A multi-pulse diode rectifier with a coupled three-phase reactor and additional small shunt active power filter

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Keywords

Active power filters, coupled three-phase power network reactors, local power network, multi-pulse power network converters, power conditioning.

Abstract

The article presents the principle of operation and results of laboratory and simulation tests of a multi-pulse power network converter systems with direct-current voltage output, mating with shunt active power filter (APF). The discussed systems allow for significant reduction of undesirable higher harmonics in the power network current, including the elimination of harmonics of an order of 23 and 25, especially in the local power network supply conditions. The multi-pulse nature of operation of the system is obtained using set of coupled three-phase power network reactors (CTR).

System description

The project is concerned with a current topic of power-electronic conversion of the alternate current power drawn from a supply line, without negative effect of the converter on this line [4]. Along with more and more popular converters realised with the aid of full-control semiconductor elements, such as power transistors and GTO thyristors, controlled by 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 and proper pairing of reactor windings makes 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 supply line current deformation is obtained by using a system of coupled power network reactors, the task of which is to 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 revealing a complicated system of secondary windings; however the power of the reactors is several times smaller. To improve the system power factor and THD coefficient, the small shunt active power filter was implemented by using a three-phase voltage-source IGBT inverter. The filter was also applied to the multi-pulse converter with CTR. The harmonic content, and reactive power absorption of described converter system are sagnificantly reduced by both CTR and shunt active filter. This shunt active power filter is composed of two distinct elements - the PWM converter (power circuit) and the

active filter controller. In order to reproduce accurately the compensating currents, the PWM converter should have a high switching rate. Normally, $f_{PWM} > 10f_{hmax}$, where f_{hmax} represents the frequency of the highest load current harmonic to be compensated. Both voltage-source (VSI) [1] and current-source (CSI) inverters can be used to implement a shunt active filter. Although they are similar to the PWM inverters used for ac motor drives, unlike the PWM inverters for shunt active filters, which must behave as a non-sinusoidal current source, almost all shunt active filters in commercial operation use voltage-source inverters. All experimental results presented in this work were obtained from a prototype realized with a VSI. Fig.1a shows the basic configuration of a shunt active filter [8], [9]. It comprises a voltage-source inverter (VSI) controlled by using Space Vector PWM. The control algorithm implemented in the shunt active filter controller determines the compensation characteristics of the shunt active filter. The controller which has been applied realizes almost instantaneous control [8], [9]. The shunt active filter operates in a closed-loop manner, sensing continuously the load current $\mathbf{i}_L$ and calculating the instantaneous values of the compensating current reference $\mathbf{i}^*_k$ for the PWM converter. For this purpose, the predictive instantnaneous power based calculator of reference current is utilized. The current is then controlled using very effective model based predictive current controller. These algorithms are supported by sophisticated estimator and predictor of distorted and unbalanced grid voltage [8]. In consequence, the controller provides supply voltage sensorless operation with filtering effectiveness limited only by circuit parameters of the shunt active filter. In an ideal case, the PWM converter of the shunt active filter can be considered as a linear power amplifier, where the compensating current $\mathbf{i}_k$ tracks strictly its reference $\mathbf{i}^*_k$.
Fig.1b presents a basic concept of a 12-pulse converter, in which the use of three-phase coupled reactors with shunt active filter allows for generation of two phase-shifted systems of three-phase voltages making the input parameters for two 6-pulse rectifiers. For the time being, examples discussed in the literature mostly apply similar 12-pulse system, however with no active filters for doubling the numbers of input voltage phases in voltage inverters supplying induction machines. Moreover, the literature has not yet provided either detailed analysis concerned with operation of such a system, or guides concerning its design algorithms. Unlikely previously discussed examples, this project included the analysis, which further constituted the basis for designing the 12-pulse system and allowed for analyzing the effect of supply line parameters, including its impedance, on the operation of the system. The researchers also developed a fragment of the general theory of improved systems with coupled reactors, which allowed synthesis of systems with increased numbers of voltage phases. Simulation tests were carried out to examine the possibility of the use of the system as a supply source in intermediate frequency converters for voltage inverters.

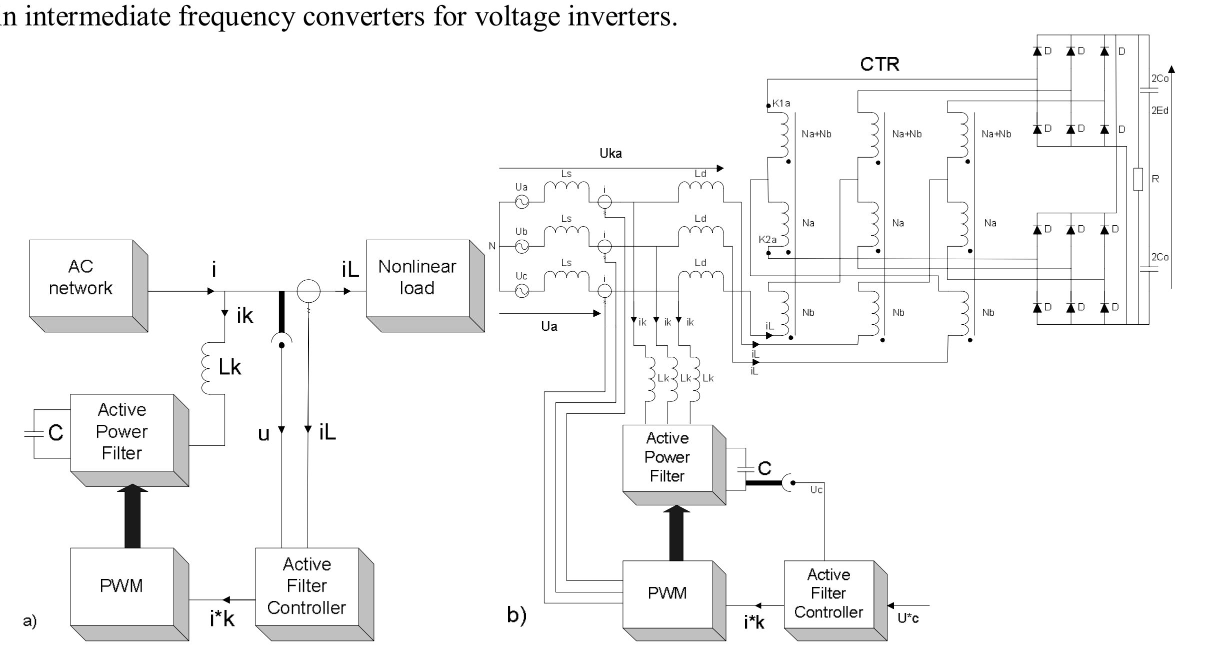


Fig.1. Basic configuration of the shunt active filter (a) and schematic diagram of 12-pulse diode rectifier with CTR coupled reactor system and shunt active power filter (b).
The methods for described system examination included theoretical analysis, simulation tests and model tests of a real converter containing two 6-valve bridge systems supplied from a three-phase

power network via a system of shunt active filter with coupled three-phase power network reactors. As it was expected, the currents drawn from the supply line had almost a sine form, of course not typical form of classical 12-pulse rectifiers, realised using three-phase converters. The test results not only can be used for verification of the developed design algorithms for the examined class of converters, they also allow for studying possibilities of application of the examined converter in the direct and alternate current driving systems. Because of the requirement of high reliability level they can be used especially in the marine applications.

The overall project aimed at developing a design method for power-electronic converters that would convert alternate voltage into one-way voltage, and would be equipped with a system of three-phase coupled reactors having the form close to a sine curve, which secure consumption of the current. The project included simulation and laboratory tests, for which a laboratory models of a 2-kVa 12-pulse and 24-pulse converters systems with shunt active filter were designed and constructed. 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 these converters is reduced consumption of the deformation power.

The essential issues associated with the realisation of the above indicated research tasks included:

- Developing a mathematical model of the system and determining analytical and synthesizing relations that allow formulation of a design procedure for a converter which would consist of a system of three-phase coupled reactors, two in-parallel paired rectifier bridges and shunt active power filter
- Working out a simulation model and carrying our detailed simulation tests of the system, to create the basis for 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 analysis and simulation tests, complemented by the interpretation of the obtained results.

The 12-pulse diode rectifier presented in the Fig.1b is supplied from a three-phase power network with the phase voltage U_n (n=a,b,c). The input circuit of the converter comprises linear power network reactors Ls, Ld, shunt active filter and coupled three-phase power network reactor CTR. Input terminals of the reactor CTR are connected with the supply network terminals through linear reactors Ls, Ld. Output terminals of the reactor CTR are, in turn, connected with phase limbs of two three-phase diode bridge systems. Direct-current terminals of all bridge systems are connected in parallel to the filtering capacitor having the capacitance Co. The task of the set of the coupled reactors is to generate three alternating voltages U_{kn}, of which waveforms take the sine shape when idling and the 12-step shape at load close to nominal. Voltages U_{kn}, measured with respect to the input circuit star point N, can be interpreted as the quantities created in result of cyclic starts of the direct current voltage $2E_d$, via the valves of two bridges. Required condition to be met in order to obtain 12-step waveforms of voltages U_{kn} is that all diodes must conduct the current during half of the supply line voltage period. The symmetry of the 12-step voltages U_{kn} results directly from the phase shift angle, equal to $2\pi/12$, between the conduction states of particular valves in the two bridges. Input terminals K_{mn} (m=1,3) of each of the two three-phase bridge systems reveal symmetrical three-phase voltages of the 6-step shape. hose two systems of three-phase voltage are relatively shifted by $2\pi/12$, and therefore creating, via systems CTR, one 6-phase system. Thus, it can be assumed that due to a CTR, the three-phase line voltage has been transformed into 6-phase voltage. Moreover, two systems of three-phase currents i_{mn} are added up in reactors CTR and are converted into one three-phase system of currents i_n, drawn from the supply line. The waveforms of these currents are very close to a sine curve. Power network reactors L_d and shunt active filter additionally reduce, to a required level, higher-order harmonics of the currents i_n, generated by corresponding harmonics of the 12-step waveforms of three-phase voltages U_{kn}.

Selected results of the system

The Figure 2 presents the selected results of simulation and laboratory experiments - the results of simulation experiments concerned with 2kW 6-pulse converter with power active filter (a), the results of simulation experiments concerned 2kW 12-pulse converter with CTR system and power active filter (b) as well as the results of laboratory experiments on 2kW 12-pulse converter only with CTR system (c). The most important in Fig (b) is visibly small power of implemented shunt active filter (small value of current i_k). In the Fig (c) is remarkable that the distortion of the net current i_a is larger than in the case of net current i, illustrated in figure (b).

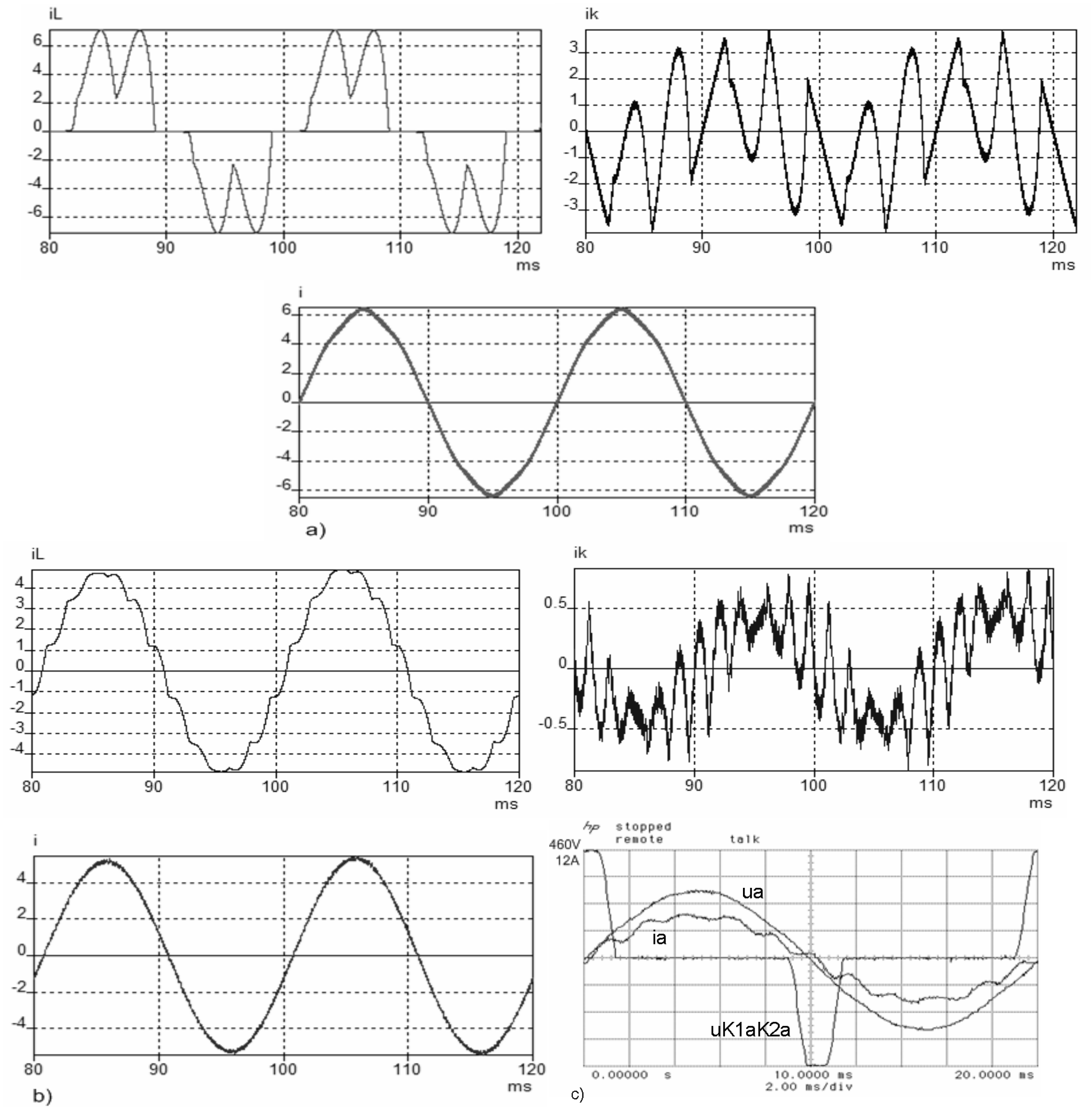


Fig.2. The results of simulation experiments concerned with 2kW 6-pulse converter with power active filter (a), the results of simulation experiments concerned 2kW 12-pulse converter with CTR system and power active filter (b) as well as the results of laboratory experiments on 2kW 12-pulse converter only with CTR system (c).

The described 12-pulse rectifier served as base for a concept of a 24-pulse rectifier, which was proposed in [5]. Fig.3 shows a schematic diagram of a 24-pulse non-adjustable rectifier supplied from a three-phase power network with the phase voltage U_n (n=a,b,c). Simulation and laboratory tests results for 2kW 24-pulse converter system are presented below.

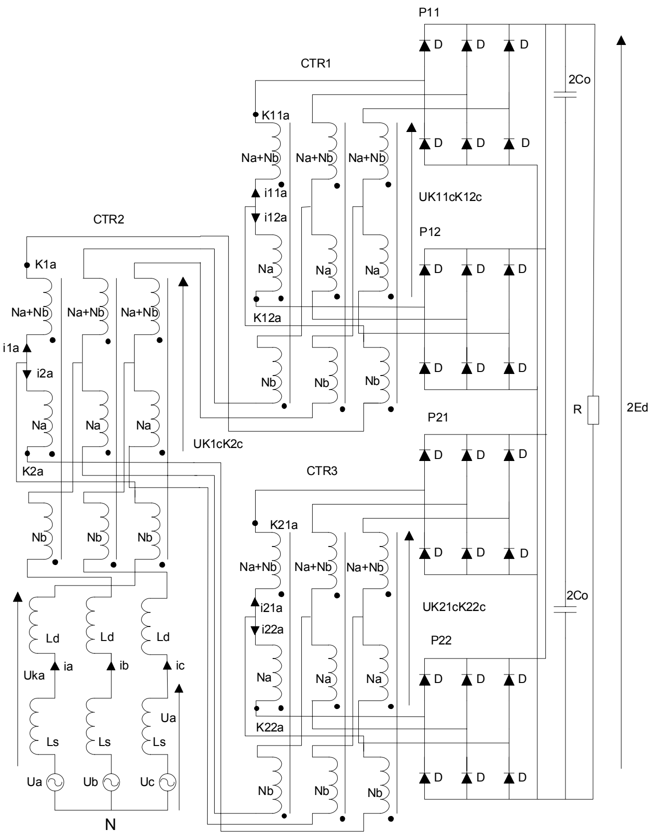


Fig.3. Schematic diagram of 24-pulse non-adjustable rectifier with a system of CTR coupled reactors

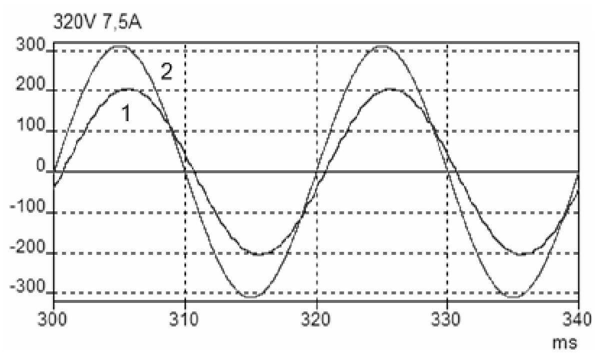


Fig.4. Waveforms of power network phase voltage u_a(2) and current i_a(1).

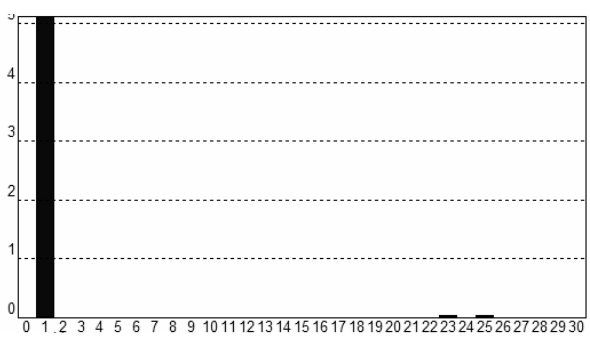


Fig.5. Spectral analysis of the waveform of supply line current i_a.

Fig.4 presents the waveforms of the voltage u_a and the current i_a in the supply line, at the nominal load of the mentioned above rectifier. The curves reveal shapes slightly different from a sine curve, preserving the relative phase shift angle close to zero. Fig.5 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. Fig.6 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. That the oscillogram of the phase voltage in the supply network does not reveal deformations only confirms correct operation of the model system under nominal load conditions. Fig.7 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 $THD_I = \frac{1}{I_1}\sqrt{\sum_{n\rangle 1}^{\infty} I_{hn}^2}\cdot 100\%$, THD_I coefficient is equal to 4,88%, which is considered to be very good.

Moreover, Fig.7 reveals visible reduction of higher harmonics of orders of 5, 7, 11, 13, 17, 19, 23, and 25.

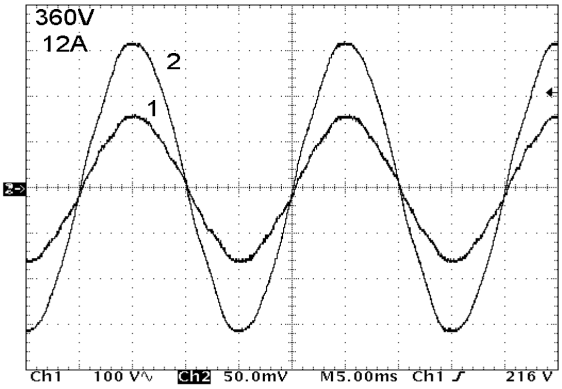


Fig.6. Oscillograms of supply network phase voltage $u_a(2)$ and current $i_a(1)$.

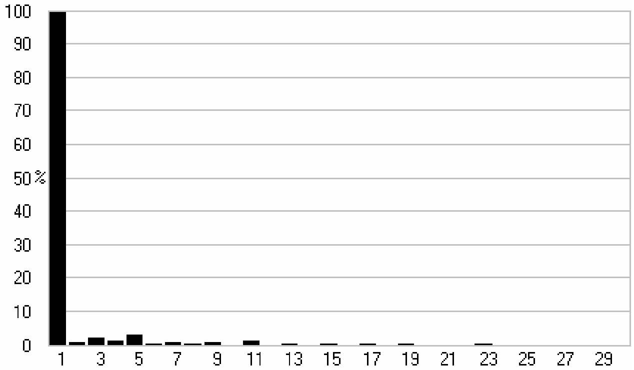
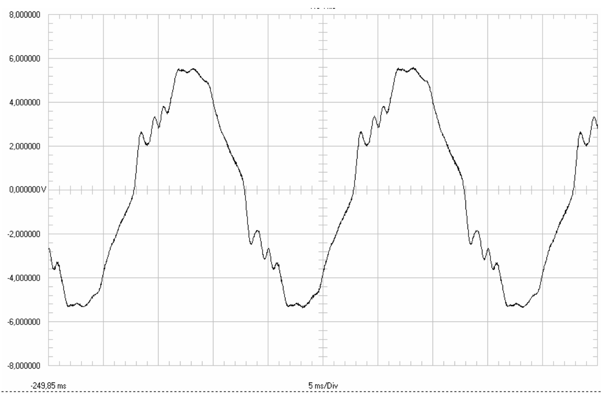


Fig.7. Spectral analysis of supply line current in the examined converter.

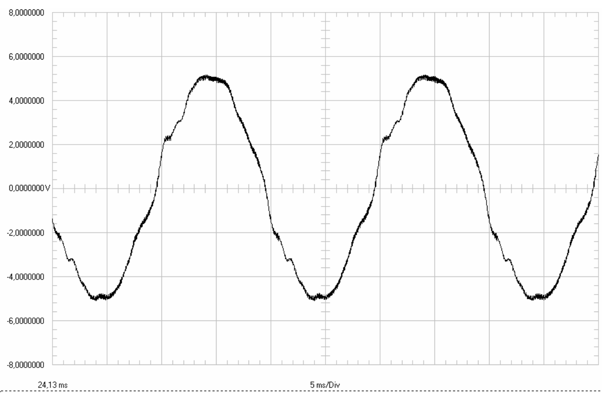
The multi-pulse converters and APF cooperation – results of a laboratory tests

Based on the above-presented relations, a series of parameters were calculated in order to prepare laboratory models of 12 and 24 pulse converters systems, that would cooperate with small APF. The obtained test results, which were performed with those models are presented below in form of waveforms of selected variables. The laboratory tests were performed in the Power Electronics Laboratory of C&T Elmech Co. Ltd., located in Pruszcz Gdański, Poland.

The limiting power of CTR system in 24-pulse rectifier was equal 21% of DC-output power (Pd) and power of APF was about 15% of Pd. The limiting power of CTR system in 12-pulse rectifier was equal 13% of Pd and power of APF was about 20% of Pd. The left columns concern work of the system without reactor Ld, the right columns – with reactor Ld.



50 iL M2 A-24-bezLd-Pn-61mH 11,66



58 iL M2 C-24-zLd-Pn-61mH 6,26

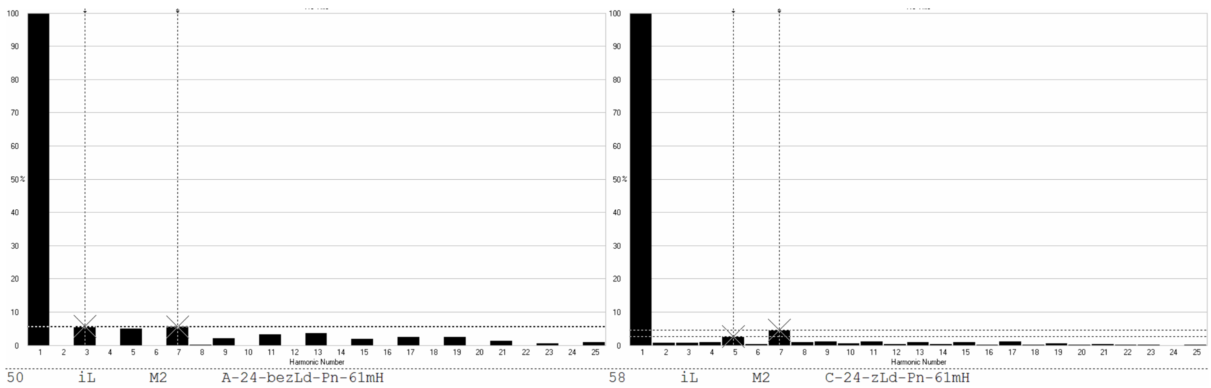


Fig.8. 24-pulse converter - supply network current and harmonics before compensation.

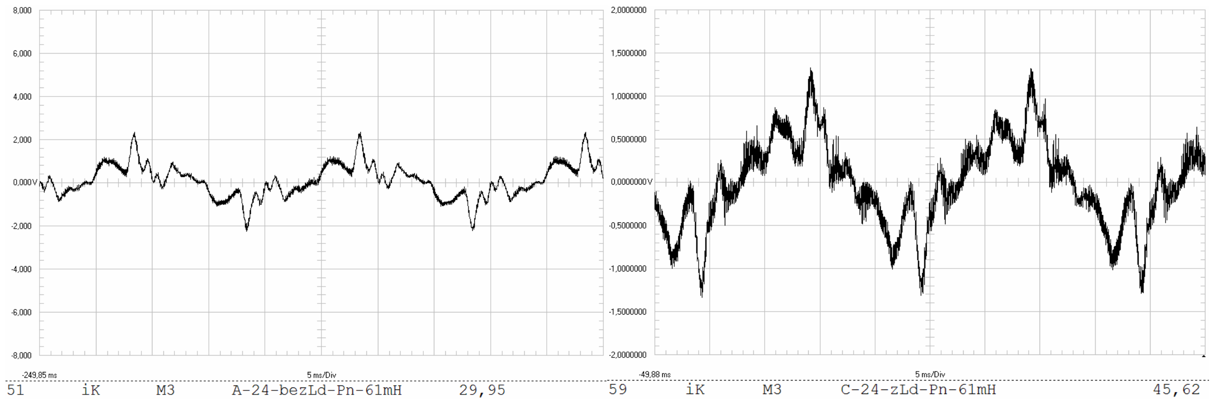


Fig.9. 24-pulse converter - compensating current waveforms.

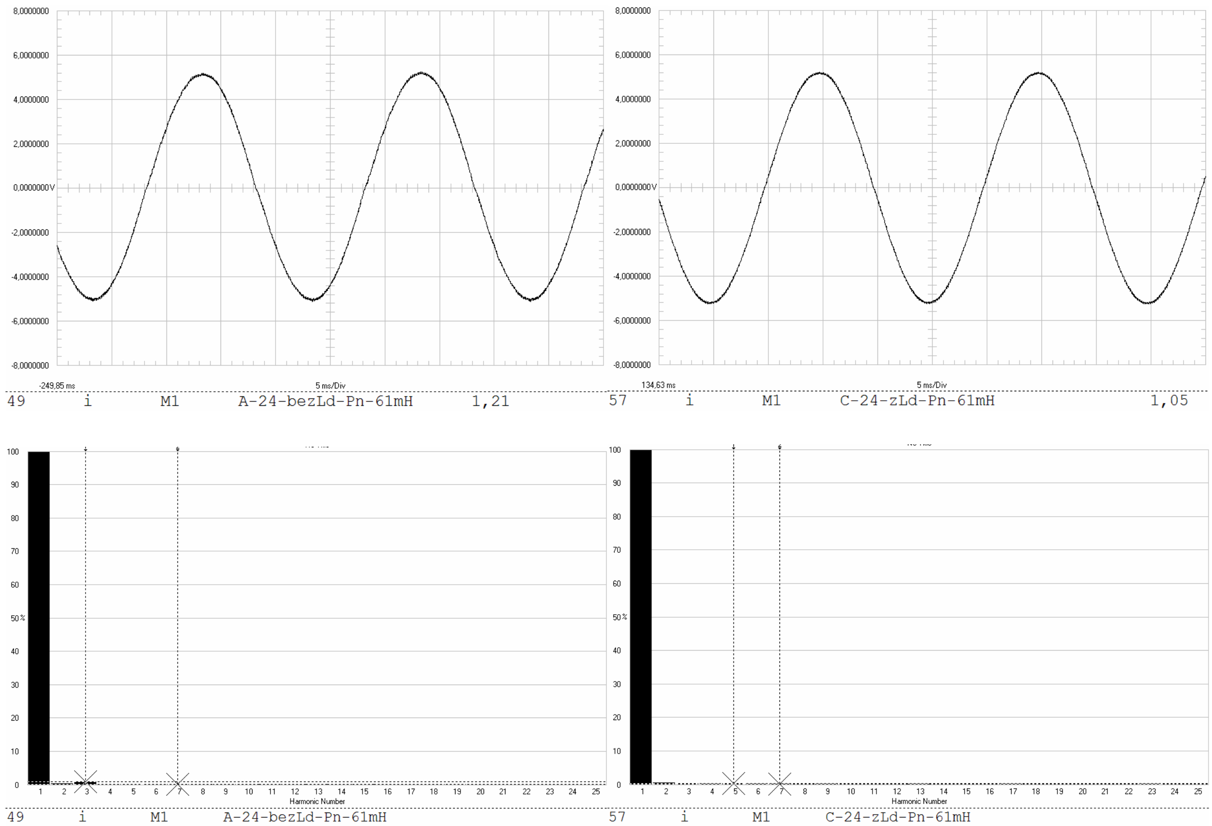


Fig.10. 24-pulse converter - power network current and harmonics after compensation.

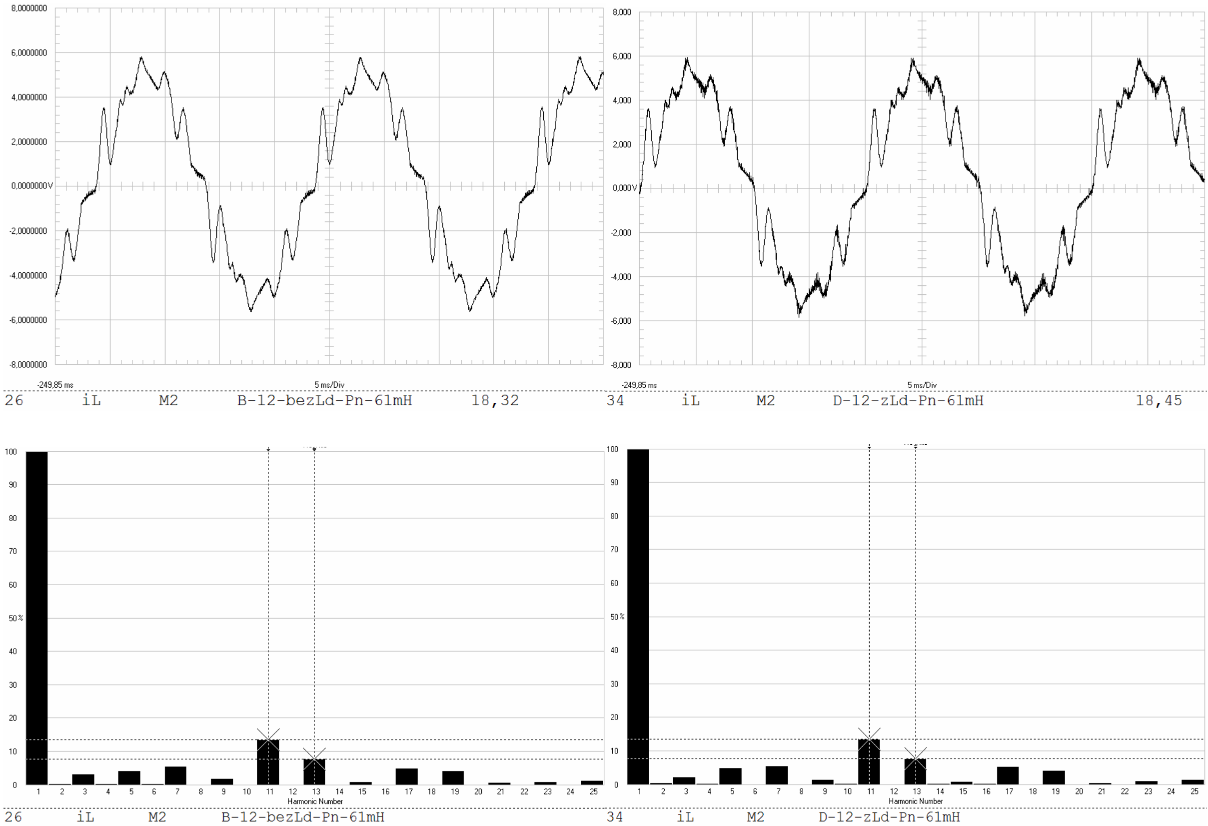


Fig.11. 12-pulse converter - supply network current and harmonics before compensation.

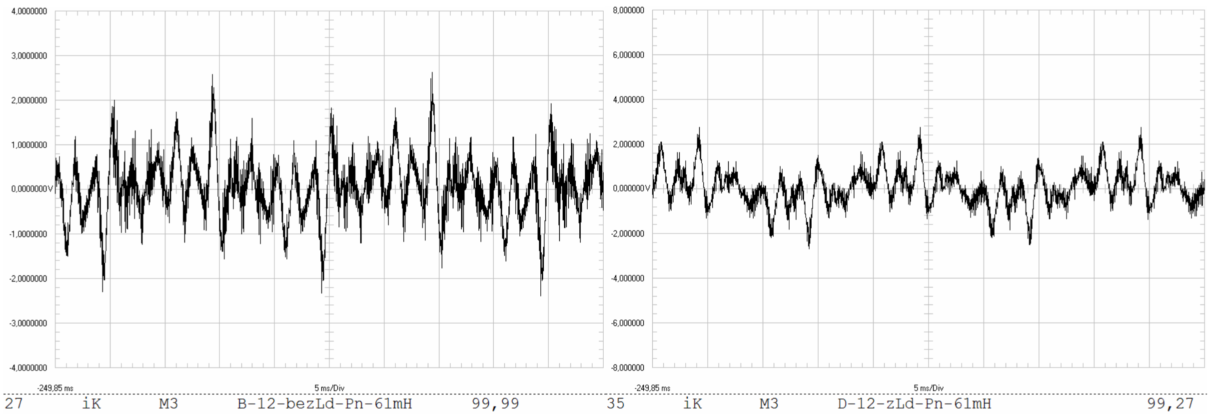
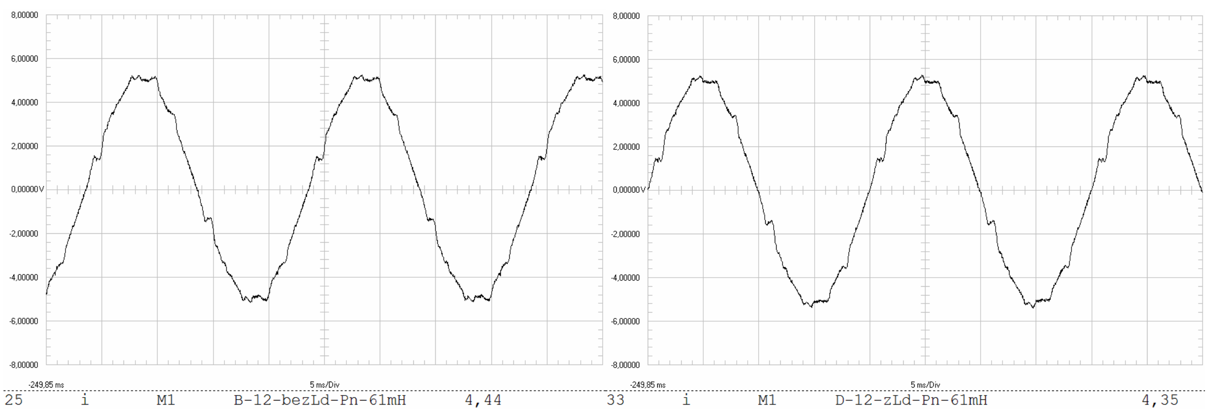


Fig.12. 12-pulse converter - compensating current waveforms.



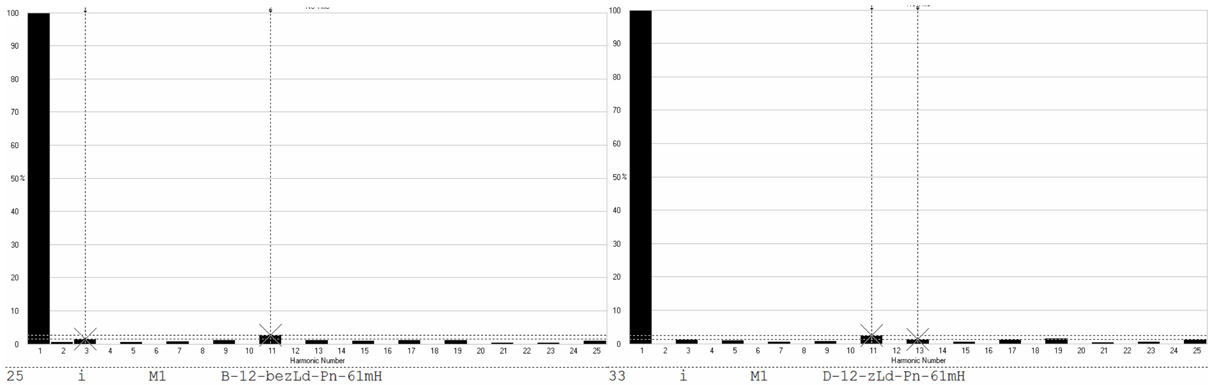


Fig.13. 12-pulse converter - power network current and harmonics after compensation.

Because of cooperation with APF, in both arrangments of multi-pulse converters, application of linear reactors L_d may be disregarded, and thereby construction cost of the system decreases. The system of multi-pulse converter cooperating with the active filter allows to achieve supply current of minor distortion. At the same time it should be noticed that applied system of coupled reactors, as well as the active filter are charactarized by low power, which testifies for their low costs. Practical application of the system may be considered with regards to local networks such as ship power networks, which more often supply non-linear receivers. However the application should take into account strict requirements to preserve parameters defining quality of energy. Exemplary network configuration, which supplies passanger ship is showed on the Figure 14.

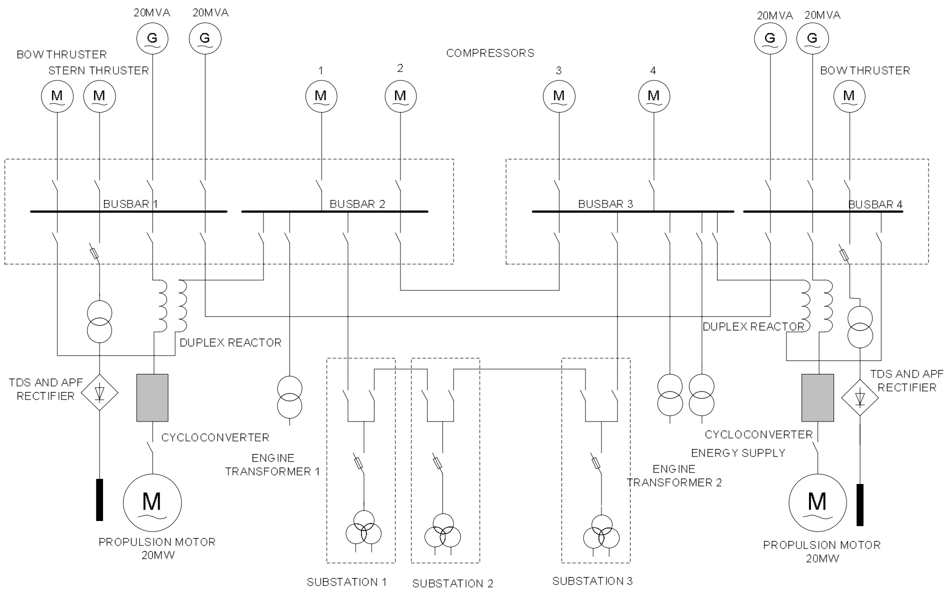


Fig.14. The scheme of passenger ship supply system.

Conclusions

1. The concept of the rectifier system with coupled reactors and the active filter is one approach to the issue of improvement of energy quality absorbed from supply power network. This approach in particular takes into consideration opportunity to construct low cost supply systems of increased reliability in environmental trying conditions, for example on board.
2. Discussing the tested systems from the point of view that focuses on reliability and practical applications in existing supply systems with high quality reguirements (EMC) is a great challenge for the presented concept simultaneusly applying CTR reactor system and APF.
3. Adventagous solution seems to be application of the system that consists of the CTR coupled reactor with multi-pulse rectifier and active power filter, because of the compromise among limiting power of reactor and filter, the reduction level for supply power harmonics, the

system simplification caused by possibility of Ld reactor elimination and realized system power factor improving.

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