4. POWER ELECTRONIC CONVERTERS

4.1. Power semiconductor switch

Power semiconductor devices are used for control of the voltage or current of the electric equipment. The advantage of switch compared to continuous controllers like resistor or continuous amplifier transistor is the lower energy losses (Figure 4.1).

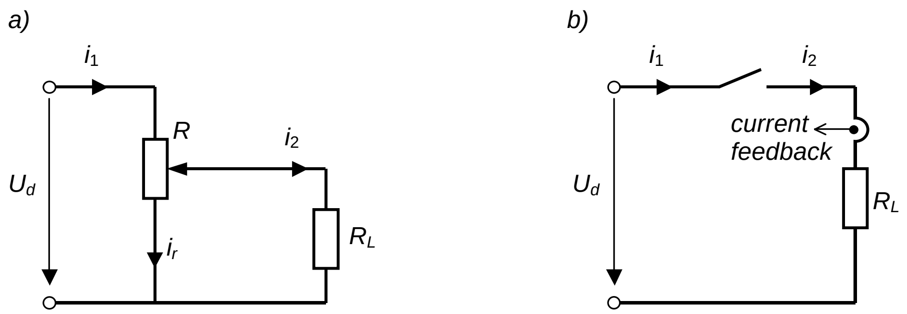

Figure 4.1. Control of the load voltage and current using a) resistor, b) switch

By controlling the current of the electricity consuming device (load resistance) R_L, the input current form power source divides between controller and output current $i_1 = i_r + i_2$. If to reduce the voltage of electricity consuming device to half (q = 0,5) from the supply voltage then the power consumed by the controller is equal to the power consumed by the electricity-consuming device. Half of the input power detaches in the controller as losses (as heat).

$$P_{reg} = q\,R\,i_1^2 + (1-q)\,R\,i_r^2 = q\,R\,(i_r + i_2)^2 + (1-q)\,R\,i_r^2 = R_L\;i_2^2\,. \qquad (4.1)$$

If the controller uses transistor to control with continuous operation the same power balance is the same. Therefore the continuous controls of power (that is control of voltage or current) suit only if consumed power is low thus the losses are unimportant. The big losses will occur in power appliances if the continuous control is used. Because of that the usage of continuous control is avoided. That types of controls have remained in some old type of direct current drives, when the resistors are connected into the armature circuit of the motor. For achieving high efficiency, the usage of pulsed control of electricity consuming devices with semiconductor switches is applied nowadays.

The most widely used type of control is the **pulse width modulation** (PWM). If the input voltage is constant, then the pulse width is proportional to the output voltage (Fig 4.2). For achieving smooth control, the switching frequency (commutation frequency) should be relatively high. The fast semiconductor devices are most suitable for use in such switches. The direct current converter according to its operation principle is named “voltage chopper”.

The switching of the active load off is not problematic, because the current is proportional to supply voltage and the current through switch stop immediately after switching off. The switching of circuits that contain reactive components thus components that store energy like capacitors or inductances is more complicated. In that case the switch should stand high current peaks on the switching on of the capacitive load or high voltage spike on switching off of the inductive load.

Should be considered, that ideal active load does not exist and every real electrical circuit has its capacitances (like isolation capacitance) and inductances (like fringing inductance). The commutation process can be considered as energy conversion processes on which the energy transfers from one component of the electric circuit to another occur. The current curve in Figure 4.2 differs on inductive load i_L from the voltage curve.

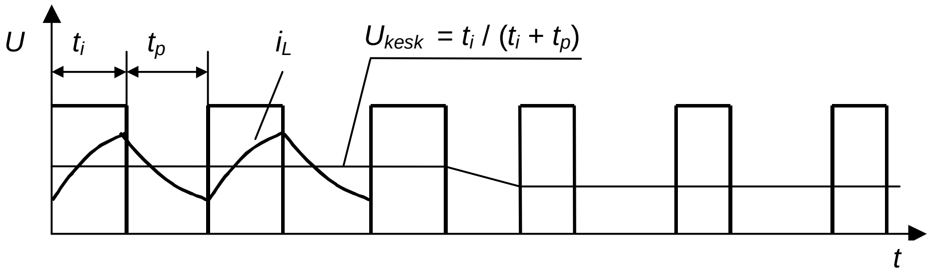

Figure 4.2. Pulse with modulation principle

For example, the energy $W_L = Li^2/2$ is stored into inductance when switching on the inductive circuit and the energy $W_C = Cu^2/2$ is stored into capacitance when switching on the capacitive circuit. On the braking of the circuit these energies divide and disperse as heat on active components. These processes are known as commutation transients (Fig. 4.3). These processes may be oscillating (1) or non-periodical (2) properties depending on the RLC circuit parameters.

On such transients, the rectangular shape is distorted and the switching (commutation) losses occur on the converters. The dangers of over-voltages exist because the oscillating processes can double voltage, during switching processes. Therefore the semiconductor switches are equipped with several protection circuits and dumping chains (*snubber circuit*), which function is dumping or dividing the switching energy into other components of the circuit.

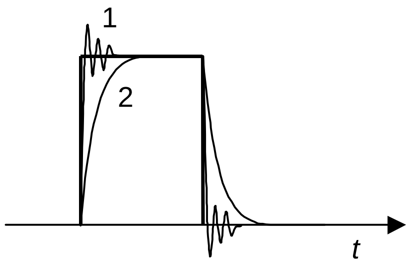

Figure 4.3. Switching transients and ringing effects

The properties of the switching processes and construction of semiconductor switches depend significantly on supply voltage (direct current voltage or alternating current voltage), load (active, reactive like inductive, capacitive or electromotive force of a generator), phase number of supply and load, type of semiconductor devices as well on their protection and control circuits. Because of the multifarious of possibilities, very different power and control circuits of semiconductor switches are widespread. The use of common thyristors requires **forced commutation** principle. In that case for closing, the current through thyristor can be reduced below holding current using special closing circuitry between anode and cathode.

The closing circuitry contains energy source (for example capacitor) those current is directed against to the current through the thyristor. This allows decreasing the sum of currents through thyristor to zero. Additional energy source is switched to the circuit by using additional thyristor. By its function this thyristor is called commutation thyristor (Fig. 4.4).

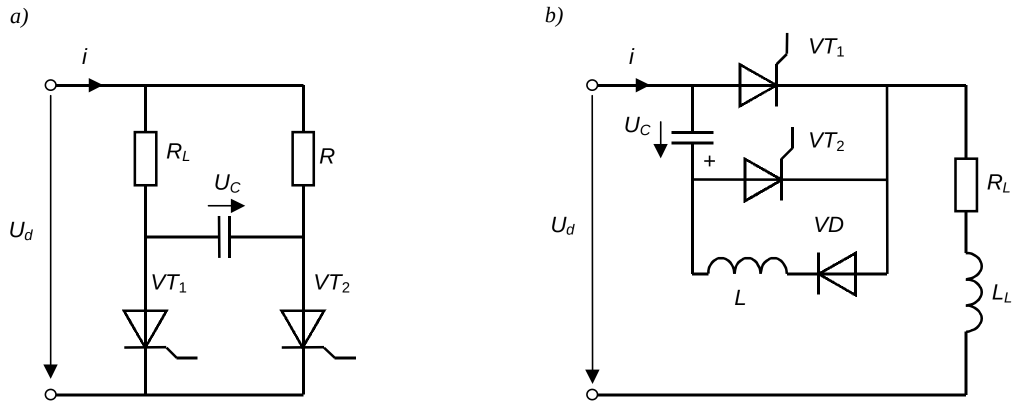

Figure 4.4. Commutation circuits of a thyristors in a direct current circuit

The closing circuit shown in Fig. 4.4, a works as follows: When the main thyristor VT_1 is in opened (conductive) state then current flows through the load R_L. The capacitor C charges through the resistor R and the voltage Uc increases about to supply voltage. For closing the main thyristor $VT_{1,}$ the auxiliary thyristor VT_2 will be opened which connects the capacitor C to the negative potential. The voltage becomes negative on the thyristor VT_1 anode relative to its cathode, because the voltage *Uc* cannot decrease immediately to zero. As voltage on the thyristor VT_1 becomes negative thyristor cannot conduct the current and closes (turns off). Load current commutates to capacitor and capacitor charges again through the load and the thyristor VT_2. Voltage on the anode of the thyristor VT_1 changes to positive again. For that time, the properties of the thyristor should be recovered (reverse recovery time). The resistor R should be chosen such that the current through auxiliary thyristor VT_2 remains below the holding current at the end. This allows closing the auxiliary thyristor as well. The disadvantage of such closing circuit is that the open state time of the thyristor cannot be widely changed, because the capacitor must charge during open state time of the thyristor through the big resistance.

Figure 4.4, b shows the closing circuit, that is considerably faster and allows to change switch on time in large scale. Circuit works as follows: If the auxiliary thyristor VT_2 is open, then capacitor C charges to the voltage $U_C = U_d$. If the capacitor is charged, then the auxiliary thyristor VT_2 closes (turns off). On the opening of the main thyristor capacitor C discharges through the branch VT_1-VD-L. Because of the inductance the current continues in this branch and the capacitor C charges to inverse polarity relative to earlier $U_C = -U_d$. For the closing of the main thyristor, the auxiliary thyristor VT_2 is opened and load current commutates to capacitor C. Voltage on the main thyristor VT_1 goes to negative and it closes (turns off). Capacitor charges through the load and thyristor VT_2 again to the voltage $U_C = U_d$. This process will repeat henceforth. Required capacitance of the capacitor C

$$C \geq t_q \frac{I_d}{U_d} \tag{4.2}$$

By using completely controlled semiconductor switches (GTO thyristors or IGBT transistors) the control simplifies, but irrespective of type of semiconductor device the redirection of the stored energy of reactive components should be solved.

Commutation over-voltage dumping circuits

On the closing of the thyristor (or diode) the huge current change di/dt occur, what cause the voltage $u = -L\ di/dt$. Because such voltage can be quite high, these over-voltages cause by commutation process are called commutation over-voltages. Over-voltages can be reduced or duped by RC- circuits (Fig. 4.5).

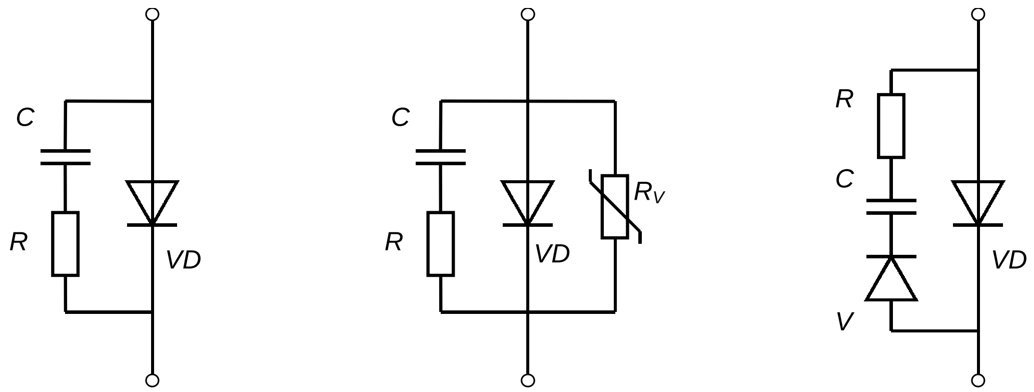

Figure 4.5. Over-voltage dumping circuits of the semiconductor switches:
a) RC-circuit, b) RC-circuit with a varistor, c) RCD-circuit

Serial or parallel connection

Serial connection of semiconductor switches is used if single switches by their producer's technical specifications do not afford required voltage. Parallel connection is used if the current required from converter is higher than current allowed by producer's technical specifications of the semiconductor switch. These possibilities are used, if the use of single switches does not allow designing required converter.

The equal distribution of switch voltages is the biggest problem of **serial connection** in closed (turned off) state and during commutation processes. Because of that, voltages should be equalized in static and dynamic operation modes. Voltages of the closed (turned off) switches can be equalized using resistors in parallel to switches. During commutation RC circuits that limit the voltage fronts on the power semiconductors can equalize the voltages. On the **parallel connection** of power semiconductors the power semiconductors with equal forward parameters should be chosen.

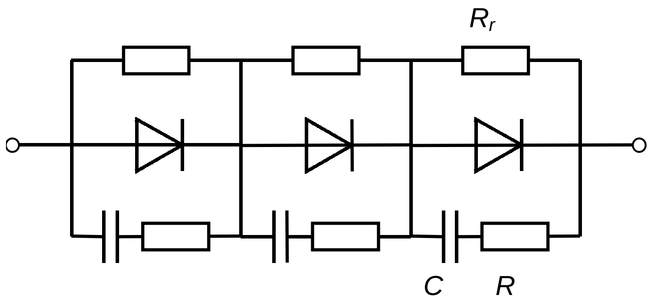

Figure 4.6. Equalization of power semiconductor voltages on serial connection

Serial and parallel connection problems of **power thyristors** are generally same than as problems arise on serial or parallel connection of power diodes. In addition, it is necessary to achieve simultaneous switching (opening or closing) of several thyristors. The single thyristor cannot stand the voltage or current of the whole circuit. On the serial connection, the calculated reverse voltage on the single thyristor should be reduced approximately 10 % (additionally). On the parallel connection, the calculated current through the single thyristor should be reduced 20 to 30 %.

4.2. Network synchronized controllable rectifiers and inverters

The sinusoidal alternating current is converted to pulsed direct current using rectifier. Rectifiers can be controlled or uncontrolled. Uncontrolled rectifier consist of diodes, controlled rectifier consist of controlled semiconductor devices like thyristors or transistors. The partially controlled rectifiers are used, in which some of the switches are controllable (thyristors) and some of them are uncontrollable (diodes). Many basic converters, incl. rectifiers and inverters are standardized and they have standardized symbols, for example M1 for half-period rectifier.

Changing turn-on moment i.e. switching angle controls the output voltage of the controlled rectifiers. These converters are called as network synchronized (online) phase controlled inverters and rectifiers. On alternating current supply the thyristor can open (switch on) only on existing positive anode voltage that occurs on the positive half wave of the voltage. Thyristor closes (turns off) when the current have been reduced below the holding current. In alternating current network, this occurs on the negative voltage half wave when the current through the thyristor decreases to zero. Should be mentioned, that control angle is measured on sinusoidal waveform form the point when positive forward voltage (anode voltage) appears on this thyristor. On single-phase rectifiers, this point is the zero voltage point of sinusoidal voltage. On three phase rectifiers the phase control angle base point and range depend on rectifier circuit. The current waveform and for this the closing point of the thyristor depend on properties of the load. On ideal active load the voltage waveform matches to current waveform. The existence of reactive components like inductance causes the phase shift. On the circuit with thyristor switch the current waveform is distorted and the zero current point comes later than zero voltage point.
Single-phase half period rectifier consists of only one semiconductor diode or transistor (Fig. 4.7). This is rarely used in practice, because it’s output voltage ripple (pulsation) is very high (Fig. 4.8). The mean value of rectified voltage u_d on active load depend on control angle α according to equation

$$U_d = \frac{\sqrt{2}U_s}{2\pi}\left(1+\cos\alpha\right) \tag{4.3}$$

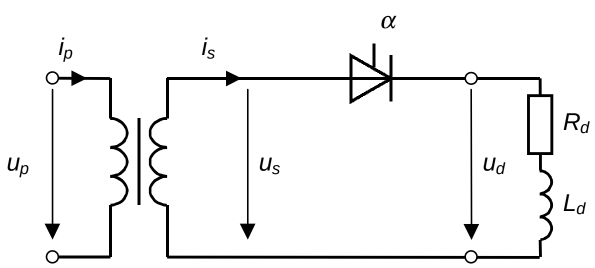

Figure 4.7. Single phase half period rectifier

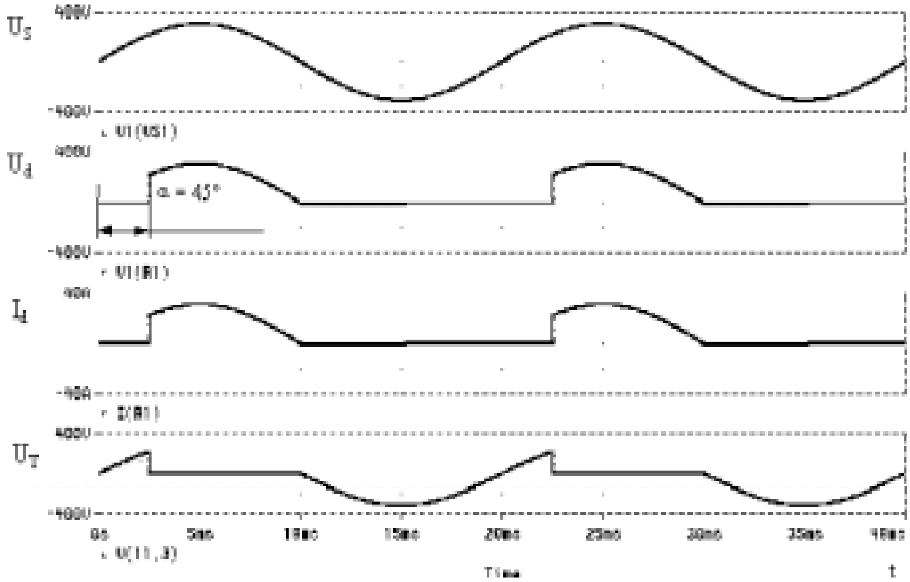

Figure 4.8. Current and voltage diagrams of the controlled half-period rectifier M1 on active load (L_d = 0) with control angle α = 45°.

On inductive load, the thyristor remains open on negative anode voltage until the current through the thyristor decreases to zero. Thus the output voltage can contain pulses form negative half waves of the voltage.

Single-phase mid-point rectifier (M2) from its construction is the parallel connection of two half-period rectifiers M1 (Fig. 4.9) whose input voltages are in inverse phase. The output voltage pulse with double frequency of it's input voltage. Controlled M2-type circuit can operate as controlled rectifier or as network synchronized inverter.

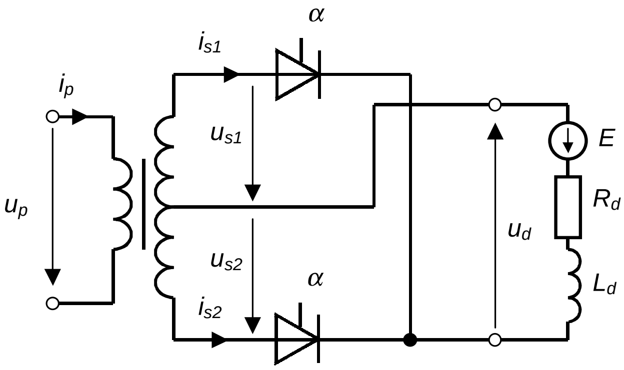

Figure 4.9. Single phase mid-point rectifier (M2)

The mean value of rectified output voltage u_d on active load depends of the control angle α according to the equation

$$U_d = \frac{\sqrt{2}U_s}{\pi}(1+\cos\alpha) \qquad (4.4)$$

On inductive load, the mean value of the rectified output voltage depends on the properties of the load current. The converter and load can work in discontinuous current operation or continuous current operation. On the discontinuous current operation, the voltage and current waveform consist of separate pulses whose length depends on inductance of the load circuit.

On the continuous current operation the output current is smoothed by load circuit inductance as much that the output current became continuous (direct). Mean value of the output voltage on the active and inductive load is given be previous equation (4.4). The properties of the output voltage and current depend of the back electromotive source that is located in the load circuit, like back electromotive force of the rotating motor.

Three-phase mid-point rectifier (M3) is the parallel connection of three single-phase mid-point rectifiers (Fig. 4.10) that are supplied from separate phases of three-phase supply network. The phases of the three-phase system are shifted by 120° degrees to each other.

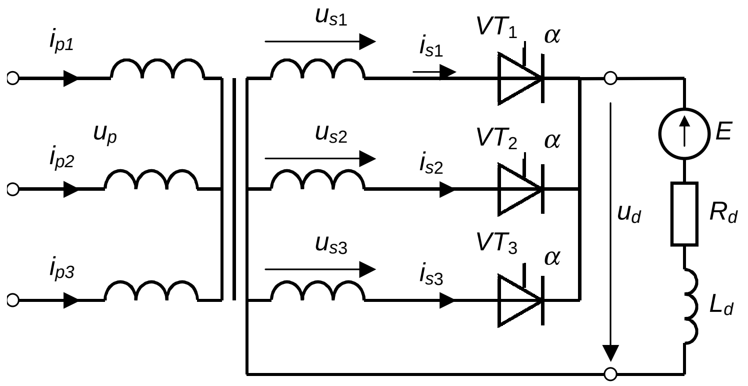

Figure 4.10 Three-phase mid-point rectifier (M3)

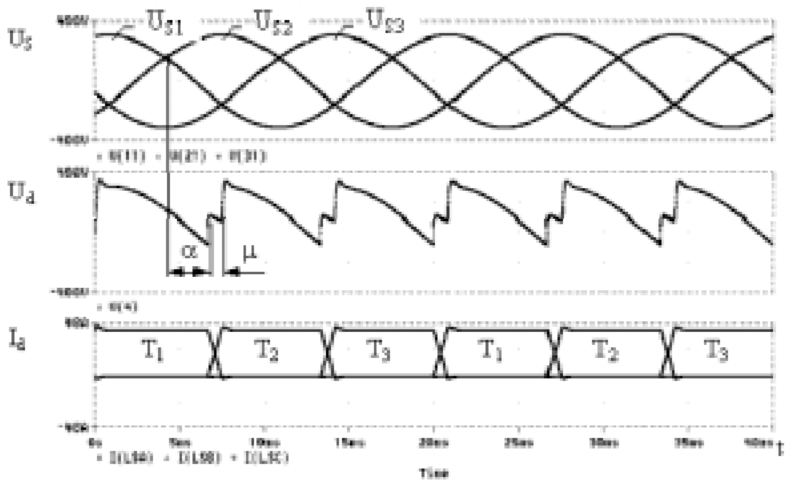

Figure 4.11. Voltage and current waveforms of three phase mid-point rectifier M3 on inductive load when the control angle α = 45° and commutation angle μ = 15°.

On the inductive load, the current continues through thyristor after the voltage on the thyristor has changed its sign. Because of that, the thyristor does not close (turn off) on the zero voltage time point, but remain open after that. Thyristor T_1 (Fig. 4.10, 4.11) remains open after the next thyristor T_2 is opened. The current transitions from one thyristor to another are called **commutation processes**. Because the thyristors of two phases are simultaneously open it's in principle the short circuit of two phases and the output is the arithmetic mean of two-phase voltages. The lengths of commutation process depend of the circuit inductance and amount of current. This process causes the reduction of rectifier's output voltage mean value. Some important calculation formulas of three phase mid-point rectifier technical specifications follow. Mean and root mean square (RMS) value of the current

$$I_{Vkesk} = \frac{I_d}{3}; \qquad I_{Vef} = I_s = \frac{I_d}{\sqrt{3}}. \tag{4.5}$$

The maximum value of the reverse voltage on the switch in closed (turned off) state is equal to the line voltage amplitude. The reverse voltage on the diode can be calculated form rectifier output voltage

$$U_{Vvp} = 2\frac{\pi}{3}U_{di}, \tag{4.6}$$

where U_{di} is the mean value of output voltage of diode rectifier or thyristor rectifier if the control angle is zero ($\alpha = 0$).

Secondary voltage of the supply transformer

$$U_s = \frac{2\pi}{3\sqrt{6}}U_{di} \tag{4.7}$$

Primary voltage and primary current of the ideal supply transformer

$$U_p = wU_s = w\frac{2\pi}{3\sqrt{6}}U_{di}; \qquad I_p = \frac{\sqrt{2}}{3}\frac{I_d}{w} \tag{4.8}$$

Secondary power of the supply transformer

$$S_s = 3\frac{2\pi}{3\sqrt{6}}U_{di}\frac{I_d}{\sqrt{3}} \approx 1{,}48\,U_{di}\,I_d \tag{4.9}$$

Apparent power of the primary winding of supply transformer

$$S_p = 3w\frac{2\pi}{3\sqrt{6}}U_{di}\frac{\sqrt{2}I_d}{w} \approx 1{,}21\,U_{di}\,I_d \tag{4.10}$$

The nominal power of the transformer is arithmetic mean of secondary and primary power.
The power factor of M3 rectifier is

$$\cos\varphi = \frac{U_{di}I_d}{S_p} = \frac{1}{1{,}21} = 0{,}83 \tag{4.11}$$

Single-phase bridge rectifier (B2) can be considered as series connection of two single-phase mid-point rectifiers (fig. 4.12), where two semiconductor switches are in common cathode connection and two in common anode connection.

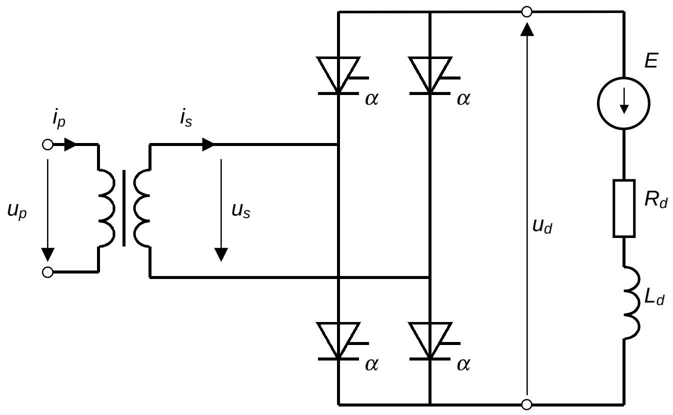

Figure 4.12. Single phase bridge rectifier (B2)

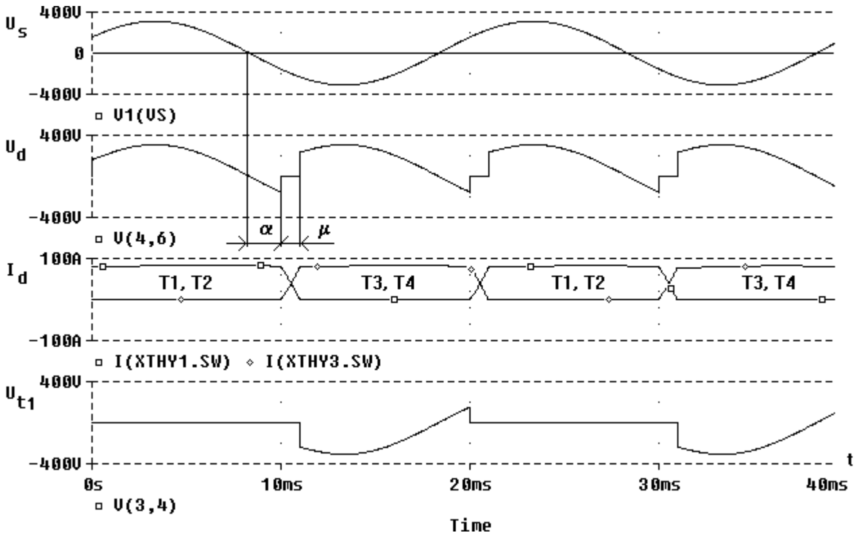

Figure 4.13. Voltage and current waveforms of the single-phase bridge rectifier B2 on ideal current smoothing, control angle α = 30° and commutation angle μ = 15°.

The reverse voltage on the switch of the single-phase bridge rectifier is 2 times lower compared with M2 rectifier, because the switches work in pair wise series. The mean and root mean square (RMS) of the switch current

$$I_{Vkesk} = \frac{I_d}{2}; \qquad I_{Vef} = \frac{I_d}{\sqrt{2}}. \tag{4.12}$$

Power of the transformer

$$S_p = S_s = 1{,}11 \cdot U_{di} \cdot I_d \frac{\sqrt{2}U_s}{\pi}(1+\cos\alpha) \tag{4.13}$$

Power factor of the B2 rectifier

$$\cos\varphi = \frac{U_{di} I_d}{S_p} = \frac{1}{1{,}11} = 0{,}9 \tag{4.14}$$

Three-phase bridge rectifier (B6) can be considered as series connection of two M3 mid-point rectifiers, where three semiconductor switches are in common cathode connection and three in common anode connection. Thus the output voltage of B6 rectifier is 2 times greater than the output voltage of the mid-point rectifier M3. The output voltage ripple is less than on the M3 rectifier, because B6 rectifier's output voltage consists of 6 pulses per input voltage period (p = 6). The switching order of semiconductor switches in Figure 4.14 is V1, V6, V3, V2, V5, V4. At least two switches are simultaneously in open state. On high load inductance the forward current continues on the negative anode voltage and the closing of the switch is delayed. Because the previously open switches are not closed (turned off) when the next switches open it is possible that 3 or even 4 switches are open during commutation process. This means that there are more that one open switch form the cathode or anode group and the current is re-switched form one phase to another.

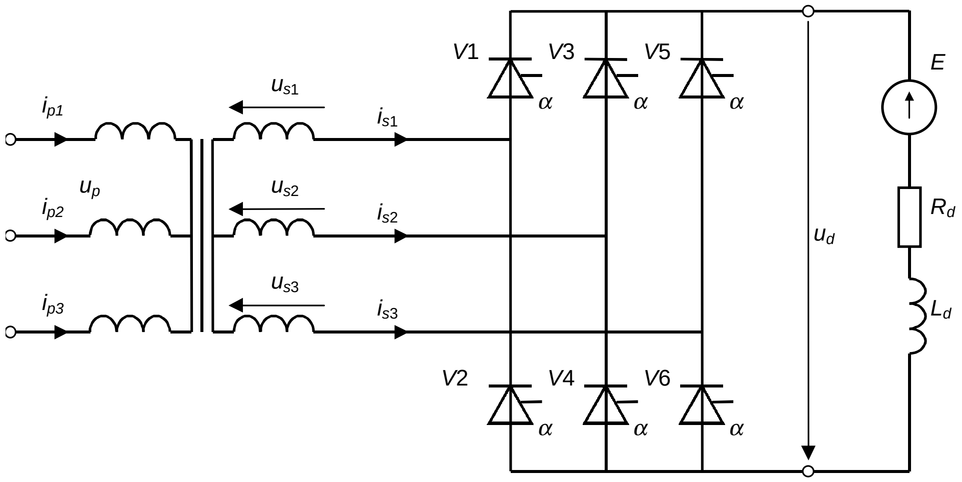

Figure 4.14 Three-phase bridge rectifier (B6)

The reverse voltage of the switch in the three phase bridge rectifier B6 is two times lower than on the mid-point rectifier M3, because the switches work pair wise series. The mean and root mean square value of the switch current

$$I_{Vkesk} = \frac{I_d}{3}; \qquad I_{Vef} = I_s = \frac{I_d}{\sqrt{3}}. \tag{4.15}$$

The nominal power of the transformer

$$S_p = S_s = 1{,}05\, U_{di}\, I_d \tag{4.16}$$

The power factor of the B6 rectifier

$$\cos\varphi = \frac{U_{di} I_d}{S_p} = \frac{1}{1{,}05} = 0{,}95 \tag{4.17}$$

Three phase bridge rectifiers are used most because of their good technical properties (low ripple, high power factor). Nowadays thyristor rectifiers are used on very powerful direct current drives. The uncontrolled diode rectifiers are used in smaller drives where voltage control is done using separate pulse width modulation control converters. Uncontrolled diode rectifiers are used too in frequency converters with direct current intermediate circuit. The advantages of the diode rectifiers are simple construction and low price, but disadvantages are that they do not allow regenerating energy back to alternating current network (for example on the generator operation of the electric drive) and their input current is distorted because of the diode commutation processes.

The controlled rectifiers allow regenerating energy back to network on the suitable control angle. It's should be mentioned, that three phase bridge circuit is used as main circuit of the inverter with different commutation elements and switches (thyristors, transistors). The bridge circuit is very widely used in power electronics as multi functional converter circuit that can be used for rectification of the alternating current or for inverting (alternating) of the direct current.

4.3. Alternating voltage controller

Alternating voltage controller allows changing root mean square of alternating current network voltage using semiconductor switches. For control of the alternating current, the bi-directional semiconductors switches (TRIAC's) or anti parallel connection of unidirectional semiconductor switches (SCR's) can be used. Single-phase alternating voltage controllers are widely used for control of drive speed in household appliances like electric drill (bit brace), washing machine, vacuum cleaner etc. Alternating voltage controllers are also used in lighting control.

Single-phase alternating voltage controller (Fig. 4.15, a) consists of two thyristor in anti-parallel connection. The voltage of the load can be changed by controlling the opening (turn-on) time of the thyristors using phase control principle. The pulse width modulation principle can be used in alternating current controller if it has turn-off capable (closing) switches.

Three-phase alternating voltage controller (Fig. 4.15, b) consists of three single-phase alternating voltage controllers. From all of the used alternating voltage controller circuits, the most widely used is W3C controller. When the neutral of star-connected load is connected to natural connector of the source N, then the control characteristics of three-phase alternating current controller is identical to the control characteristics of the single-phase controller. When there is no connection to neutral connector N, then thyristors can only switch pair wise and this will deteriorate the control properties.

The main applications of three-phase voltage controllers are contact-less switches (like semiconductor contactors) and soft starters of asynchronous motors. The main advantage of contact-less semiconductor switch compared to common contactor is the high capable switching frequency and spark free (arc free) commutation process. The last is extremely important in the electrical equipment whose are installed into flammable environment.

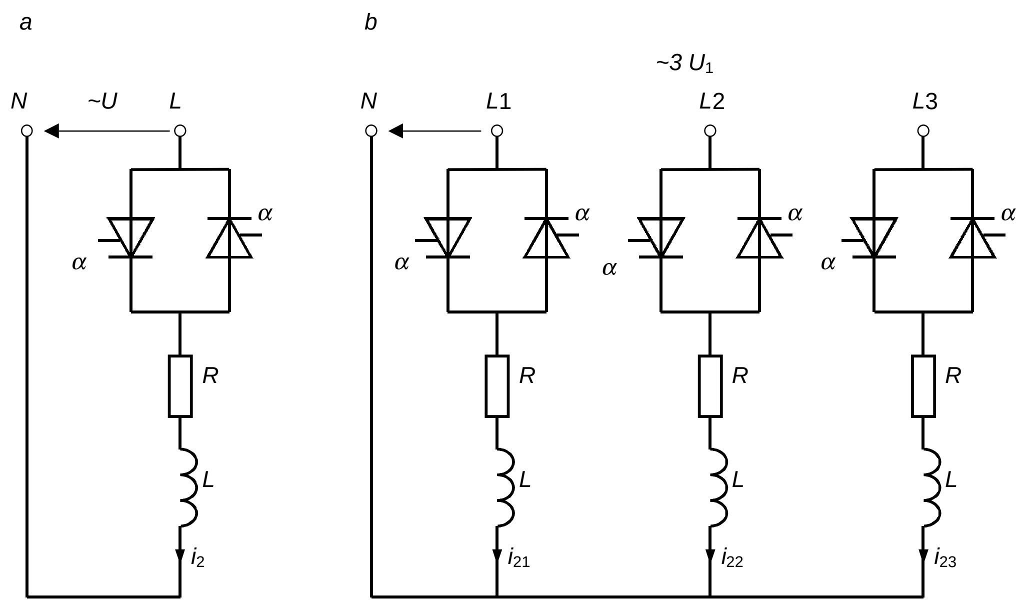

Figure 4.15. Alternating current controllers: a) single-phase controller, b) three-phase controller

4.4. Direct current converters and controllers

Direct current controllers are classified according to polarity of the output current or voltage (sign) and properties and Figure of their volt-ampere-characteristic as one, two or four quadrant converters. This means, that their volt-ampere characteristics cover one, two or four quadrants on *U-I* plane accordingly.

Converter with unidirectional current and one voltage polarity called as **single quadrant pulse width converter** allows controlling the output voltage below the input supply voltage. That's why this converter is called as **step-down converter** or **buck converter**. Buck converter (Fig. 4.16) is used for control and supply of unidirectional rotating direct current machine. On the equivalent circuit the direct current motor can be mapped as series connection of active resistance, inductance *R-L* and source back electromotive force E_L.

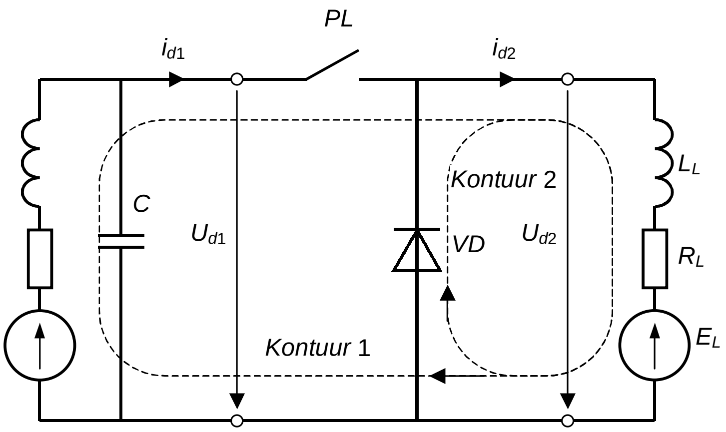

Figure 4.16. One-quadrant step-down (buck) DC pulse width converter together with supply and load circuits (for example motor)

One quadrant pulse width converter consists of semiconductor switch PL and freewheeling diode VD. The semiconductor switch PL must be completely controllable switch – transistor, GTO thyristor or SCR thyristor with closing circuits. For simplification the resistance of the switch in open (turned on) state can be considered as zero and the resistance in closed (turned off) state as infinite. For simplification the diode resistance on forward current is considered as zero and infinite on reverse current. For simplification the state change on switching process can be considered as immediate. Both supply and load circuit consist of active-inductive resistance and the sources of electromotive forces. Usually, the *LC*-filter is connected into switch circuit between the supply and the load, which decreases the influences of the high frequency ripple to the supply circuit (supply network). The semiconductor switch is controlled using pulse width modulation principle (p. 4.1).

If the switch PL is switched ON and the electromotive force of supply source is bigger than the back electromotive force of the load then there will be positive current through the load (branch, path 1) $i_{d2} = i_{d1}$, because the diode VD has reverse voltage and it will not conduct current. The voltage and the active-inductive resistance of the load determine the rise of the current. The current through switch PL breaks when the circuit is switched off. But the current through the load that contain inductance cannot decrease to zero immediately, because the energy stored into inductance does not disappear and it must be converted (transferred). Load current switches over to freewheeling diode circuit (branch, path 2) and the energy stored in inductance transfers to heat in load active resistance. If the current through path (branch) 2 attenuates to zero before the switch is switched on again then **discontinuous current operation** will occur in circuit. The boundary (edge, border) between the continuous and discontinues operation depends on parameters of supply and load circuits and relative duty cycle of the switch. The output characteristics of step down converter (buck-converter) depend on relative pulse length q (Fig. 4.17.). When the load current decreases the converter goes form continuous operation into discontinuous operation and the voltage starts to increase abruptly, because when the current has stopped and the diode has closed (turned off) the voltage of the secondary circuit depend on back electromotive force caused by the rotation of the motor.

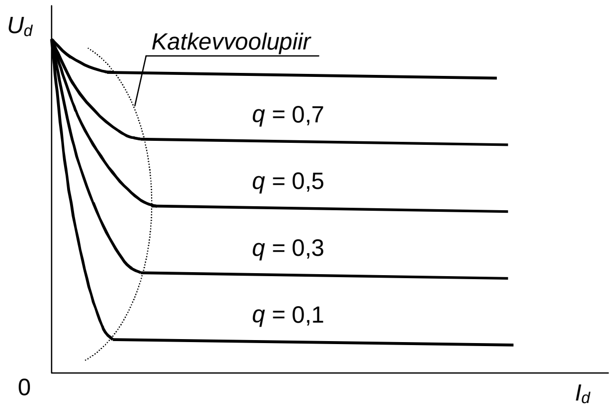

Figure 4.17. Output characteristics of step-down DC converter

Step-up pulse width converter (*boost converter*) allows getting the higher voltage on the output than supply voltage. Such converter is used in active filters and in compensators of reactive power. The circuit diagram of step-up converter is shown in Figure 4.18.

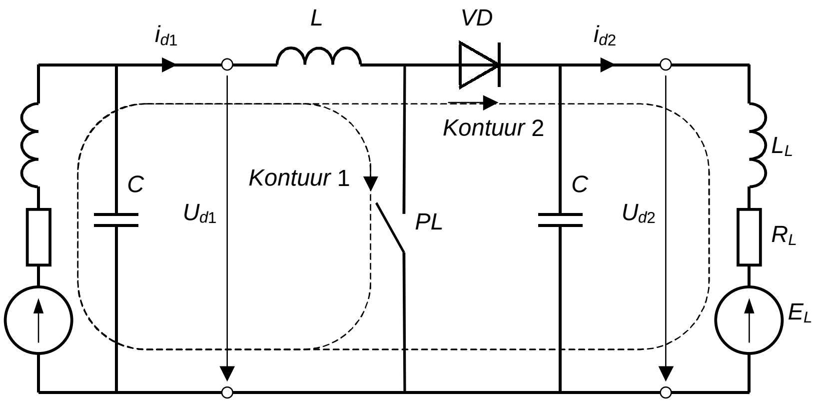

Figure 4.18. Step-up (boost) DC converter

If the semiconductor switch PL conducts current (path, branch 1), then part of the supply energy is stored into magnetic field of the inductance L. When the semiconductor switch turns off and bakes the circuit, then the current through the inductance commutates trough the diode VD to load and capacitor C (branch, path 2) and the stored magnetic field energy of the inductance $W_L = Li^2/2$ is transferred and converted to electric field energy of the capacitor $W_C = Cu^2/2$. The output voltage of the converter depends on the relative duty cycle of the semiconductor switch. The output voltage is equal to the input voltage if the switch PL is continuously switched off (does not conduct the current). Switching of the PL allows increasing the voltage of the output capacitor using additional energy from inductance. When the switch PL is switched on then the current through the inductance increases. When the switch is switched off, then the capacitor charging current is higher and the voltage on will increase.

Required inductance and capacitance

$$L = (U_{d2a} - U_{d1}) \frac{U_{d1}^2}{U_{d2a}^2} \frac{T}{2\, I_{d2\min}}; \qquad C \geq \frac{T\, I_{d2\max}}{\Delta U_{d2a}^2} \tag{4.18}$$

Current I_{d2} should not be lower than the minimal current

$$I_{d2\min} = (U_{d2a} - U_{d1}) \frac{U_{d1}^2}{U_{d2a}^2} \frac{T}{2\, L} \tag{4.19}$$

If the step-down (buck) converter is connected series to step-up (boost) converter then it allows increasing and decreasing the input voltage. Such direct current converter is called *buck-boost converter*. One of such multifunctional direct current converter is the voltage-inverting converter that is called *Cuk converter* the name by its inventor.

4.5. Direct current converters used in electrical drives

Converters mentioned above can be used only in drive with single directional rotating motor operation. For the regeneration of energy on the drive braking it is necessary to change the current direction in semiconductor switch. The **two-quadrant pulse width converter with variable current direction** (Fig. 4.19) can be used for that purpose.

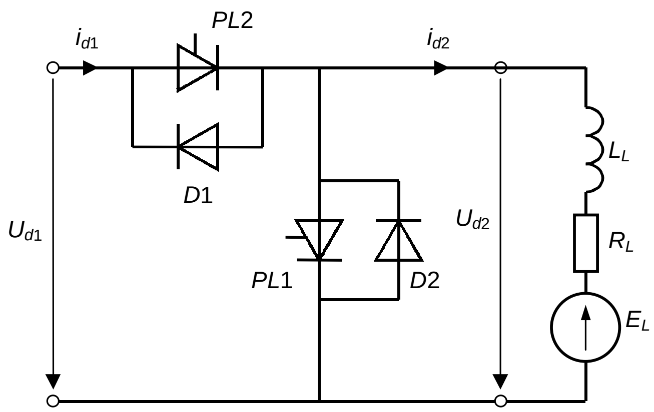

Figure 4.19. Two-quadrant, variable current direction DC converter

Two quadrant converter consist of two separate converters: step-down converter PL2 and D2 and step-up converter PL1 and D1. The step-down converter works in motor operation. Switch PL1 is continuously switched off (does not conduct current). The diode D1 has reverse voltage on it and is closed (turned off) too. The step-up (boost) converter (PL1 and D1) functions in generator operation and allows redirecting energy back to supply source.

Two-quadrant converter with variable voltage polarity is sown in circuit diagram 4.20. Semiconductors switches PL1 and PL2 are switched simultaneously on and off. The current through the motor is unidirectional in this example. When the direction of the machine changes, then the sign of electromotive force and voltage polarity on the machine terminals is inverted too, but the direction of the current remains unchanged.

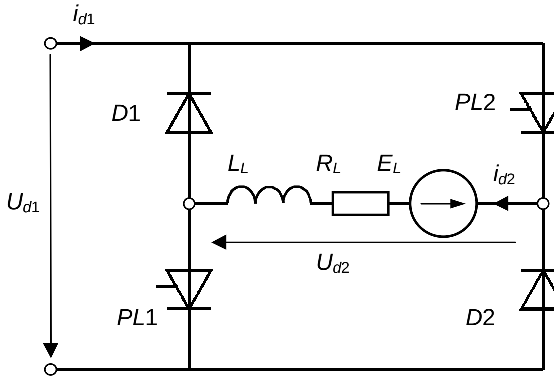

Figure 4.20. Two-quadrant, variable output voltage polarity DC converter

Four-quadrant pulse width converter is the converter that allows variable current direction and controlled output voltage with variable polarity. In principle this is combination of two two-quadrant direct current converters (Fig. 4.21). The four-quadrant converter is called also as reversible direct current converter. This is used in electrical drives with variable rotation direction (reversible electric drives). In the motor operation the electromotive force is less than the voltage of the supply source $E_L < U_d$. The converter voltage and motor speed is controlled with semiconductor switches PL1 and PL2. Switches PL3 and PL4 are continuously switched off. When the switches PL1 and PL2 are switched on then the current through the motor is positive and increases. When one of them is switched off then the current continues through the diode D1 or D2 and decreases. For changing the rotation direction it is necessary to change the voltage polarity and current direction. This is done by switching off the switches PL1 and PL2, and by switching on the switches PL3 and PL4.

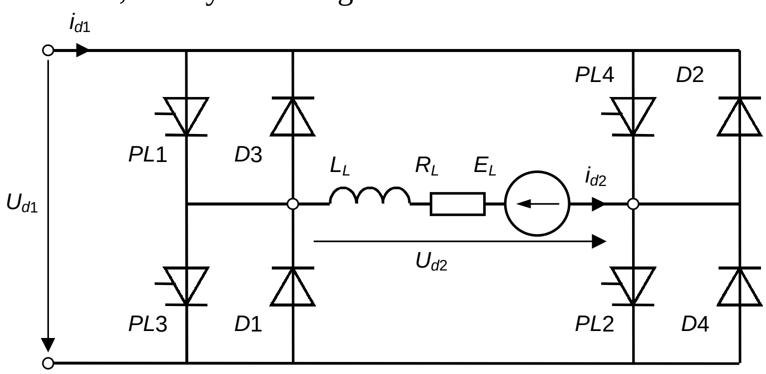

Figure 4.21. Four-quadrant DC converter

In generator operation (operating as a brake) the voltage polarity remains the same, but the current direction is changed compared to motor operation. According to the load voltage polarity shown in Figure the diodes D3 and D4 will open and the direction of currents i_{d1} and i_{d2} is reversed compared to the arrows shown in Figure 4.21. The operation of four-quadrant converter when only two semiconductor switches are working (other two are switched off) is called **uni-polarity operation**. Four quadrant converter can be used in operation where semiconductor switches are switched pair wise (PL1, PL2) and (PL3, PL4). In that case the alternating square-wave voltage (bipolar voltage) will be formed at the output whose mean value can be controlled by relative duty cycle of the semiconductor switches. On equal relation between positive and negative half wave the mean value of the voltage is zero. This control method is widely used in direct current positioning servo drives.

4.6. Inverters

Inverter converts direct current voltage to alternating voltage and direct current to alternating current. The invertors are classified as voltage or current invertors. The supply source of the **voltage source inverter** is the voltage source with low internal resistance. Its feature is commonly the capacitor with high capacity connected parallel to supply source that keeps the voltage constant. The output current of the voltage inverter is shaped according to (depend on) voltage value and to the load resistance. The supply source of the **current source inverter** is the direct current source with constant current. Its feature is the high inductance connected series to supply source, which keeps the current constant. Current is feed to the output via semiconductor switches. The output voltage of the current source inverter is shaped according to (depend on) the voltage drop on the load caused by the output current.

The circuit diagram of the inverter with two symmetrical supply sources and two semiconductor switches (half-bridge) is shown in Figure 4.22. Note, that it is possible to use an artificial middle point instead of symmetrical double voltage source (Fig. 4.22, b). Such circuit is a voltage divider, which consists of two series-connected capacitors and resistors. The offline inverter with semiconductor switch is shown in Figure 4.23.

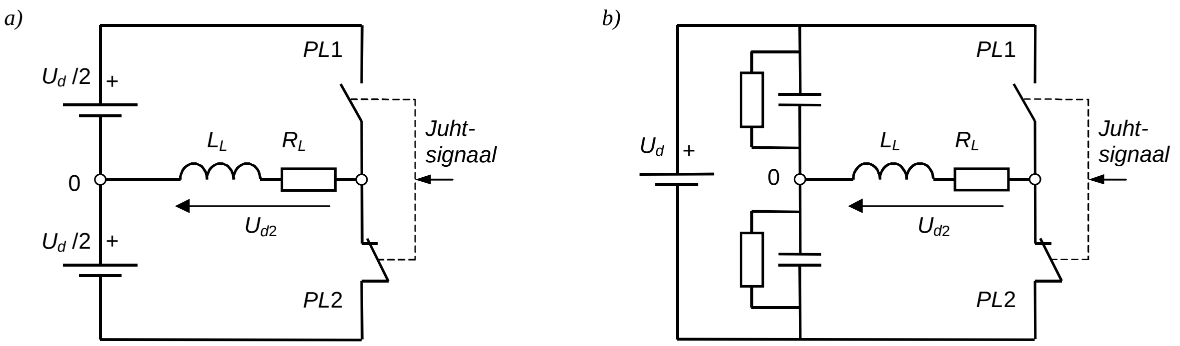

Figure 4.22. Inverter circuit diagrams: a) with two symmetrical supply sources, b) with voltage divider (artificial middle point)

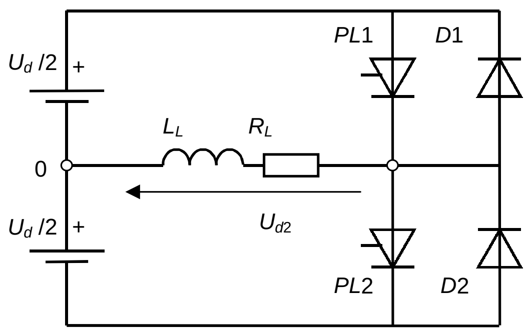

Figure 4.23. The circuit diagram of an offline half-bridge inverter with power thyristors and freewheeling diodes

The inverters are controlled using block or pulse control principle. On the block control principle one opening (turn-on) and closing (turn-off) of the semiconductor switch forms the positive or negative half period of the voltage. Thus the rectangular voltage blocks are formed at the output of the inverter. The sinusoidal output voltage cannot be achieved using block control principle. The output voltage diagram of the voltage inverter that is using block control principle is piecewise exponential curve, which significantly differs form sinusoidal curve. The circuit diagram of simple block-controlled inverter is shown in Figure 4.23. Semiconductor switches PL1 and PL2 are switched after each other. Both switches should not be simultaneously on, because this is a short circuit condition. The special dead-time interlocking controls are used to avoid this condition (similar switching blockages are used on contacts of mechanical switches as well). When the pulse control is used, then the switches are switched on several times during half period of the output voltage. The duty cycle is then changed according to she required shape of the output voltage and this means that the output voltage is formed using pulse width modulation principle. If the pulse with modulation is done according to sinusoidal wave then the output of the converter has pulsed voltage whose mean value varies according to sinusoidal wave. The switching frequency used on the pulse control is significantly (ten times or more) higher than on the block control.

Single-phase bridge inverter circuit shown in Figure 4.24 is often used is practice for single phase alternating voltage supply. The magnitude of the output voltage is two times higher (doubled) than on the half-bridge inverter shown in previous Figure 4.23. This circuit does not require double supply source with middle point.

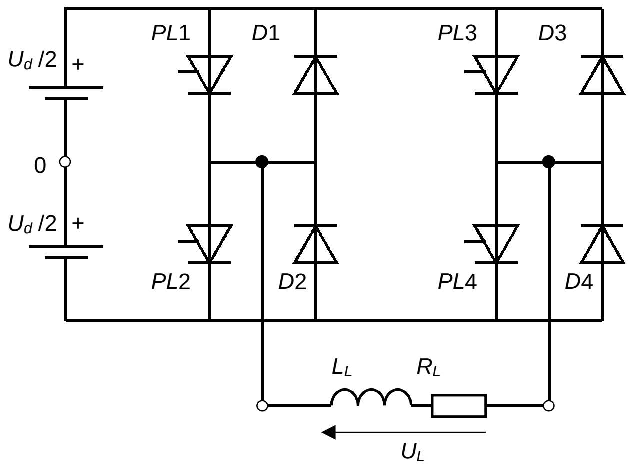

Figure 4.24. Offline inverter based on single-phase bridge circuit

The single-phase bridge inverter can be controlled using block or pulse control principle. On block control the bridge branches are switched so that their output voltages are shifted to each other by the angle β. If there is no shift angle $\beta = 0$, then the voltage is in same phase and output voltage of the converter is zero. If the phase angle between these two branches is $\beta = \pi$ then the voltages are in opposite phase and the output voltage is maximal $U_L = U_d$. Thus the output voltage depends on the phase angle β. The voltage and current waveforms of the single-phase bridge inverter on block control, inductive load and maximum output voltage (β =180°) are shown in Figure 4.25.

Root-mean square (RMS) of the load voltage is

$$U_L = \sqrt{\frac{1}{2\pi} 2\int_0^{\beta} U_d^2 \, d\omega t} = U_d \sqrt{\frac{\beta}{\pi}} \tag{4.20}$$

Because the shape of the output voltage differ significantly from the sinusoidal the voltage consist higher harmonic components besides the main harmonic. Although the amount of the main harmonic on the values of angle β, $\pi/2 < \beta < \pi$ is relatively high 80...90 %. The block control is well applicable in this control range and allows controlling the frequency and RMS of the output voltage main harmonic.

If the pulse control is used then the voltages of both branches are controlled using pulse width modulation principle. When the modulation is done according to sinusoidal curve then the output of the converter is pulsed voltage whose mean value varies according to sinusoidal curve. The pulse control allows controlling the output voltage, frequency and the angle β between the branch (phase) voltages very flexibly. The circuit shown in Figure 4.24 can be used for control of two-phase asynchronous motor. In that case the phase voltages should be shifted by $\beta = 90°$ and the middle point of motor windings have to be connected to the middle point of the symmetrical supply source (or to it's artificial middle point).

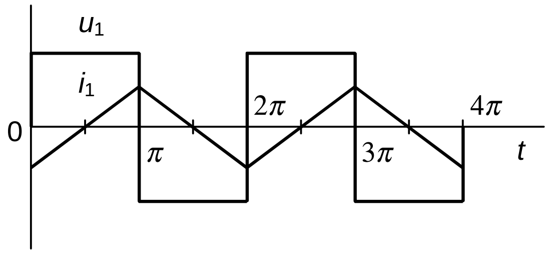

Figure 4.25. The waveforms of the output voltage and current on block controlled inverter.

Three-phase voltage inverter is shown in Figure 4.26. This bridge type offline voltage inverter can be used for supplying three-phase electricity consuming device with controlled frequency and voltage amplitude. Such circuit is mainly used for frequency control of alternating current drives and it is part of frequency converter power circuits. On symmetrical phase voltages the phases are shifted by 120 degrees to each other and shapes and amplitude of voltage and current curves in different phases is similar.

As on previously described converter circuits the three-phase inverter allows applying block and pulsing control principle. Because of the wide use of the frequency control of electrical drives and the operation principle of three phase electrical machines (the symmetrical three-phase supply voltage causes the rotating magnetic field in space-symmetrical stator winding system) the **vector control principle** is widely used. In principle this means, that the aim of the inverter control is not the symmetrical phase voltage generation, but the generation of such voltage system whose voltage complex-vector rotates in complex plane. Such inverter control principle is called **voltage vector control**. Three-phase symmetrical system of sinusoidal voltages whose phases are shifted to each other by 120° (Figure 4.27) assures the smooth rotating of the voltage vector. The same result can be achieved in two ways.

a) The symmetrically shifted voltages with same shape and equal amplitude are generated in three phases. These voltages are used to supply the electrical machine.
b) Such switching order of semiconductor switches is chosen, that causes the rotating magnetic field in the electrical machine.

The last (b) method is called voltage vector control (Figure 4.28). Choosing the suitable semiconductor switches and their control on pulse with modulation principle allow to create suitable voltage vector. By changing the semiconductor switches and pulse width the voltage vector can be rotated in required way in complex plane.

Compared to pulse control the voltage vector control allows higher phase voltage and thus the higher output power of the converter. The output voltage amplitude in pulse control is U_d /2.

On voltage vector control the amplitude is equal to the inner-circle radius of the hexagon $U_d / \sqrt{3}$. Thus the maximal voltage on voltage vector control is 15,5 % higher than on pulse control. Note, that by using the three-phase bridge rectifier the result of 220V phase voltage rectification is 540 V direct current voltage U_d = 540 V. If the inverter works in 6-pulse (tact) block control and it's output voltage is stepped then the amplitude of it's maximal output voltage is $U_m = 2 \cdot U_d / 3$ = 360 V. The mean value of the output voltage is then 240 V, which is 18 % higher than the mean value of the network voltage (198 V). Thus the voltage converter have some kind of voltage reserve in that case and motor can allow higher output torque in higher frequency, but this is achieved by price of abandoning the sinusoidal output. Note, that this will cause higher losses caused by higher harmonic components.

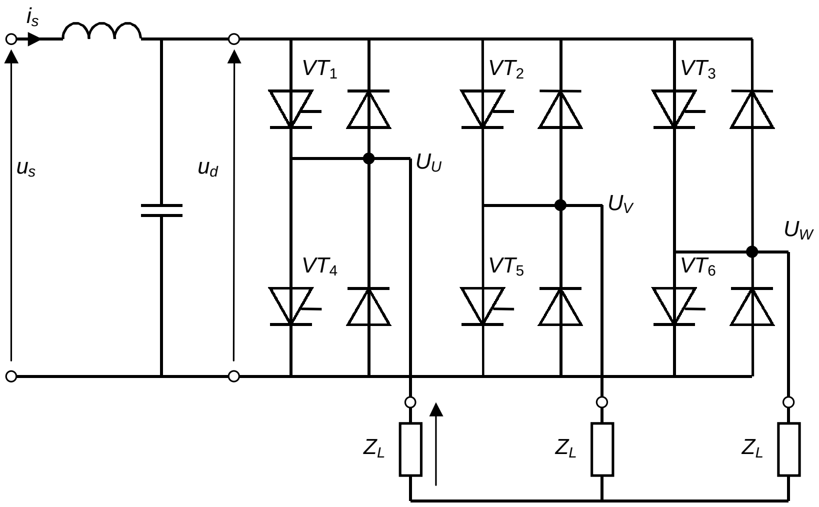

Figure 4.26. Three phase offline voltage inverter

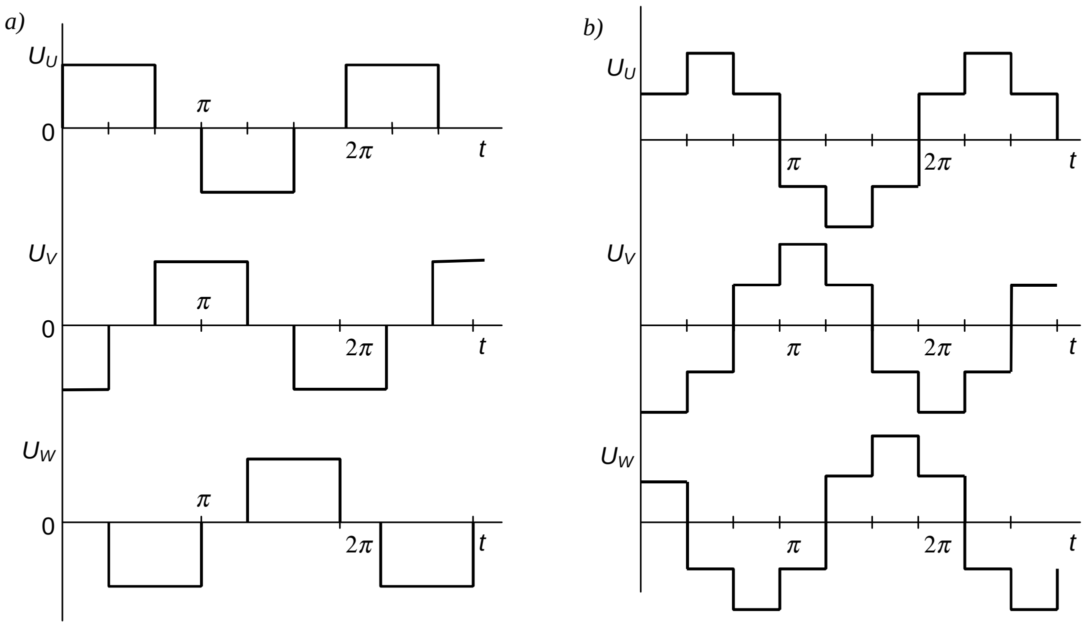

Figure 4.27. Output voltages of six-pulse three-phase inverter with block-control:
a) By two simultaneously open switches, b) by three simultaneously open switches

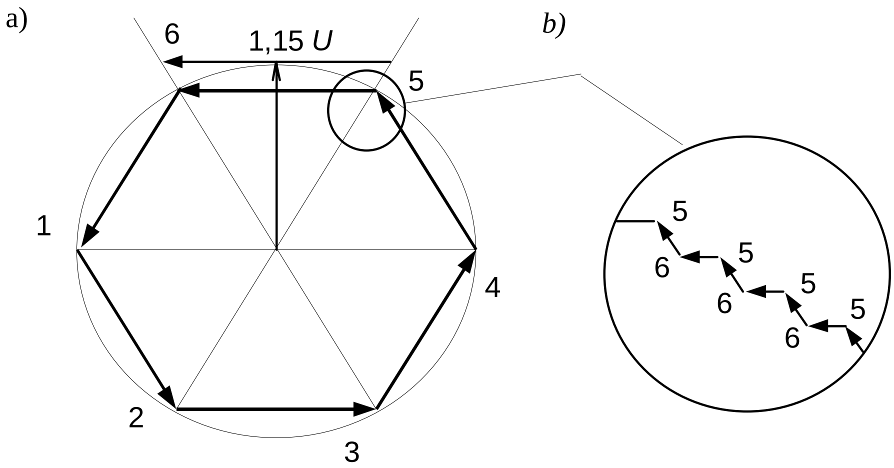

Figure 4.28. The operation of inverter with voltage vector control:
a) the state polygon of vector, b) the control of vector

Current source inverters are usable for such electricity consuming devices (electric-arc furnace, induction heating etc.) on which is important to control the current value (not voltage value). Compared to voltage inverters the usage of them is lower, because the voltage inverter can be used too as a current source with appropriate current feedback. When using common thyristors (SCR's) then current source inverters have some advantages compared to voltage source inverters because the simpler commutation (switching) of the thyristors. Nowadays these advantages are not as important because well controllable switches (IGBT's, etc.) are available

Resonant inverters consist of switching (commutation) circuit and of *LC* resonant circuit that forms the alternating voltage for the load. The parallel, series resonant circuits or their combination as mixed resonant circuits are used in resonant inverters. The semiconductor switches are commutated in the way, that *LC*-resonant circuit can work near to it's resonant frequency thus the natural frequency of the resonant circuit is near to the commutation frequency of the switches. On thyristor switches it is possible to achieve the situation where thyristors are closing by output voltage natural commutation as in network-synchronized (online) inverters. As different form online inverters the frequency of the output voltage is fixed by the natural frequency of the resonant circuit. The frequency of the resonant converters cannot be changed by reference signal of the control system.

The main application of resonant converters is electro-thermal processing, where these converters are used for supply of the heating equipment. These converters suit for microwave furnaces and for ultrasound equipment where is need for high frequency but uncontrolled supply sources. When the rectifier is switched to the output of the resonant converter then it is a resonant converter of direct current voltage.

4.7. Frequency converters

Frequency converters can be divided as frequency converters with intermediate direct current link and direct frequency converters. **Frequency converter with intermediate direct current link** consists of rectifier, smoothing filter and offline (autonomous) inverter. Alternating current voltage is rectified and inverted (alternated) to alternating voltage with variable magnitude and frequency. Changing the voltage and frequency allow to control the rotating speed of three phase asynchronous motors in wide range starting from zero an up to several nominal speed (if mechanical properties of the motor allow it). The simplified block diagram (structure, circuit diagram) is given on Figure 4.29.

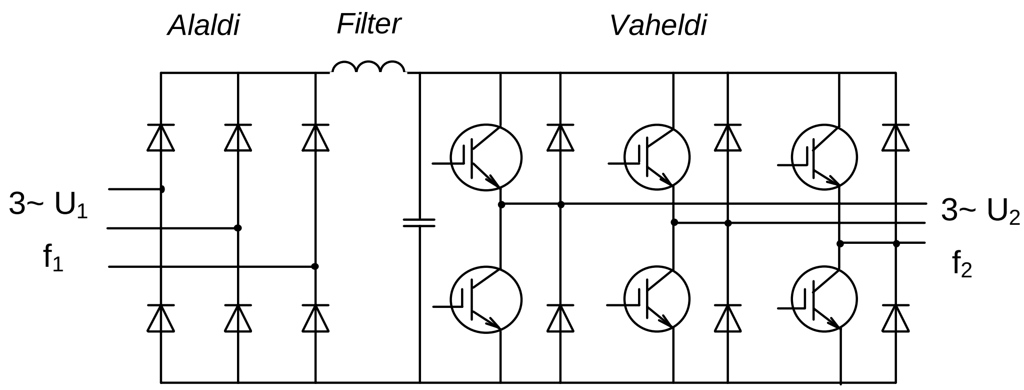

Figure 4.29. Power circuit diagram of Frequency converter with uncontrolled diode rectifier and transistor inverter

The rectifier is commonly three-phase uncontrolled (diode) bridge. The fully or partially controlled network synchronized rectifiers (with thyristors or transistors) are sometimes used. These allow regenerating energy back to supply network. Several types of **DC intermediate circuits** are used. DC intermediate circuits consist of smoothing low-pass filter or only a big inductor, which together with rectifier form a constant current source. Intermediate circuits with low-pass filters are used together with voltage source inverters. The big inductor based intermediate circuits are used together with current source inverters. The intermediate circuit can contain a converter that varies its voltage (commonly decreases) and improves the power factor of the converter.

Intermediate circuit of an electric drive usually contains a braking resistor, which is switched on if the fast stopping of the motor is needed. The braking resistance is needed for dispersal of the braking energy of the motor to avoid the increase DC intermediate circuit voltage. Note, that if the rectifier is not capable for feeding the energy back to network, then the voltage on the intermediate circuit capacitor rises over allowed limit.

Inverter (alternator) converts input direct current voltage to alternating voltage with required frequency. Using inverter the root mean square of the output voltage can be controlled too. In inverters are used pulse width modulation, pulse-magnitude modulation, voltage vector modulation or current vector modulation principles for output voltage modulation. When the pulse-magnitude modulation principle is used then the voltage of the DC intermediate circuit using a controlled rectifier controls inverters output voltage. In that case the duty cycle of the inverter is not controlled and kept on the value that conforms to the maximal output voltage $q = \sin\omega t$.

In direct frequency converters do not contain energy storage in intermediate circuit and their frequency of the input alternating voltage is directly converted to the output voltage. Their efficiency is higher, which is very important on high power application. The main direct frequency converters are double pulse width modulation frequency converters, cycloconverters and matrix frequency converters.

The double PWM converter consist of pulse with modulation controlled rectifier and inverter (Figure 4.30). Such frequency converter allows flexible bi-directional transmission of the energy from network to the electric motor and from the motor in generator mode back to electrical power network.

The circuit diagram of the pulse with modulation rectifier is similar to offline (autonomous) inverter, but is operates as network synchronized converter. The low-frequency ripple of the output voltage of such rectifier is low, because of it minimal filtering is needed and there is no need for energy storage although the DC intermediate circuit exist.

These converters could become prosperous in high power applications and they will compete with cycloconverters. Compared to the cycloconverters the output frequency of double PWM frequency converters is controllable in a wide range below and up form the supply frequency. The good property of it is a simple energy redirection by using the symmetrical circuit.

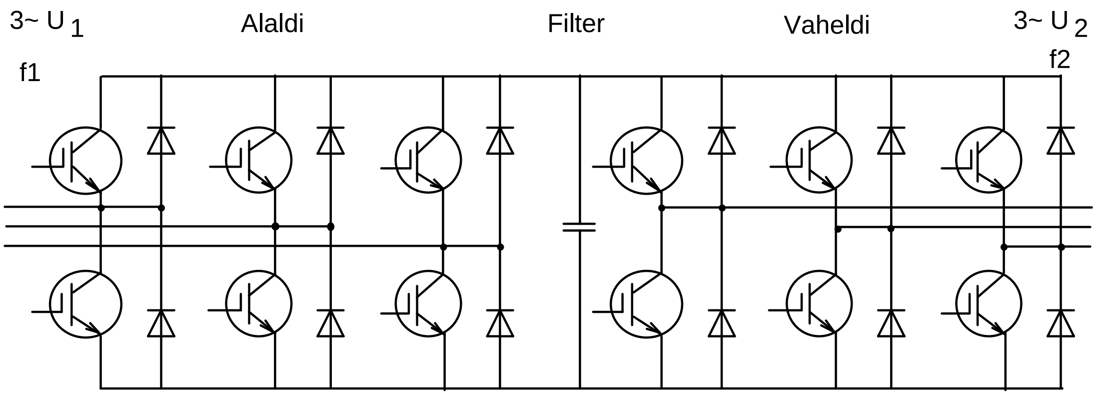

Figure 4.30. The power circuit diagram of the pulse width frequency converter with transistor rectifier and inverter

Cycloconverters are direct frequency converters that are directly synchronized to supply network, on which the used semiconductor switches are power thyristors. Note, that other direct frequency converters use fully controllable semiconductor switches (turn-off capable thyristors and power transistors). The cycloconverters are used in high power applications (up to ten's of megawatts) and lower frequencies of the supply voltage. The feature of this converter is that the thyristors are closing on natural commutation (turn-off on zero current). The 6-, 12- and 24-pulse cycloconverters are known. The circuit diagram of the simple six-pulse cycloconverter is in Figure 4.31.

The frequency converter consists of two anti-parallel connected three-phase bridge rectifiers. The converter operates in following way. The switches of the first bridge conduct on the positive half-wave of the output voltage U_2 and on the negative half-wave of the output voltage U_2 conduct the switches of the second bridge. The control angles are controlled in the way that the output voltage is kept near to sinusoidal.

There are several ways to control the cycloconverter. The simplest is the triangle control on which the control angles of the active bridge are change linear. Output voltage U_2 alters nearly to sinusoidal in this case. The output voltage waveform on triangular control is given in Figure 4.32. When using single-operation thyristors (SCR's) the commutation is done by network voltage. Thus the frequency of the output voltage cannot precede the frequency of the supply voltage and is always at least 2 times lower. For smooth commutation of the current from one bridge to another the control angle is momentary changed over 90° (the network synchronized rectifier goes into inverter operation mode).

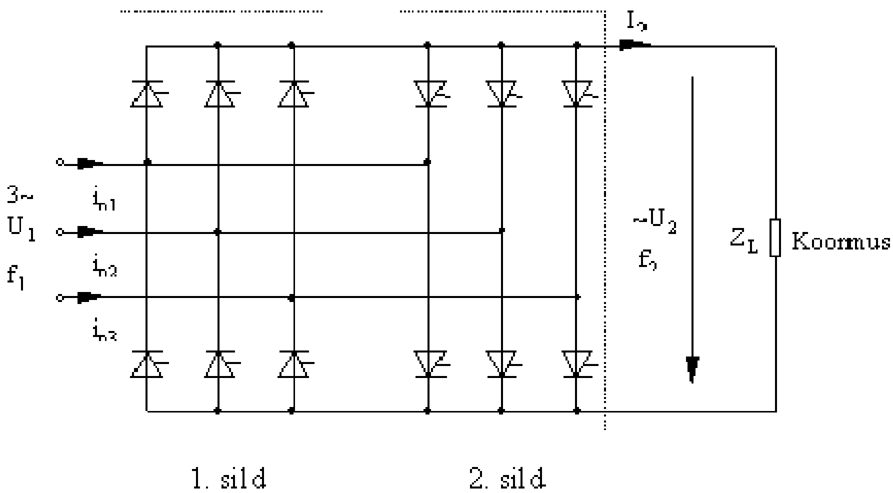

Figure 4.31. Circuit diagram of the Single-phase cycloconverter

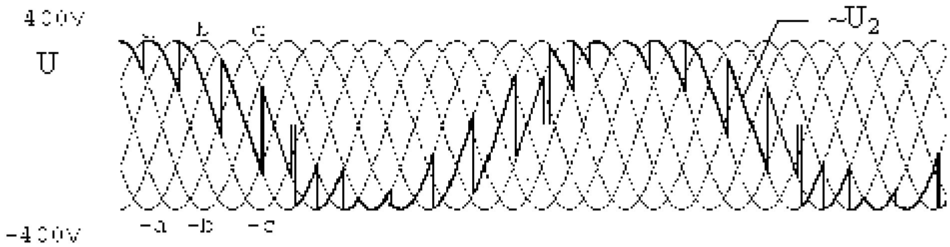

Figure 4.32. Output voltage waveform of the single-phase cycloconverter

Matrix frequency converter (matrix converter) or forced commutation cycloconverter (Figure 4.33) forms its output voltages directly from multi-phase network voltage. The pieces of the output voltage are conducted (feed) to outputs in appropriate moments and the output voltages with required frequency, number of phases, phase and amplitude are modulated. The frequency can be freely varied in wide range and the upper limit is only limited by capabilities of the capabilities of the semiconductors. For example, the three-phase matrix converter consists of nine pairs of power transistors, which allow commutating the current on both directions.

On the control of matrix converter the pulse with modulation, pulse amplitude modulation and vector modulation principles are used. The matrix converters are not considered as prosperous because of the big amount of semiconductor switches and complexity.

Frequency converters of multi-motor drives are produced as sets (units) for the machines that contain several drives, for example for crane. On higher power applications is reasonable to use one network-synchronized rectifier with bi-directional energy flow and separate inverters for each motor. In this case several parallel inverters are supplied from local direct current network (DC bus). The energy flows are possible between different inverters and between the network and local direct current bus. The converters with flexible energy exchange capabilities (flows) become more prosperous because the need exist for economical use and saving of electrical energy.

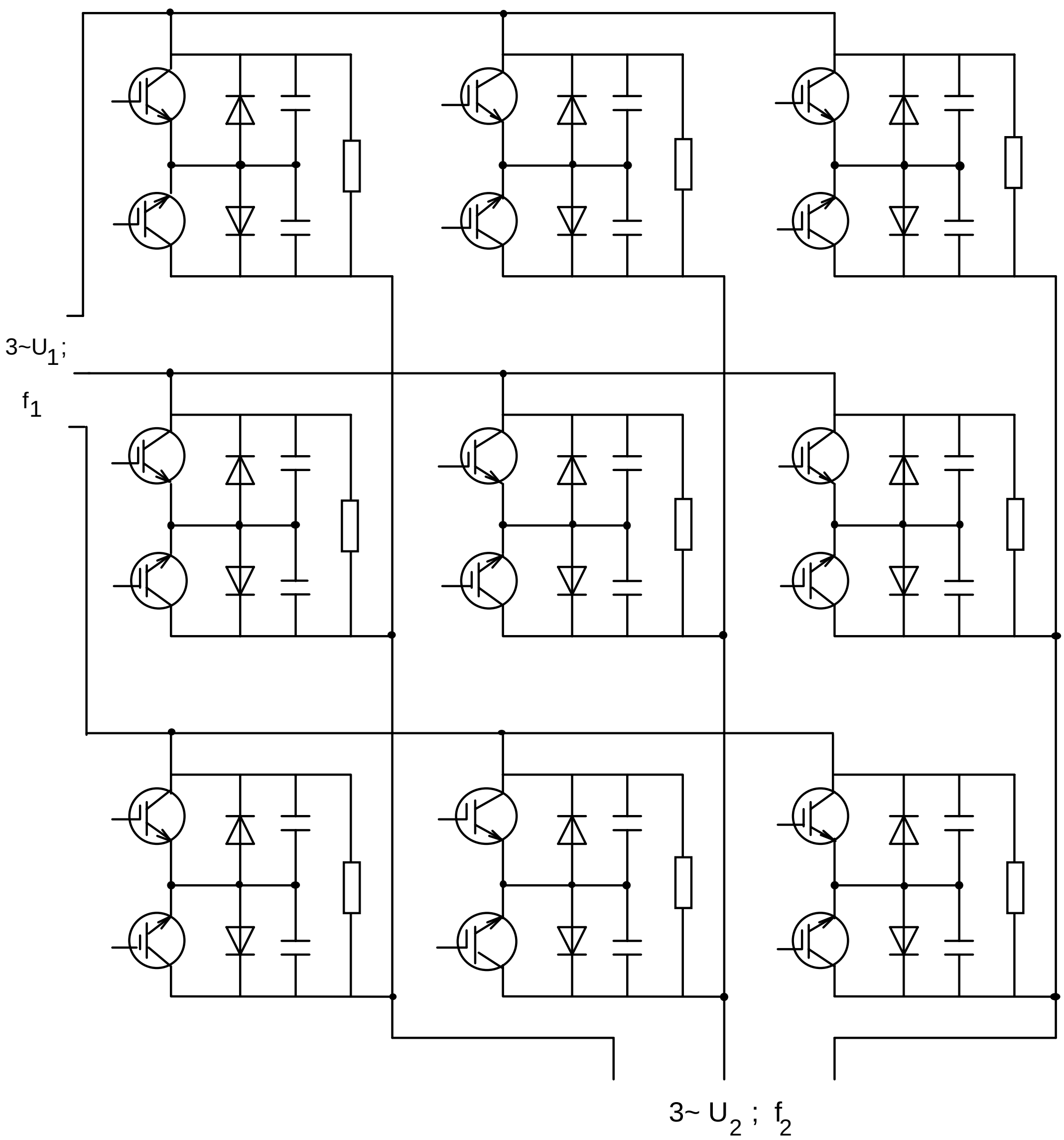

Figure 4.33. Power circuit diagram of the matrix converter