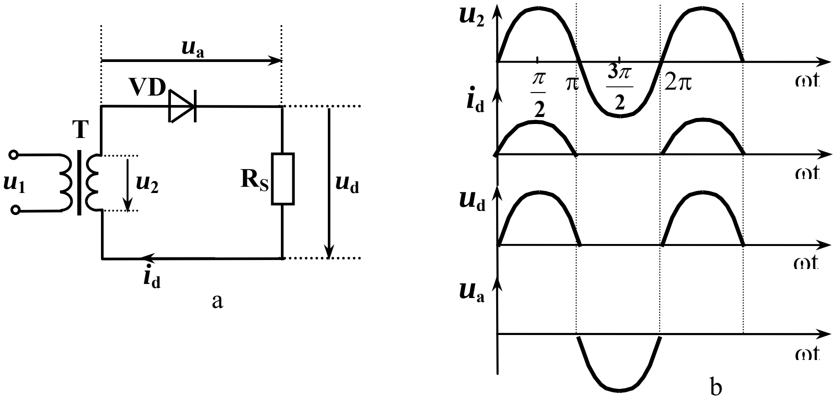


Fig.1.2. The scheme of the half-wave rectifier (a) and the waveforms of voltages and current (b)

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):

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

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 $i_1 = i_d$.

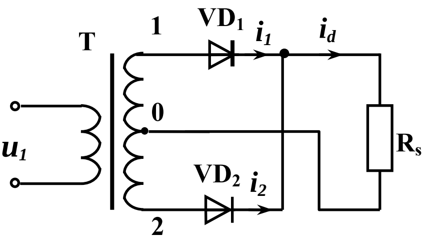
During the next (negative) alternation (half-wave) (ωt=π÷2π) the voltages $u_{1\text{-}0}$ and $u_{2\text{-}0}$ change polarities. The valve **VD$_2$** is polarized directly and the diode **VD$_1$** is blocked. The voltage drop on the valve **VD$_2$** will be null and voltage u_2 falls (drops) on the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

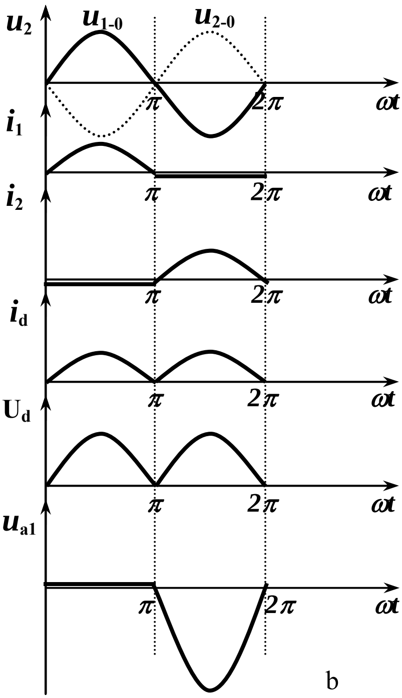
$$U_d = \frac{1}{\pi}\int_0^{\pi} U_{2m}\sin(\omega t)d(\omega t) = \frac{2U_{2m}}{\pi} = 2\frac{\sqrt{2}}{\pi}U_2. \qquad (1.7)$$

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



b

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

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.

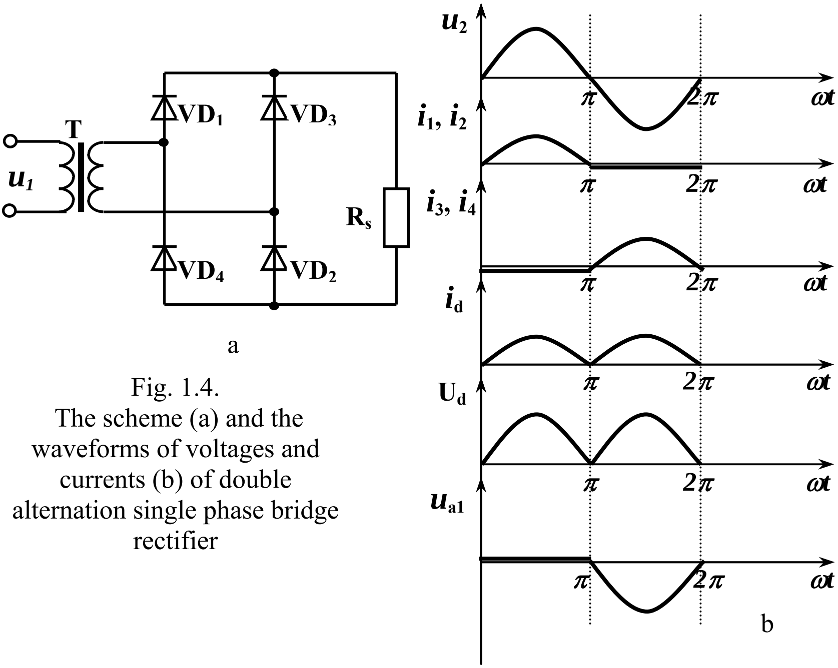


Fig. 1.4.
The scheme (a) and the waveforms of voltages and currents (b) of double alternation single phase bridge rectifier

During the positive alternation (half-wave) of voltage u_2 (ωt=0÷π) 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) (ωt=π÷2π) 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:

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

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).

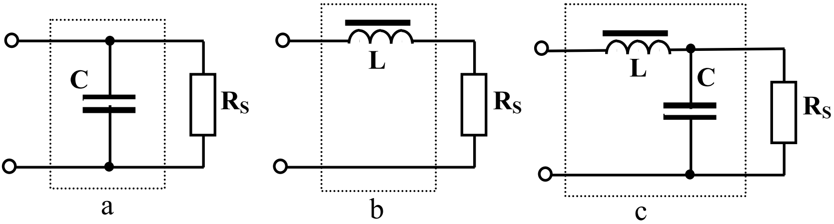


Fig.1.5.The schemes of elemental smoothing filters
a – capacitive, b – inductive, c – mixed

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

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

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:

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

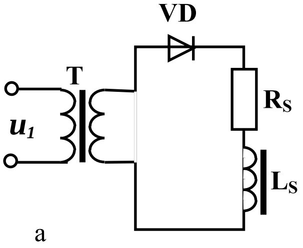
Inductive filters are used for low-resistance loads and large currents to smooth the pulsations of the rectified current.

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.



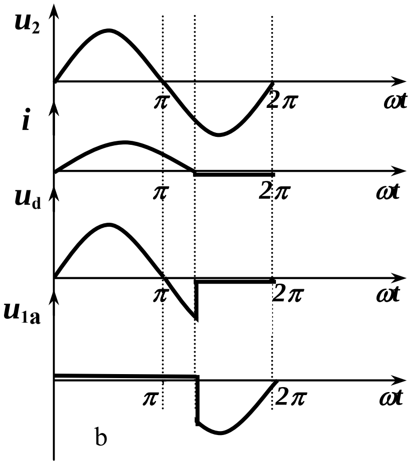


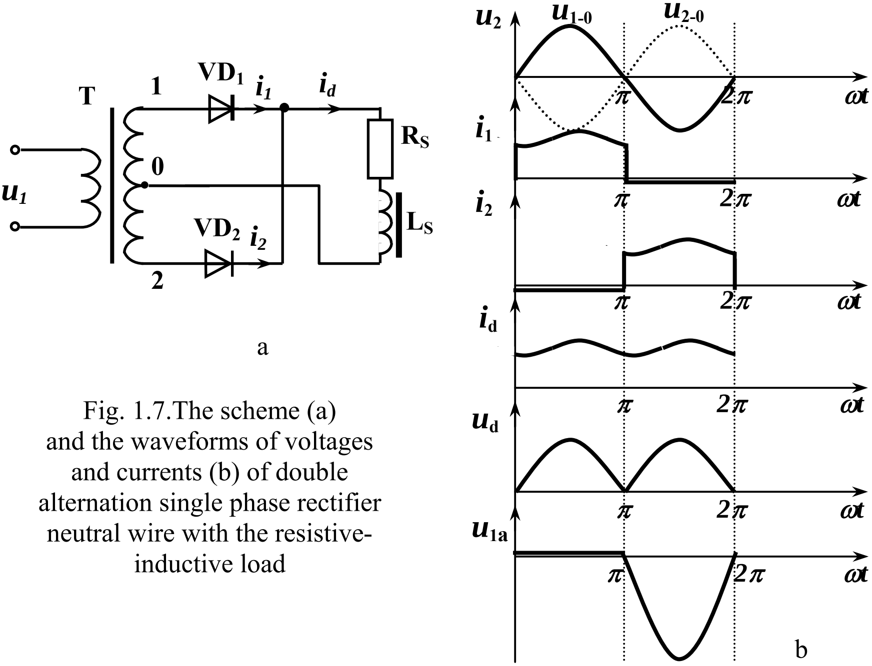
Fig. 1.6.
The scheme of the half-wave rectifier with the resistive-inductive load (a) and the waveforms of voltages and current (b)

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:

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

($L_S \to \infty$) 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.***

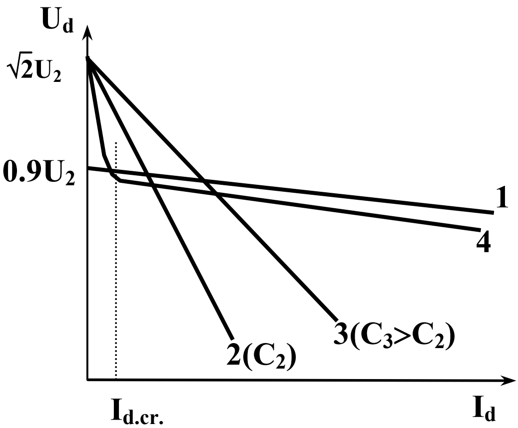


Fig.1.8.The external characteristics

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.

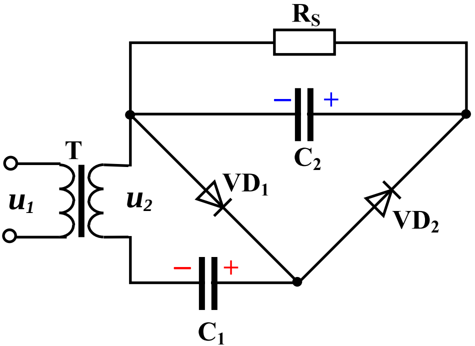


Fig. 1.9. The schema of half-wave rectifier circuit with doubling voltage

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.

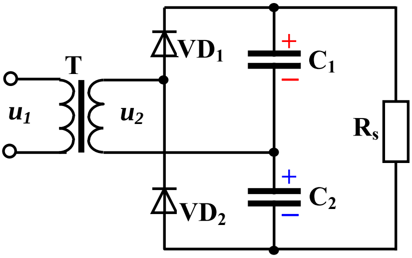


Fig. 1.10. The schema of double alternation rectifier circuit with doubling voltage

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 (**VD$_3$** and **C$_3$**) 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.

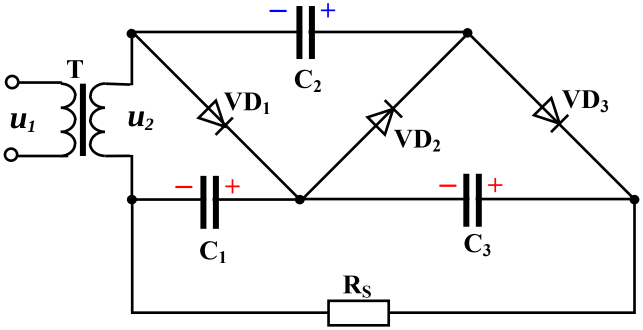


Fig. 1.11. The schema of half-wave rectifier circuit with tripled voltage

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 (**VD**$_1$, **VD**$_2$**, 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 **VD**$_1$ is maximal in the rectifier circuit and **VD**$_1$ is in conduction. The current flows through **VD**$_1$ and load **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 **VD**$_2$ – u_{2BA}, and on **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 **VD**$_2$ is maximal in the rectifier circuit and **VD**$_2$ is in conduction. The current flows through **VD**$_2$ and load **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 **VD**$_1$ – u_{2AB}, and on **VD**$_3$ – u_{2CB}.

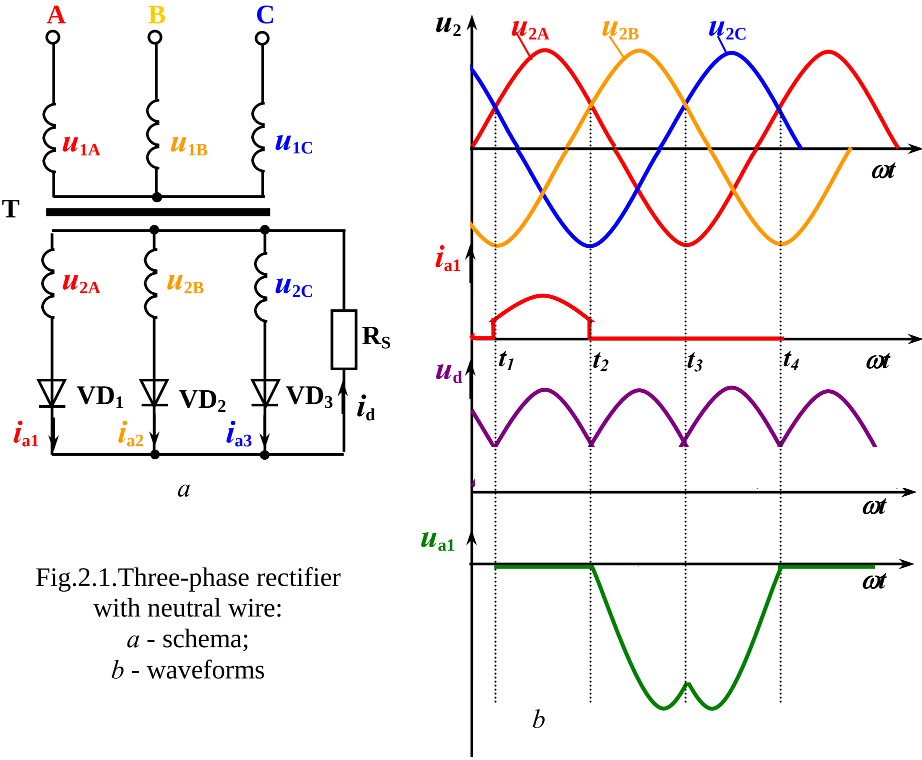


Fig.2.1.Three-phase rectifier
with neutral wire:
a - schema;
b - waveforms

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.

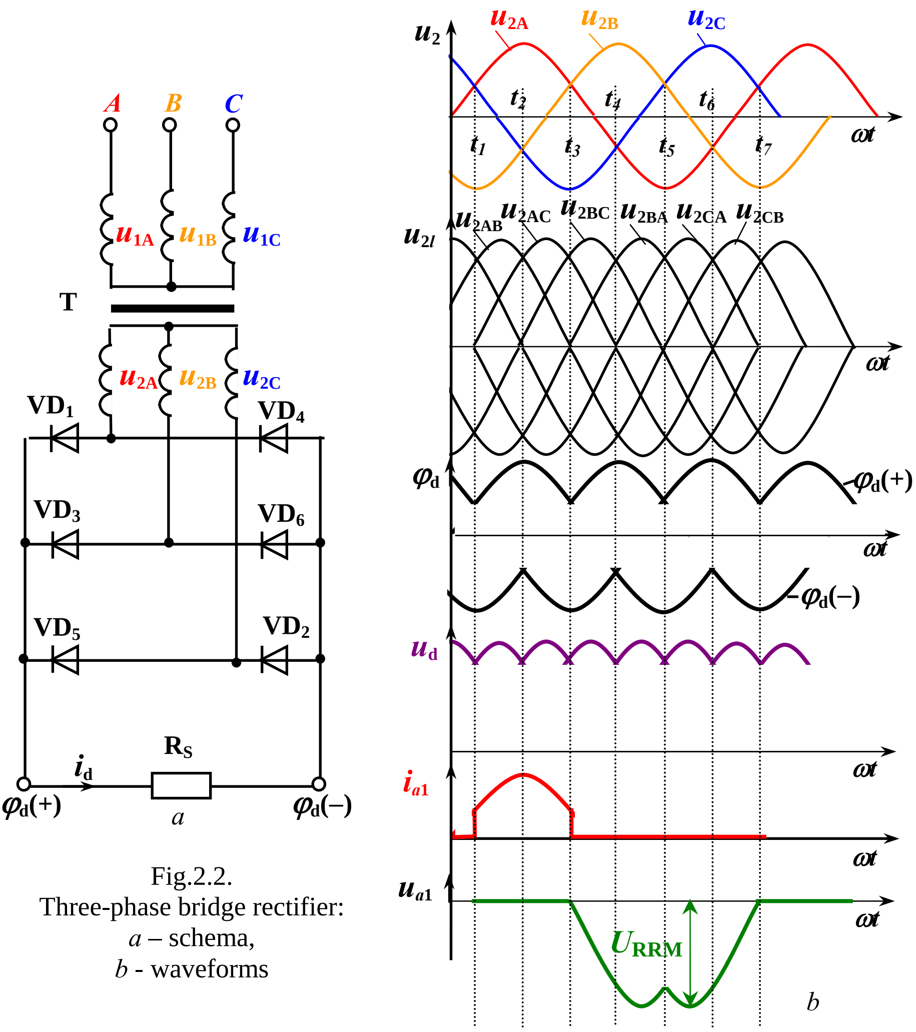


Fig.2.2.
Three-phase bridge rectifier:
a – schema,
b - waveforms

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:

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

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).

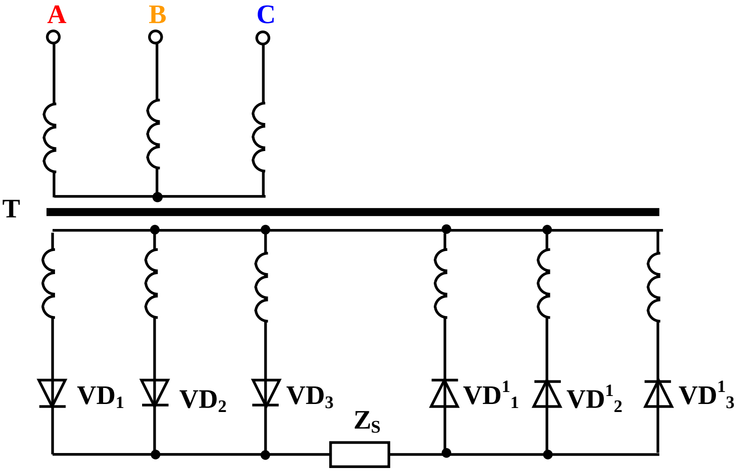


Fig.2.3. The scheme of series connection of null wire rectifiers

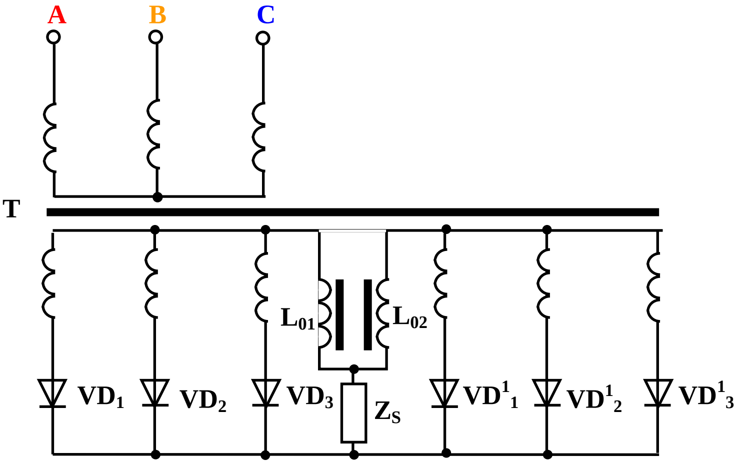


Fig.2.4. The scheme of parallel connection of the null wire rectifiers

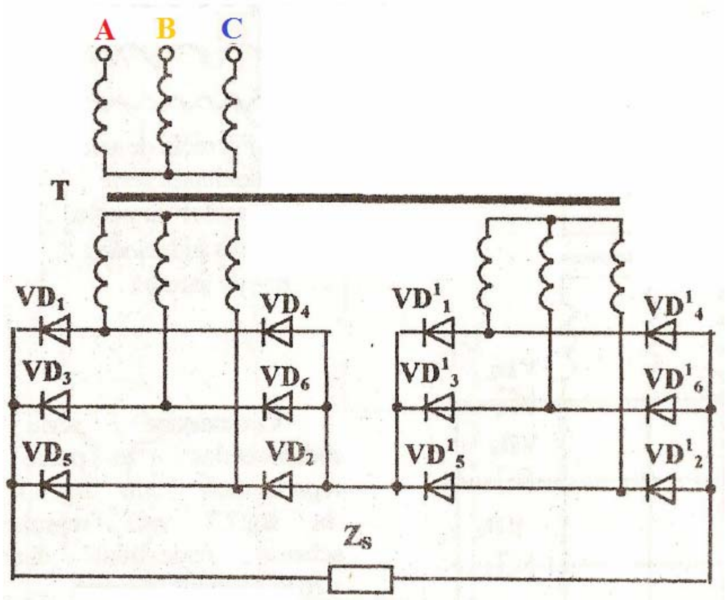


Fig.2.5.The scheme of series connection of bridge rectifiers

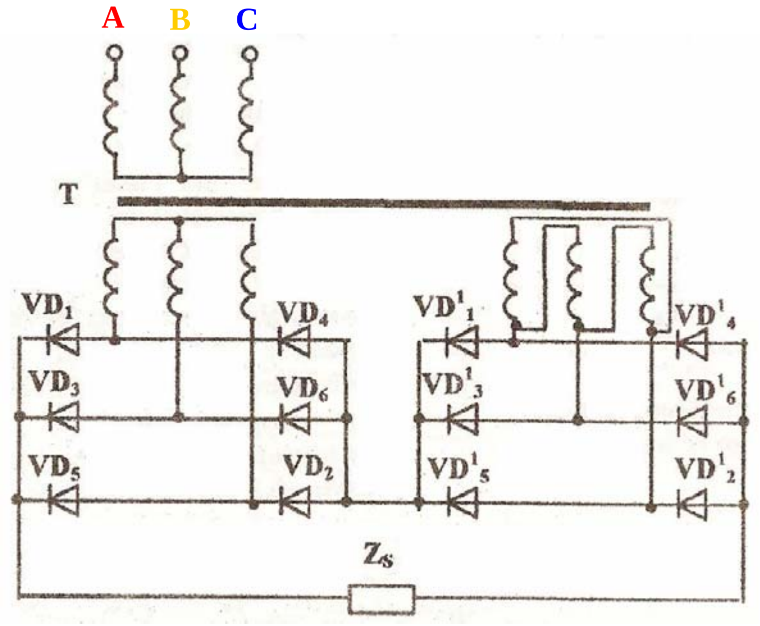


Fig.2.6. The scheme of series conection of bridge rectifiers

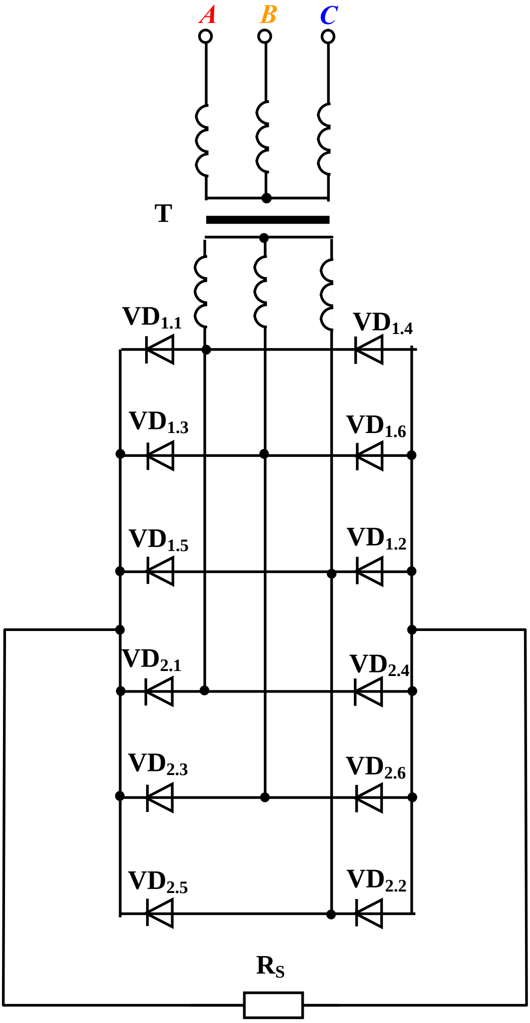


Fig.2.7.The scheme of parallel connection of bridge rectifiers

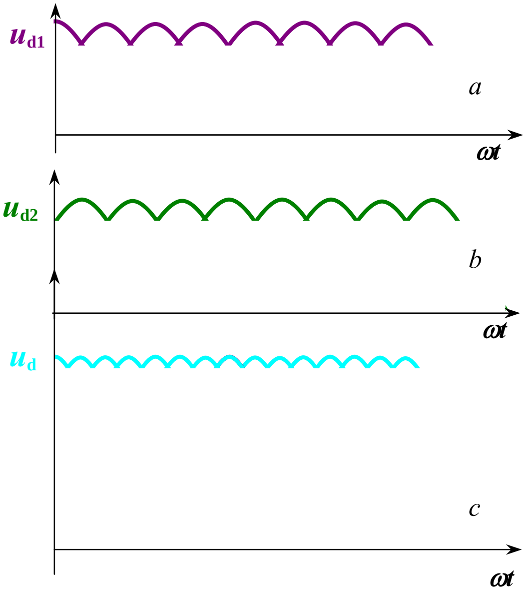


Fig.2.8. Waveforms of rectified voltages in series star-triangle connection of bridge rectifiers: *a*, *b* – from each bridge, *c* – on load