

# A MULTI-PULSE DIODE RECTIFIER WITH A COUPLED THREE-PHASE REACTOR – THE DESIGN METHOD AND RESULTS OF THE SIMULATION AND LABORATORY TESTS

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**Summary:** The article presents the principle of operation, design method, and results of laboratory and simulation tests of a 24-pulse power network converter system with direct-voltage output, the concept and practical realisation of which was worked out within the framework of a research project financed by the State Committee for Scientific Research. The presented converter allows significant reduction of undesirable higher harmonics in the power network current, including the elimination of harmonics of an order 23 and 25. The 24-pulse nature of operation of the system is obtained using three sets of coupled three-phase power network reactors (CTR).

**Key words:**

*Power conditioning, Multi-pulse power network converters, Coupled three-phase power network reactors*

## 1. INTRODUCTION

Along with more and more popular converters realised with the aid of full-control semiconductor elements, such as power transistors and GTO thyristors, controlled using modulation techniques applied to pulse width, there is a possibility to build power-electronic converters which convert the energy of the alternate current into that of the direct current with the aid of a set of properly paired coupled reactors installed between the supply line and the semiconductor rectifier. Proper magnetic pairings, along with proper pairing of reactor windings make it possible to convert the three-phase voltage system of the supply line into the system with a larger number of phases without the use of transformers. At the same time, the power of the three-phase coupled reactors is several times lower than that of classical converter transformers. Minimisation of the deformation of the supply line current is obtained using a system of coupled power network reactors which increase the number of phases of the converter input voltage with the aid of diodes, or conventional thyristors. The coupled reactors play here a similar role to that of the converter transformers with a complex system of secondary windings, but the power of the reactors is several times smaller.

The project aimed at developing a design method for power-electronic converters, which convert alternate voltage into one-way voltage and are equipped with a system of three-phase coupled reactors securing consumption of the current having the form close to a sine curve. The project included simulation tests, along with the design, construction and laboratory tests of a model 2-kVA 24-pulse converter system. The realisation of the project has made it possible to formulate a more precise theory of and develop a design methodology for power-electronic converters used for converting the energy of the alternate current into that of the direct current. A significant feature of those converters is reduced consumption of the deformation power.

The basic concept of a 24-pulse converter bases on the application of three-phase coupled reactors which allow ge-

neration of four phase-shifted systems of three-phase voltages making the input parameters for four 6-pulse rectifiers. For the time being, examples published in the literature most often discuss the use of a similar 12-pulse system for doubling the numbers of input voltage phases in voltage inverters supplying induction machines. The literature does not provide a detailed analysis of operation of such systems, nor guides concerning its design algorithms. Therefore a fragment of the general theory of systems with coupled reactors was developed, which allowed the synthesis of systems with increased numbers of voltage phases.

The essential issues connected with the realisation of the above named research tasks included:

- Developing a mathematical model of the system and determining analytical and synthesizing relations that make the basis for formulation of a design procedure for a converter consisting of a system of three three-phase coupled reactors and four in-parallel paired rectifier bridges;
- Working out a simulation model and carrying out detailed simulation tests of the system to allow verification of the theoretical results and final formulation of the conditions to be met by a magnetic system of reactors and the set of properly configured power semiconductor elements;
- Experimental verification of the results of the theoretical analyses and simulation tests, complemented by the interpretation of the obtained results.

## 2. THEORETICAL ANALYSIS OF THE SYSTEM

### 2.1. Introduction

Being non-linear systems, power-electronic power network converters draw from the supply line the current whose waveform considerably diverges from a sine curve. In case of Q-pulse rectifiers, the supply currents include harmonics of orders of  $n_h$ , determined by the relation:

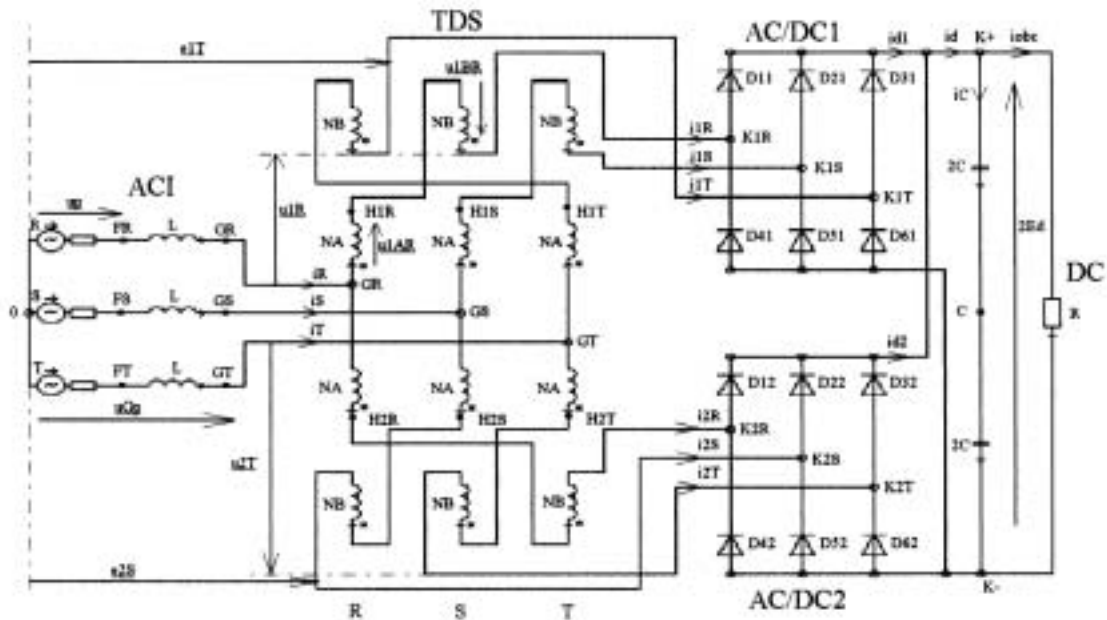


Fig. 1. Schematic diagram of 12-pulse diode rectifier with CTR system

$$n_h = k \cdot Q \pm 1, \quad \text{for } k = 1, 2, 3, \dots \quad (1)$$

These current harmonics, especially in the case of an autonomic supply line revealing relatively low short-circuit power, are the source of significant voltage deformations in the line. Designing multi-pulse rectifiers with minimised negative effect on the power network involves the use of expensive converter transformers with complex secondary winding connection systems. As a result, the reduction of the contribution of higher components in the power network current is paid by higher cost of the system. In classical designs of 12-pulse rectifiers, for instance, the supply circuit contains a transformer with two secondary windings, of which one has star connection while the other — delta connection, or, in large-power systems, two transformers with star-star connection or delta-star connection. Moreover, the parallel connection of the elementary converters requires the use of a 2-winding coupled reactor to compensate differences in instantaneous voltages recorded at the outputs of the two transformers. Refs. [3], [4], [8] present interesting solutions of the parallel connection of two three-phase diode converters which, loaded with a capacitive filter, convert alternate voltage into direct voltage using a three-phase coupled reactor to obtain two symmetrical phase voltages relatively shifted in phase by  $30^\circ$ . The basic system of the three-phase coupled reactor, also referred to as a harmonic blocking current transformer, makes use of the solution proposed by Meier, which makes it possible to eliminate current harmonics of an order of  $6k \pm 1$ , ( $k = 1, 2, 3, \dots$ ) in independent inverters supplying an induction motor [2, 6]. The present paper discusses the principle of operation of the coupled reactor and gives the method of determination of its limiting power capacity. The paper also develops a basic concept of a magnetically coupled reactor for the construction of a 24-pulse rectifier

with non-adjustable output voltage, supplied from a three-phase line via a system of three coupled three-phase power network reactors (CTR). When connected in the circuit instead of a converter transformer, those reactors improve waveforms of the currents drawn from the supply line, at the same time revealing relatively low power consumption compared to that of the converter. The present system, considerably reducing input current harmonics, is especially useful in cases of power supply from a low-voltage three-phase power network revealing relatively high short-circuit impedance and thus being prone to voltage deformations.

## 2.2. Three-phase coupled reactor (CTR)

A concept of a 24-pulse rectifier is based on a 12-pulse system proposed in [3] and [4]. In this context it is purposeful to briefly discuss the 12-pulse system first. Figure 1 presents a schematic diagram of the 12-pulse diode rectifier, loaded with a capacitance filter, with a three-phase coupled reactor (CTR). The operation of the reactor bases on an assumption that the reactor represents zero impedance for harmonic voltages of an order of  $12k \pm 1$ , ( $k = 0, 1, 2, \dots$ ) and infinitely high impedance for harmonics of an order of  $6k \pm 1$ , ( $k = 1, 2, 3, \dots$ ). The reactor consists of three separate magnetic cores, on which are wound up four windings ( $2 \times N_A + 2 \times N_B$ ) with flow directions shown in Figure 1. Proper selection of the transmission makes it possible to obtain two symmetric three-phase voltages, relatively phase-shifted by  $30^\circ$ , at the reactor output. Assuming that the conduction angles of the transformer diodes are equal to  $\pi$ , the input voltage of the reactor for a nominal current of the receiver has an ideal 12-step shape, which only reveals harmonics of an order of  $12k \pm 1$ , ( $k = 0, 1, 2, \dots$ ). That means that phase currents of the supply source are also close to an ideal 12-step shape with the same orders of harmonics.

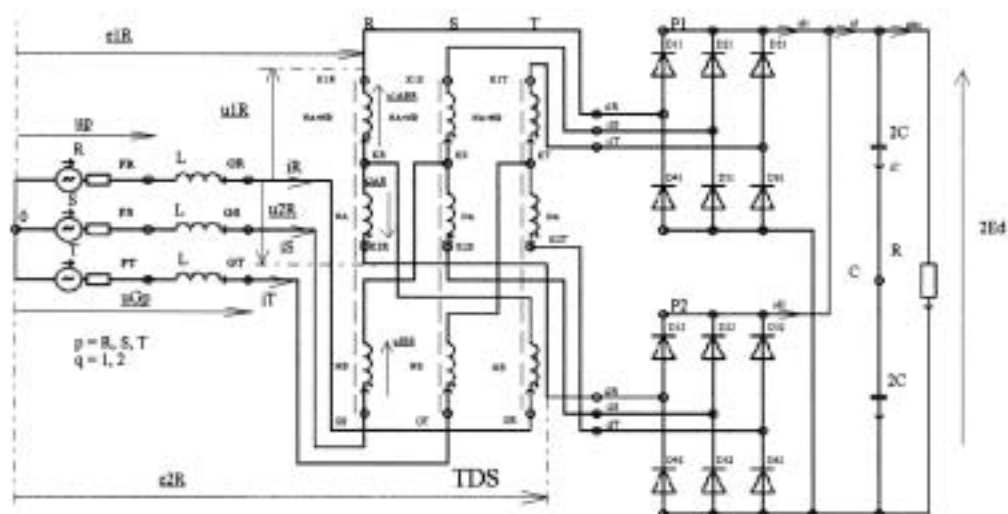


Fig. 2. Schematic diagram of 12-pulse diode rectifier with  $CTR\lambda$  coupled reactor system

### 2.3. The $\lambda$ version of CTR system windings

Figure 2 presents a schematic diagram of a 12-pulse diode rectifier making use of parallel operation of two three-phase bridge converters, in another design version of the three-phase coupled reactor ( $CTR\lambda$ ), different from that shown in Figure 1.

The reactors connected to the phase circuits of the supply source are needed for securing the conduction angle value equal to  $\pi$  in the rectifier diodes. The task of the reactors is to create a voltage spatial vector  $U_G$ , whose projections onto R,S,T axes take a sine shape for idling and a 12-step shape during supply voltage period T, at nominal load. The symmetry of  $U_G$  voltages directly results from the phase shift angle, equal to  $2\pi/12$ , between diode conduction states in the two bridges. Thus, the reactor system in the version shown in Figure 2 plays an identical role as that in the version from Figure 1. The correctness of winding connections in the  $CTR\lambda$  system version from Figure 2 directly results from the vector diagram of voltages, shown in Figure 3a, and symbolical presentation of geometrical winding locations, shown in Figure 3b.

## 3. 24-PULSE DIODE RECTIFIER

### 3.1. Description of the system

Figure 4 presents a schematic diagram of a 24-pulse non-adjustable rectifier supplied from a three-phase power network with the phase voltage  $u_p$  ( $p = R, S, T$ ). The input circuit of the converter comprises linear power network reactors  $L$ , a coupled three-phase power network reactor  $CTR2$  in  $\lambda$  version, mounted in series, and two in-parallel mounted coupled three-phase power network reactors  $CTR1$  and  $CTR3$ , in  $\lambda$  version as well. Input terminals of the reactor  $CTR2$  are connected via linear reactors  $L$  with the supply network terminals, while its output terminals are used for supplying reac-

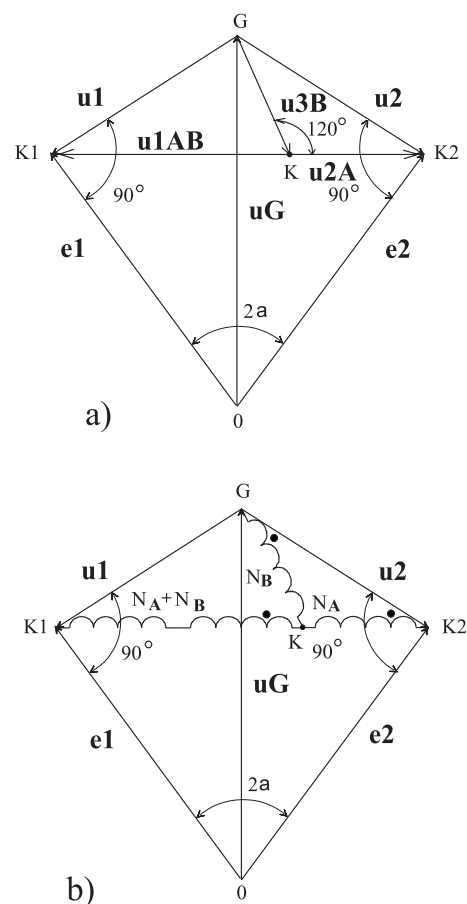


Fig. 3. Spatial voltage vectors of 12-pulse rectifier with  $CTR\lambda$  system (a) and symbolical presentation of geometrical winding locations (b)

tors  $CTR1$  and  $CTR3$ . Output terminals of the reactors  $CTR1$  and  $CTR3$ , in turn, are connected with phase limbs of four three-phase diode bridge systems. Direct-current terminals of all bridge systems are connected in parallel to the filtering capacitor having the capacitance  $C$ . The task of the set of the

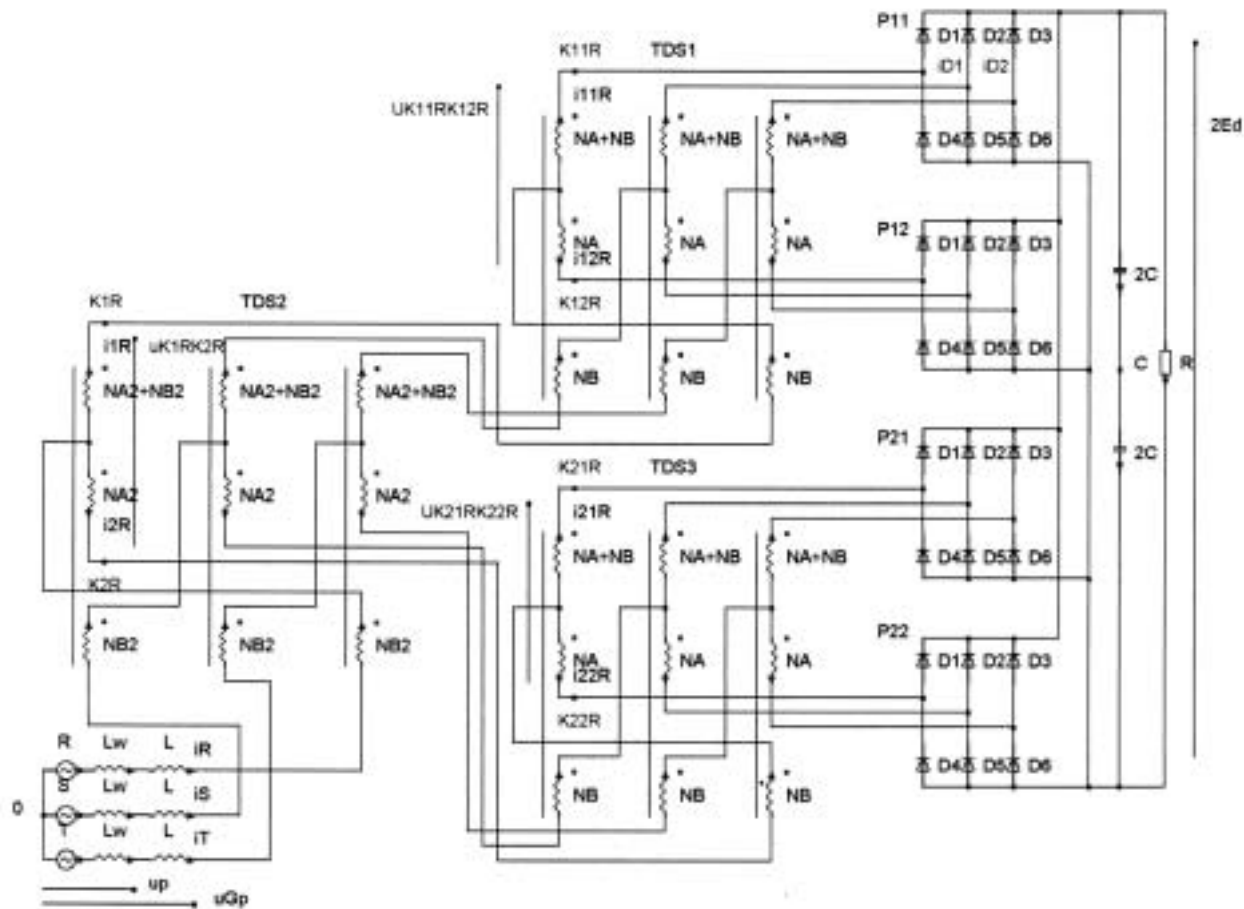


Fig. 4. Schematic diagram of 24-pulse non-adjustable rectifier with a system of CTR coupled reactors

coupled reactors is to generate three alternating voltages  $u_{Gp}$ , the waveforms of which take the sine shape when idling and the 24-step shape at load close to nominal.

Voltages  $u_{Gp}$ , measured with respect to the star point 0 of the input circuit, can be interpreted as the quantities created as a result of cyclic starts of the direct current voltage  $2E_d$ , via the valves of four bridges. A condition to be met to obtain 24-step waveforms of voltages  $u_{Gp}$  is for all diodes to conduct the current during half of the supply line voltage period. The symmetry of the 24-step voltages  $u_{Gp}$  results directly from the phase shift angle, equal to  $2\pi/24$ , between the conduction states of particular valves in the four bridges. Input terminals  $K_{mp}$  ( $m = 11, 12, 21, 22$ ) of each of the four three-phase bridge systems reveal symmetrical three-phase voltages having a 6-step shape.

Those four systems of three-phase voltage are relatively shifted by  $2\pi/24$ , thus creating, via systems CTR1 and CTR3, two 6-phase 12-step systems, displaced by  $2\pi/24$ . The system CTR2 converts it into one 12-phase 24-step system. Moreover, four systems of three-phase currents  $i_{mp}$  are added up in reactors CTR1, 2, 3 and are converted into one three-phase system of currents  $i_p$ , drawn from the supply line. The waveforms of those currents are very close to a sine curve. Power network reactors L additionally reduce, to a required level, higher-order harmonics of the currents  $i_p$ , generated by corresponding harmonics of the 24-step waveforms of three-phase voltages  $u_{Gp}$ .

Figure 5 presents a diagram of spatial vectors of the currents in the system, explaining the principle of creation of four three-phase supply systems with the aid of CTR1, 2, 3. The voltages induced on CTR2 windings with the numbers of turns  $N_{A2}$ ,  $N_{B2}$ ,  $2N_{A2}+N_{B2}$  compose a spatial vector of the supply network voltage. At the same time these voltages generate phase shifts. As a result, two vectors are obtained of three-phase voltages, shifted relatively by  $2\pi/24$ , which supply the systems CTR1, 3. In order to preserve the symmetry of the voltages supplying the diode rectifiers, the phase angle between spatial vectors of output voltages in CTR1, 3 must equal  $2\pi/12$ . This is simultaneously the condition for 24-pulse operation of the entire rectifying system.

The waveforms of voltages and magnetic flux referring to the 24-pulse rectifier with a system of coupled three-phase reactors CTR $\lambda$ , determined using a method given in [12], are shown in Figure 6.

### 3.2. System design method

According to the above presented discussion, the phase angle between spatial vectors of output voltages in systems CTR1, 2, 3 (Fig. 4) will depend directly on the turn number ratio ( $N_{B2}/N_{A2}$ ,  $N_B/N_A$ ) of corresponding windings in particular CTR systems. According to [13], the turn number ratios meeting the above condition are the following:

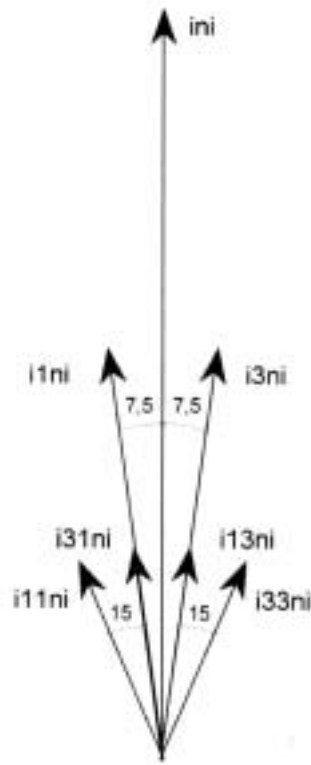


Fig. 5. Spatial vectors of CTR coupled three-phase power network reactor winding currents

$$\frac{N_{B2}}{N_{A2}} = \frac{\sin 7,5^\circ}{\sin(60^\circ - 7,5^\circ)} = 0,1645 \quad (2)$$

$$\frac{N_B}{N_A} = \frac{\sin 15^\circ}{\sin(60^\circ - 15^\circ)} = 0,366 \quad (3)$$

The idealised direct-current voltage at the system output can be calculated (acc. to [3], [4], [13]) from the following equation:

$$2E_{di} = \frac{1,504 \cdot \sqrt{2} \cdot U_N}{\sqrt{3}} = 1,228 \cdot U_N \quad (4)$$

where  $U_N$  is the rms value of the nominal line-to-line voltage in the supply network.

It is noteworthy (Fig. 4) that the output voltage  $2E_{di}$  is cyclically delivered, via diodes of four bridges, to terminals  $K_{qp}$  ( $q = 1,2$ ) of CTR2 reactors with number of turns  $2N_{A2} + N_{B2}$  for a time duration equal to  $1/24$  of the time period  $T$  of the supply network voltage. The similar situation is for the windings of CTR1,3 reactors with the number of turns  $2N_A + N_B$ . Therefore the numbers of turns  $2N_{A2} + N_{B2}$  and  $2N_A + N_B$  have to be selected in such a manner that the permissible values of fluxes through the cores of reactors CTR2 and CTR1,3 are not exceeded.

Hence, according to [9] and [12]:

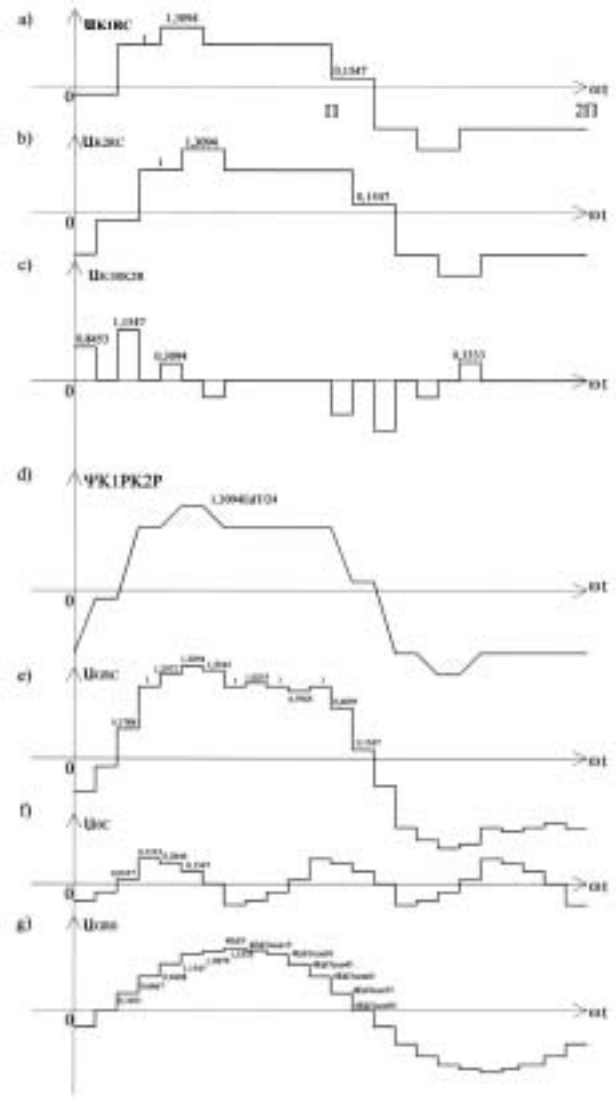


Fig. 6. Waveforms of voltages and magnetic flux, referring to the system shown in Fig. 4

$$\Psi_{Kqi} = 1,3094 \cdot E_{di} \cdot \frac{T}{24} \quad (5)$$

$$\Psi_{Kmpi} = 2 \cdot E_{di} \cdot \frac{T}{24} \quad (6)$$

The approximate value of the nominal direct-current voltage  $2E_{dN}$  that takes into account the nominal efficiency coefficient  $\eta$  ( $\eta \approx 0,97$ ) of the system is given by the relation:

$$2E_{dN} \approx 2E_{di} \cdot \eta \cdot \sqrt{1 - U_{KOZ}^2} \quad (7)$$

where  $U_{KOZ}$  is the relative short-circuit voltage of the line ( $L_w$  – short-circuit reactance of the generator) and of the reactors  $L$ , measured according to vector  $u_{Gp}$  (Fig. 4.).

This voltage directly depends on the inductance  $L$  and can be determined from the relation:

$$U_{KOZ} = \frac{\omega L \cdot I_{pN}}{U_N \cdot \sqrt{3}} \quad (8)$$

where  $I_{pN}$  is the nominal *rms* value of the phase current drawn from the power network supplying the system.

It has resulted from further test that the selection of  $U_{KOZ}$  at the approximate level of 10% secures the reduction of current harmonics in the line down to acceptable levels. In those circumstances the average value of the nominal direct current  $i_{dN}$  can be calculated using the assumed nominal power of the direct-current circuit:

$$i_{dN} = \frac{P_{dN}}{2 \cdot E_{dN}} \quad (9)$$

The reactor windings with numbers of turns  $N_{B2}$  and the windings of the power network reactor  $L$  should be selected in proportion to the current  $I_{pN}$ , while the windings with numbers of turns  $N_{A2}$ ,  $N_{A2}+N_{B2}$ ,  $N_B$  – in proportion to the current  $I_{qpN}$ , and the windings with the numbers of turns  $N_A$ ,  $N_A+N_B$  – in proportion to the current  $I_{mpN}$ .

The CTR1 and CTR3 reactors are to be designed following the principles formulated for 12-pulse systems [3], [4], [6], and taking into account half of the power in the direct-current circuit, and the direct-current voltage given by formula (4). Iron cores of CTR reactors can be most easily made as nine separate one-phase units.

The limiting power of the 24-pulse rectifier magnetic system can be expressed as the sum of limiting powers of particular components in CTR reactors. For the CTR2 system, according to [13] and assuming  $Q=24$  ( $Q$  – number of system's pulses), we arrive at:

$$U_{Gm} = 1,329E_d \quad (10)$$

Neglecting power losses, the ideal rectified voltage can be expressed using a relation similar to (4):

$$2E_{di} = (2/1,329)U_{Gm} = 1,504U_{Gm} \quad (11)$$

Taking into consideration relation (10) and relations presented in [13], as well as the fact that for the CTR2 system the angle  $\alpha=7,5^\circ$ , the following formula for power can be written down:

$$P_d = 2E_d I_d = 3 \cdot \frac{1,329 E_d}{\sqrt{2}} (I_{1,1} + I_{1,2}) \cos 7,5^\circ \quad (12)$$

where  $I_{1,1}$  and  $I_{1,2}$  stand for *rms* values of basic harmonics of the currents in windings of CTR2 reactors. Assuming  $I_{1,1} = I_{1,2} = I_1$  from [13], we arrive at:

$$I_1 = 0,358 I_d \quad (13)$$

The *rms* value of the current drawn from the network is equal to the vector sum of currents  $I_{1,1}$  and  $I_{1,2}$ :

$$I_s = 2I_1 \cos 7,5^\circ = 0,7099 I_d \quad (14)$$

According to [13], the limiting power of the CTR2 reactor can be expressed as:

$$S_{CTR\lambda 2} = (1,5\pi \frac{\sqrt{2}}{T}) [\Psi_{K1K2max} I_1 + \frac{N_B}{2N_A + N_B} \cdot \Psi_{K1K2max} I_S] \quad (15)$$

where  $I_S$  is the phase current drawn from the supply source.

Having placed  $\Psi_{K1K2max} = 1,091 E_d \cdot 10^{-3}$  (from Fig. 6), as well as  $I_1 = 0,358 I_d$  (formula 13) and  $I_S = 0,7099 I_d$  (formula 14), in the right-hand side of formula (15) we arrive at:

$$S_{CTR\lambda 2} = 1,5\pi \frac{\sqrt{2}}{20 \cdot 10^{-3}} [1,091 E_d 10^{-3} (0,358 I_d + \frac{0,1645}{2+0,1645} \cdot 0,7099 I_d)] = 0,0748 (2E_d I_d) \quad (16)$$

Finally:

$$\frac{S_{CTR\lambda 2}}{P_d} = 7,48\% \quad (17)$$

For the coupled reactor systems CTR1 and CTR3, when calculating the limiting power one should take into account half of the power at the direct-current side, the rectified voltage given by formula (10), the angle  $\alpha = 15^\circ$ , and flux maximum value shown in [13]. According to formula (12) adapted for the current case, the below presented relation for power:

$$0,5 \cdot P_d = E_d I_d = 3 \cdot \frac{1,329 E_d}{\sqrt{2}} (I_{1,1} + I_{1,2}) \cos 15^\circ \quad (18)$$

allows determination of the following values of currents:

$$I_1 = 0,1836 I_d \quad (19)$$

$$I_s = 2I_1 \cos 15^\circ = 0,3547 I_d \quad (20)$$

Making use of formula (15) for the limiting power, we arrive at:

$$S_{CTR\lambda 1,3} = 1,5\pi \frac{\sqrt{2}}{20 \cdot 10^{-3}} [1,666 E_d 10^{-3} (0,3703 I_d + \frac{0,366}{2+0,366} \cdot 0,715 I_d)] = 0,1335 (2E_d I_d) \quad (21)$$

Table 1. The relations between system's pulses number of multi-pulse converter and total limiting power of CTR system.

| System's pulses number | Total limiting power |
|------------------------|----------------------|
| 12                     | 13,35% $P_d$         |
| 18                     | 16,51% $P_d$         |
| 24                     | 20,84% $P_d$         |

This relation can be written down in the following way:

$$\frac{S_{CTR\lambda 1,3}}{P_d} = 6,68\% \quad (22)$$

Finally, the total limiting power of the 24-pulse converter magnetic system is given by the relation:

$$\begin{aligned} S_{CTR\lambda 2} + S_{CTR\lambda 1} + S_{CTR\lambda 3} = \\ = (7,48\% + 6,68\% + 6,68\%) \cdot P_d = 20,84\% \cdot P_d \end{aligned} \quad (23)$$

On the basis above-mentioned method calculated relations between system's pulses number of multi-pulse converter and total limiting power of CTR system are presented in Table 1.

### 3.3. Simulation tests results

A simulation model was worked out of a 24-pulse converter, comprising four 6-valve bridge systems supplied from a three-phase power network via a system of three coupled three-phase reactors. The simulation model was designed using the TCAD6.2a package and the simulation tests were carried out with the aid of the same programme. A series of simulation tests confirmed correct behaviour of the model and allowed determination of the ranges of parameters securing numerical stability and good conditioning of the model equations. Another series of simulation tests aimed at the determination of static and dynamic characteristics of the system. Spectral analysis of the obtained waveforms was also carried out. It was found that certain simulated dynamic characteristics of the examined converter are also sufficient for more severe conditions required by asynchronous drives with fast control. The results of those tests determined possibilities of the use of the tested converter in alternating and direct current driving systems (cooperation with voltage or current inverter), and made the basis for verification of the design methods developed for a given class of converters. The simulation test also allowed the analysis of the effect of supply line parameters, including line impedance, on the operation of the system. Generally, the computer tests, carried out with the simulation model, revealed good agreement of the recorded characteristics of the 24-pulse rectifier system with those expected from the theory. The results of those tests could be used to the full when preparing a real model.

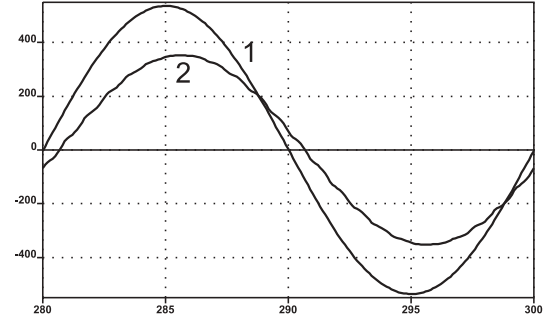


Fig.7. Waveforms of power network phase voltage  $u_R$  (1) and current  $i_R$  (2)

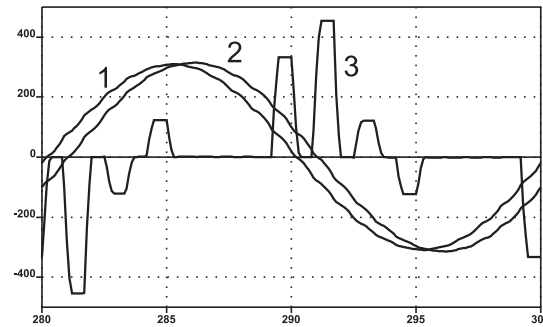


Fig. 8. Waveforms of currents  $i_{1R}$ (1) and  $i_{2R}$ (2), and voltage  $u_{K1RK2R}$  (3) in CTR2 windings

The simulation tests were carried out for the system with the following parameters:

$U_N = 380V$  – nominal line-to-line voltage

$P_{dN} = 2kW$  – nominal power of direct current

$U_{K0Z} = 11\%$  – percentage of short-circuit voltage of power network reactor

$J = 2,5A/mm$  – current density in CTR windings

$B_m = 1,5T$  – maximum induction in magnetic cores

$S_{Fe} = 0,0009m^2$  – core column cross section

$N_A = 195$  – number of turns in  $N_A$  winding

$N_B = 71$  – number of turns in  $N_B$  winding

$N_{A2} = 138$  – number of turns in  $N_{A2}$  winding

$N_{B2} = 23$  – number of turns in  $N_{B2}$  winding

$Q = 24$  – number of converter pulses

$2\delta = 15^\circ$  – shift angle of input current vectors in diode bridges

$L = 30,9mH$  – inductance of power network reactor

$L_w = 1mH$  – inductance of supply line phase

$C = 11,2mF$  – capacitance of filtering capacitor

$R = 100\Omega$  – load resistance

These parameters were determined using the above-presented mathematical relations. The results of the simulation tests have mainly the form of waveforms of characteristic currents and voltages. Time axes are scaled in milliseconds.

Figure 7 presents the waveforms of the voltage  $u_R$  and the current  $i_R$  in the supply line, at the nominal load of the rectifier. The presented curves reveal shapes slightly different from a sine curve, preserving the relative phase shift angle close to zero.

Figure 8 shows the waveforms of the output currents leaving the CTR2 system and the voltages at its main windings. Noticeable is the zero-voltage average value per period, as well as correct relations between maximum currents.

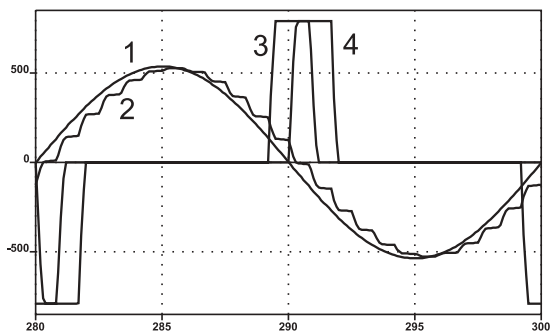


Fig. 9. Waveforms of power network voltages  $u_R(1)$  and  $u_{GR}(2)$ , and voltages  $u_{K11RK12R}(3)$  and  $u_{K21RK22R}(4)$  at main windings of CTR1 and CTR3 systems.

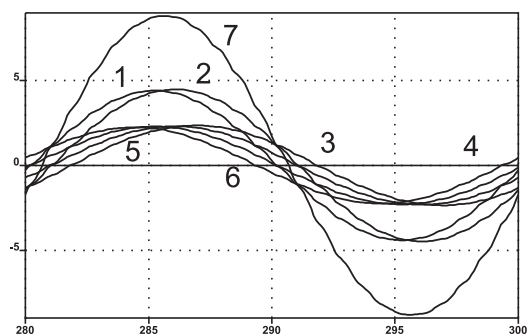


Fig.10. Waveforms of currents  $i_{1R}(1)$ ,  $i_{2R}(2)$  in CTR2 windings, currents  $i_{11R}(3)$ ,  $i_{12R}(4)$  in CTR1 windings, and currents  $i_{21R}(5)$ ,  $i_{22R}(6)$  in CTR3 windings, on the background of the waveform of power network current  $i_R(7)$

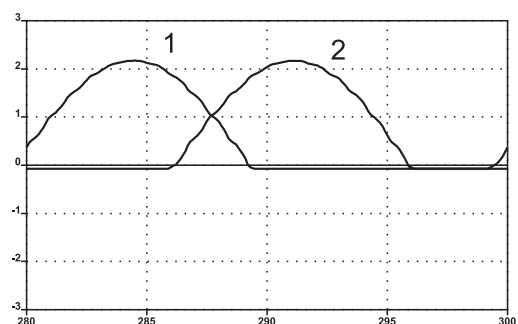


Fig.11. Waveforms of currents in selected diodes  $D1-i_{D1}(1)$  and  $D2-i_{D2}(2)$  of non-adjustable converter P11

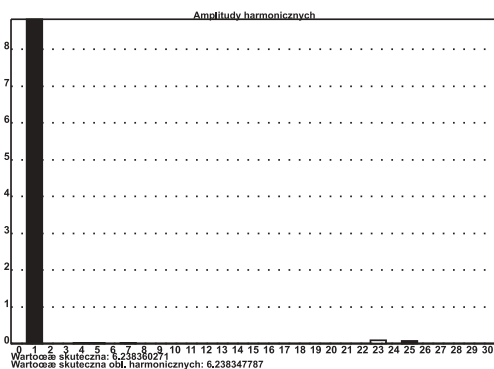


Fig.12. Spectral analysis of the waveform of supply line current  $i_R$

Figure 9 shows the waveforms of the voltage at the CTR1 and CTR3 main windings, on the background of voltages  $u_R$  and  $u_{GR}$ . A relatively low average half-period value of this voltage is decisive of low power of CTR magnetic elements. Noteworthy is the 24-step waveform of input voltage  $u_{GR}$ , which testifies to correct, transformer-like operation of the system of CTR reactors.

Figure 10 presents the waveforms of power network current  $i_R$ , as well as the currents in windings CTR2- $i_{1R}$ ,  $i_{2R}$ , CTR1- $i_{11R}$ ,  $i_{12R}$  and CTR3- $i_{21R}$ ,  $i_{22R}$ . The waveforms of these currents reveal shapes similar to that of a sine curve. Current  $i_{1R}$  is ahead of current  $i_{2R}$  by  $15^\circ$  while current  $i_{11R}$  is ahead of  $i_{12R}$  by  $30^\circ$ . Similarly, current  $i_{21R}$  is ahead of current  $i_{22R}$  by  $30^\circ$ . The above relations, along with the fact that the pairs of currents:  $i_{1R}$  and  $i_{21a}$ , and  $i_{2R}$  and  $i_{12R}$ , are in phase, make it possible to obtain the required phase shift of  $15^\circ$  between the four three-phase systems supplying the bridge systems.

Figure 11 shows the waveforms of the currents in selected diodes of the non-adjustable converter P11. Noteworthy is a characteristic, close to  $\pi$ , conduction angle of each connector. The shapes of connector currents, revealing the 24-step form, and their conduction times depend on inductance  $L$ , which was confirmed by detailed studies. Figure 12 shows the spectral analysis of the current in the line supplying the 24-pulse converter. Of the highest significance is the fact that higher harmonics, of orders of 17, 19, are not practically recorded, while the harmonics of orders of 5, 7 and 23, 25 are significantly reduced.

### 3.4. Results of laboratory tests

Based on the above-presented mathematical relations, a series of parameters was calculated to prepare a laboratory model revealing parameters given in the previous Chapter. The results of the tests performed with this model are presented in the figures below in the form of waveforms of selected variables. The laboratory tests were performed in the Power Electronics Laboratory, Gdynia Maritime University.

Figure 13 shows voltage and current oscillograms in the line supplying the 24-pulse converter, working in nominal load conditions. Noteworthy is relatively small deformation of the line current. The fact that the oscillogram of the phase voltage in the supply network does not reveal deformations confirms correct operation of the model system in nominal load conditions. When the voltage waveform  $u_{Gp0}$  (see Figure 4) changes shape from a 24-step curve at overload to a sine curve at idling, the deformation components of voltage  $u_{Gp0}$  and power network currents  $i_p$  decrease. A slight phase shift, visible in Figure 13, between the oscillograms of voltage and supply network current corresponds to the angle  $\varphi$  approximately equal to  $10.8^\circ$ , which returns the power coefficient at the level of about 98%. This result is in general agreement with the theoretical considerations and confirms high power qualities of the system. At the same time, the

relation:  $\cos\varphi_1 = \sqrt{1 - \sin^2\varphi_1} = \sqrt{1 - u_{K0Z}^2}$ , allows the assessment that in the real system the relative nominal voltage of the reactor  $L$  is approximately equal to 16%, which is slightly higher than the assumed value.



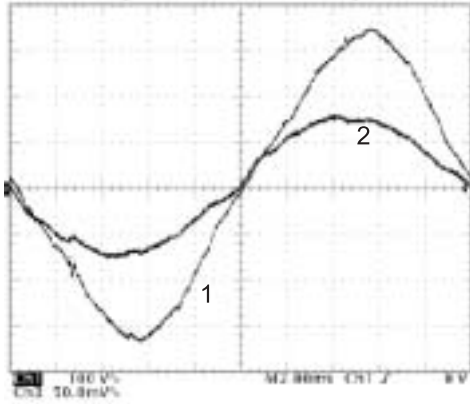


Fig.13. Oscillograms of supply network phase voltage  $u_R(1)$  and current  $i_R(2)$

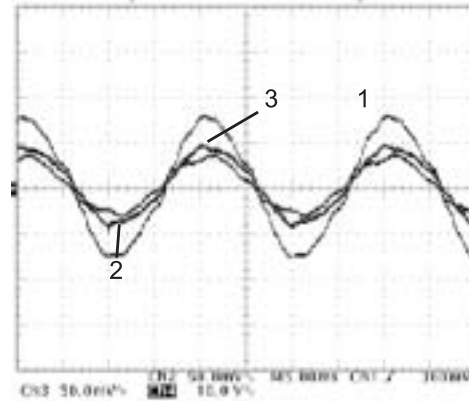


Fig.14. Oscillograms of power network current  $i_R(1)$  and CTR2 winding currents:  $i_{1R}(2)$ ,  $i_{2R}(3)$

Figure 14 shows the waveforms of the power network current  $i_R$  and CTR2 winding currents –  $i_{1R}$ ,  $i_{2R}$  (marked in Figure 4). Relatively small differences in shapes of the elementary currents are caused by slight asymmetry of reactor windings in the CTR2 system. The relative phase shift of these currents confirms the assumed sine shapes of alternating currents, adopted when developing theoretical current relations.

Figure 15 shows the oscillograms of currents in selected diodes D1 and D2 of converter P11 (Figure 4), whose conduction angles are close to  $\pi$  and phase shifts between the currents are very close to  $120^\circ$ el. Like in previous case, the waveforms obtained from simulations are very similar to corresponding curves recorded for the real model.

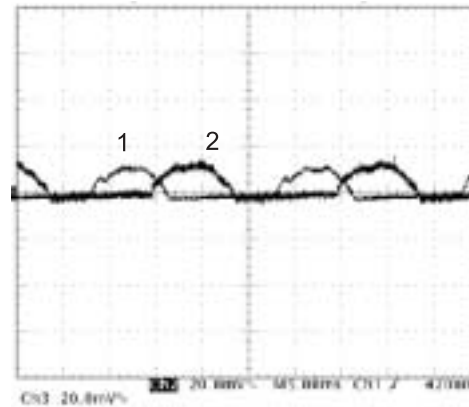


Fig.15. Oscillograms of diode currents  $i_{D1}(1)$ ,  $i_{D2}(2)$  of non-adjustable rectifier P11

Figure 16 shows mutual relations between the waveforms of the currents supplying two, out of four, bridge systems (marked P11, P21 in Figure 4). Here also – slight differences in amplitudes of the elementary currents are caused by slight asymmetry of reactor windings in CTR1 system. Figure 17 presents a frequency spectrum of the current drawn from the supply network, with the percentage values of higher harmonics related to the basic harmonic. Calculated from formula

$$W_{hl} = \frac{1}{I_1} \sqrt{\sum_{n=1}^{\infty} I_{hn}^2} \cdot 100\% , \text{ THD coefficient is equal to } 4.88\% ,$$

which is considered very good. Moreover, Figure 17 reveals visible reduction of higher harmonics of orders of 5, 7, 11, 13, 17, 19, 23, and 25. The harmonic components of orders 23 and 25, which are to be expected in the 24-pulse system, will increase with the load increase. The harmonics of orders of 5, 7, 11, 13, 17, 19, which should not exist in an ideal case, are generated by the harmonics of corresponding orders existing in the power network voltage. If the power network voltage included the harmonic of an order of 5 at the approximate level of 1.8% during the measurements, then for a relative nominal short-circuit voltage  $u_{K0Z}$  equal to 10%, for instance, this harmonic component of the power network voltage would generate the current of the harmonic of the order of 5 at the level of about 3.6%. The power network current deformation component tends to decrease from its maximum value at nominal conditions to zero at idling. The presented oscillograms were recorded using the oscilloscope made by FLUKE.

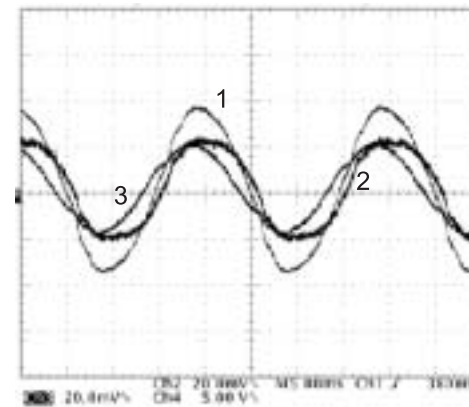


Fig. 16. Oscillograms of CTR1 winding currents:  $i_{1R}(1)$ ,  $i_{11R}(2)$ ,  $i_{12R}(3)$  for nominal converter load

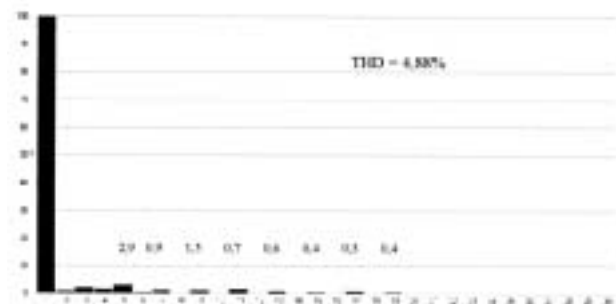


Fig. 17. Spectral analysis of supply line current in the examined converter

The presented oscillograms reveal that the supply source is affected by frequent disturbances, which lead to temporary deformations of the supply network voltage. However, the results of the experimental tests, shown in Figs. 13–17, justify a conclusion that the system works correctly, and that the obtained waveforms are sufficiently close to the theoretical curves.

#### 4. CONCLUSIONS

The presented system of a 24-pulse rectifier can be used in cases when the output voltage is not adjusted and the supply is drawn from a three-phase low-voltage power network. The range of application of such a system extends to the levels of power usually taken directly from the three-phase low-voltage network. The simplicity of the system, along with resulting reliability and ability to use power network reactors optimally selected to the requirements concerning permissible negative effects of the action of the system on the supply network, decide on wide range of possible applications of the system. Depending on the type of a local supply network, various levels of contribution of higher harmonics ( $W_h$  coefficient) generated by systems supplied from this network are permitted. Rigorous requirements concern the supply line voltage deformations defined by  $W_{hU}$  equal to 5% and referring, for instance, to the ship supply network, while  $W_{hU}$  at the level of 7% is recorded in local inland networks. From the point of view of the system design, of high significance is the parameter concerning the short-circuit power of the network, defined as the short-circuit reactance. This parameter makes it possible to determine the approximate inductance of the network, which will match the inductance of the network reactors  $L$  in the converter system.

In the case, when resonance conditions for a three-phase supply network are known, a rectifier system with a number of pulses  $Q$  should be selected for which higher harmonics of the current with resonance frequencies are avoided. Special care should be taken in cases of power networks with capacitor systems, without reactors, used for compensating reactive component of the current. In practice, it should be taken into account during the cooperation of the multi-pulse rectifier system with the local power network that the higher order harmonics, already existing in the power network voltages due to operation of other devices, generate currents of the same frequency, which add to the harmonics of the current drawn by the examined rectifier.

The presented considerations allow the formulation of the following conclusions:

- The analysis of the waveforms of characteristic voltages and currents of the examined system confirms the correctness of its operation and design principles
- The effect of the system on the supply network within the range of harmonic of orders of 23 and 25 is extremely reduced
- The system reveals high efficiency and power coefficient nearing one
- The construction cost of the prototype is low due to low powers of the magnetic elements

- Noteworthy is the simplicity and high reliability of the system
- The range of application seems to be wide, due to more and more frequent use of converter drives, which require more advanced supply sources.

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