No. 119/21, 31–44
ISSN 2657-6988 (online)
ISSN 2657-5841 (printed)
DOI: 10.26408/119.03

Submitted: 30.04.2021
Accepted: 22.06.2021
Published: 30.09.2021

ACTIVE FILTER FOR MULTI-PULSE RECTIFIERS WITH MAGNETICALLY COUPLED REACTOR

Piotr Mysiak[1]*, Adam Muc[2]

[1,2] Gdynia Maritime University, Morska 81-87, 81-225 Gdynia, Poland, Faculty of Electrical Engineering, Department of Ship Automation

[1] ORCID 0000-0002-1792-7027, e-mail: p.mysiak@we.umg.edu.pl

[2] ORCID 0000-0002-9495-087X

*Corresponding author

Abstract: The article presents the simulation and laboratory tests of multi-pulse rectifiers with magnetically coupled reactors, connected to the power grid and cooperating with an active parallel filter (APF). In the study, two types of multi-pulse AC/DC rectifiers were compared, namely 12- and 24-pulse rectifiers. It presents the operating principle and the results of the simulation and laboratory tests. The considered systems enable the reduction of undesired high harmonics in the power supply grid current. For the manufacture of multi-pulse rectifiers, assemblies of magnetically coupled spring reactors configured in the TDSλ system were used.

Keywords: active power filters, grid 3-phase coupled reactors, multi-pulse grid converter, energy conditioning.

1. INTRODUCTION

The power-supply of the grid generates undesirable, higher harmonics of the current flowing in the grid. With an increase of the converter pulse number, the THD (*Total Harmonic Distortion*) of the current decreases. To eliminate higher harmonics of the current flowing in the grid, APF (*Active Power Filter*) filters may be used. The power generated by the APF must be proportional to the distortion power. By increasing the converter pulse number, for example using a set of properly selected magnetically coupled grid reactors, the distortion power is reduced. This solution, however, does not enable the complete elimination of distortions. An advantage, on the other hand, is the possibility of using lower power APFs.

The publications [Iwaszkiewicz and Mysiak 2019; Iwaszkiewicz, Muc and Mysiak 2019; Muc et al. 2021] present proposals to use the above-listed rectifiers as multi-level inverter power supply systems. In these applications, problems are revealed with the negative impact of rectifier bridges on the energy system. This forces additional mechanisms to improve the shape of the currents flowing in the power grid. The purpose of using multi-phase rectifiers seems reasonable due to its properties, which are discussed in more detail further in the study. However, the publication [Śleszyński, Cichowski and Mysiak 2020] presents the concept of applying a serial active filter cooperating with an 18-pulse rectifier.

2. DESCRIPTION OF DIODE RECTIFIER SYSTEM SUPPORTED BY ACTIVE POWER FILTER

The AC/DC rectifier systems with an active filter described in the study do not have the disadvantage typical of diode rectifiers, which consists in the introduction of higher harmonics to the power supply line [Miyairi 1986; Mysiak 1996]. Using fully controlled semiconductor components, such as power transistors or GTO thyristors, controlled by the commonly know and easy to implement PWM (*Pulse-Width Modulation*) modulation method, enables the manufacture of power electronics converters that convert AC power into DC power, which can be classified as CPC (*Clean Power Converters*). In the considered uncontrolled rectifier design, magnetically coupled reactors were used. They were installed between the power supply line and the diode rectifier bridges. The magnetically coupled reactors with properly selected winding enable the conversion of the 3-phase voltage of the power supply line to a system with a higher number of phases, without using transformers. At the same time, the power of the coupled 3-phase reactors is several times lower than in traditional conversion transformers. At this point, another feature of the reactor system in use should be noted, namely that they enable a reduction of the harmonics voltage on the order of 6k ±1 (where: k is any natural number), at the output of the 3-phase power supply system, including a reduction of the higher harmonics in the current drawn.

The operation of the diode rectifier with 3-phase coupled reactors, the determination of voltage and current waveforms, the design and the simulation and experimental test results are discussed in studies [Tunia, Barlik and Mysiak 1998; Mysiak 2005]. Due to the voltage type of the load and the use of TDSλ reactors, the diode conducting angle in the bridge rectifiers is π (in the case of a current source type load, the conducting angle is $2\pi/3$).

The reactors consist of three separate magnetic cores (Fig. 1) with a properly selected number of coils (Na, Nb, Na+Nb). With a properly selected reactor winding ratio, two 3-phase symmetrical voltage loads are obtained at the output, shifted by the angle of $\pi/6$ relative to one another in the phase.

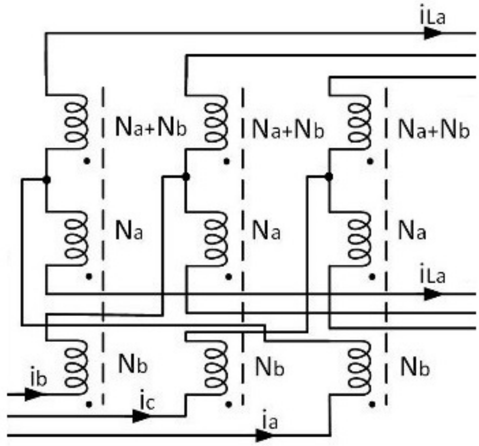

Fig. 1. Diagram of magnetically coupled reactors;
i_a, i_b, i_c – input currents, i_{La} – example output current

Assuming that the diode conducting angle in the converter is π, the voltage on the output terminals of two diode bridges has a 12-step waveform at the rated load current, or close to sine wave in idle operation.

In this system, magnetically coupled reactors act similarly to conversion transformers. However, relative to conversion transformers, they are characterised by several times lower power, but a more complex system of secondary winding. To further improve the power factor and THD, a low power active filter is used, which is based on the 3-phase voltage inverter concept. The content of higher harmonics, originating from 3-phase rectifier bridges, and the reactive power absorption in the described systems, are significantly limited by the TDSλ system and the parallel active filter. It consists of two separate circuits, being the PWM modulator and active filter controller. For a precise reflection of the compensation currents, the PWM modulator should feature a high switching frequency, which is determined by f_{PWM}. Usually, $f_{PWM} > 10 f_{hmax}$, where f_{hmax} represents the frequency of the highest harmonics of the load current to be compensated. To implement the active filter, both a voltage inverter (VSI) [Aredes 1996] and a current inverter (CSI) may be used. All experimental results presented in this study are obtained from the system prototype implemented using the VSI inverter [Depenbrock 1990; Strzelecki and Supronowicz 1997; Akagi, Watanabe and Aredes 2007].

Figure 2 presents the basic configuration of the parallel active filter [Supronowicz and Strzelecki 2000; Wojciechowski 2005, 2006], connected between the grid and the multi-pulse rectifier using magnetically coupled reactors. It consists of a 3-phase voltage inverter VSI, in which the voltage source is the charged condenser C_F. The voltage inverter supplies the compensating current power supply line i_F through the reactor L_F. In addition, an active filter controller system is identified in the system that performs the control algorithm. The purpose of the active filter system presented in Figure 2 is to continuously track the load current i_o and to calculate the instant compensating current reference value i^*_k for the PWM controller. If the PWM frequency is high enough, the current i_k will include higher harmonics, which can be easily filtered using high pass filters. Ideally, the PWM controller may be considered as a linear power amplifier, in which the compensating current i_k strictly follows its reference i^*_c. The control algorithm implemented in the parallel active filter controller determines the compensation characteristics of the system.

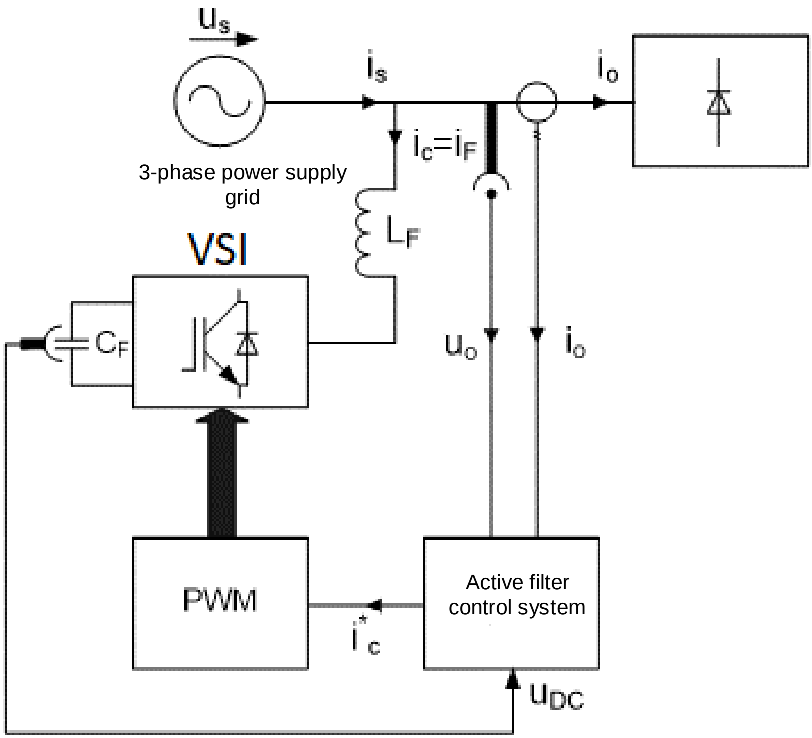

Fig. 2. Block diagram of the active filter cooperating with the diode rectifier

Figure 3 presents the basic concept of the 12-pulse rectifier, in which the application of 3-phase magnetically coupled reactors with a parallel active filter enables the generation of two phase-shifted 3-phase voltage systems, which constitutes the input voltage for two diode bridge rectifiers.

The cases discussed in the literature mainly refer to 12-pulse AC/DC converters without active filters. In addition, the literature does not include a detailed description of the operation of a such system or the algorithms used in it. The previously-discussed examples [Tunia, Barlik and Mysiak 1998; Mysiak 2005], included the analysis that constituted the basis for the design of the 12-pulse system and enabled the analysis of the impact of the power supply line parameters, including the impedance, on the operation of the system. It also includes formulation of a piece of the general theory of the systems with coupled reactors, which enabled the synthesis of systems with an increased number of power supply voltage phases.

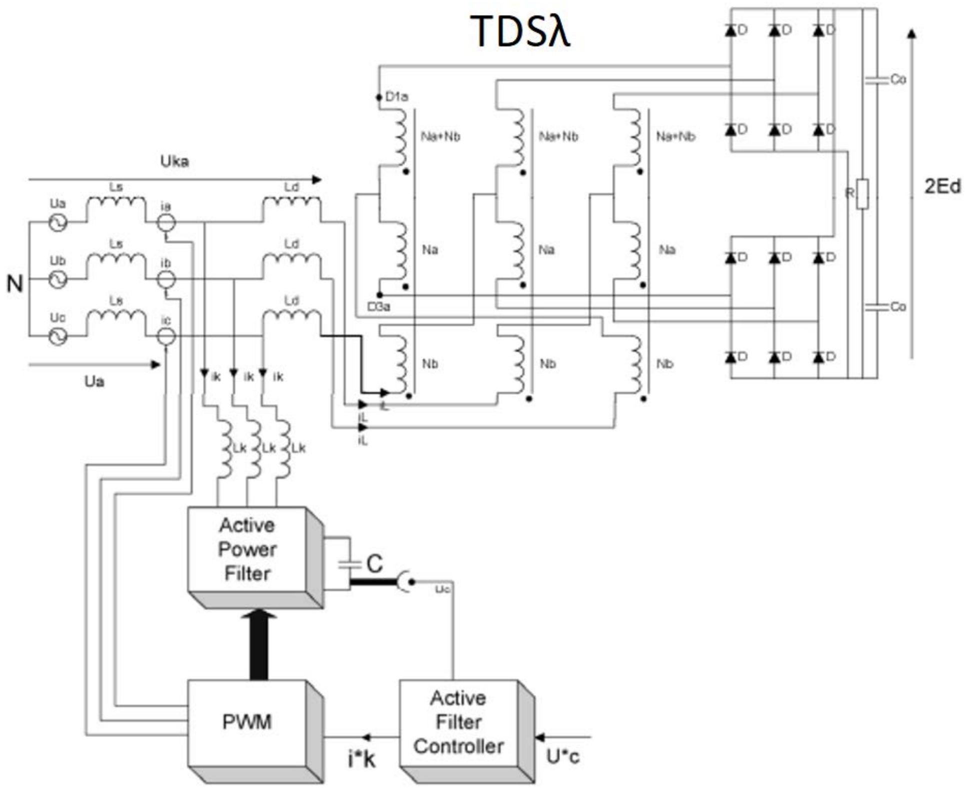

Fig. 3. Block diagram of the 12-pulse diode rectifier with the coupled TDSλ reactors system and parallel active filter

The testing methods of the described system with an active filter included the theoretical analysis, simulation research and examination of the actual converter with two 6-pulse diode bridge systems, supplied from the 3-phase power grid through a system of magnetically coupled reactors. In accordance with predictions, the currents drawn from the power supply line had an undistorted sine wave, which is atypical for classic 12-pulse rectifiers, produced using 3-phase rectifiers. The test results may be used not only to check the design methods developed for the examined converter class, but also to check the feasibility of using the considered converter type in DC and AC drive systems, as the first stage in the frequency converter. Due to the high level of reliability that these systems are able to provide, they can be used in marine applications.

The purpose of the completed works was to develop the method of designing power electronics converters that will convert alternating voltage with a shape similar to a sine wave into unidirectional voltage, and would be equipped with a 3-phase system of magnetically coupled reactors.

The actions undertaken included simulation and laboratory tests, for which the laboratory models of 12- and 24-pulse converter systems with a power of 2 kVA and parallel active filter were designed and completed.

The detailed analysis of the problem enabled formulation of the theory and development of the design methods for specific AC/DC energy converters.

The significant problems related to the completion of the abovementioned research tasks include:

- Development of the mathematical model of the system and definition of analytical and synthetic relationships enabling the formulation of the design procedure for the development of the rectifier consisting of the systems: 3-phase magnetically coupled reactors, two parallel-connected rectifier bridges and a parallel active filter.
- Development of the simulation model and completion of detailed simulation research on the system to develop a method to verify the theoretical results, final formulation of the conditions to be met by the system of magnetically coupled reactors, and assembly of properly configured semiconductor power components.
- Experimental verification of the results of theoretical analysis and simulation research, and interpretation of the obtained results.

The 12-pulse diode rectifier presented in Figure 3 is supplied from the 3-phase grid with phase voltage U_n (n = a, b, c). The input circuit of the converter includes linear grid reactors L_s (representing the power supply grid), L_d, the parallel active filter, and the 3-phase magnetically coupled TDSλ reactors assembly (Fig. 3). The input terminals of the TDSλ reactor are connected to the terminals of the grid supplied by linear reactors L_s, and L_d.

The input terminals of the assembly of TDSλ reactors are in turn connected with phase lines to two 3-phase diode bridge systems. The direct current terminals of all bridge systems are parallel-connected with the filtering condenser C.

The purpose of the assembly of magnetically coupled reactors is to generate three alternating voltages U_{Kn}, with sine wave no-load waveforms. The voltage U_{Kn} measured relative to the star point N of the input circuit may be interpreted as generated by cyclic switching of constant voltage $2E_d$ through two bridge connectors.

The pre-requisite for obtaining 12-step voltage waveforms U_{Kn} is the requirement to conduct all diodes through the angle π.

The 12-step symmetry of voltage U_{Kn} is a direct result of the phase shift angle 2π/12 between the conduction condition of the individual diodes in two bridges. The input terminals D_{mn} (m = 1, 3) of each of the two 3-phase bridge systems show symmetrical 3-phase 6-pulse voltages. These two 3-phase voltage systems are shifted by 2π/12, thus forming, through the TDSλ systems, a single 6-phase system. Therefore, it may be assumed that, due to TDSλ, the 3-phase grid voltage was converted to 6-phase voltage.

In addition, two 3-phase current systems i_{mn} are summed in the TDSλ reactors and converted to one 3-phase system of the currents drawn from the power supply line. The waveforms of these currents are very similar to a sine wave. In addition, the grid reactors L_d and the parallel active filter reduce the harmonics of the higher order currents to the required level.

Figure 4 presents selected results of the simulation and laboratory research – results of the simulation research on the 6-pulse 50 kW converter with active filter (Fig. 4a), results of simulation research on the 12-pulse 50 kW converter with the TDSλ system and active filter (Fig. 4b) and the results of laboratory research on the 12-pulse 2 kW converter with the TDSλ system only (Fig. 4c).

In Figure 4b, the most important information is the clearly the low power of the parallel active filter in use. Figure 4c is unusual in that the current distortion i_a (Fig. 4a) is higher than for the current i_a, as shown in Figure 4b.

3. 24-PULSE CONVERTER WITH ACTIVE POWER FILTER

The described 12-pulse rectifier was used as the basis for the concept of the 24-pulse rectifier that was proposed in the study [Mysiak 2005].

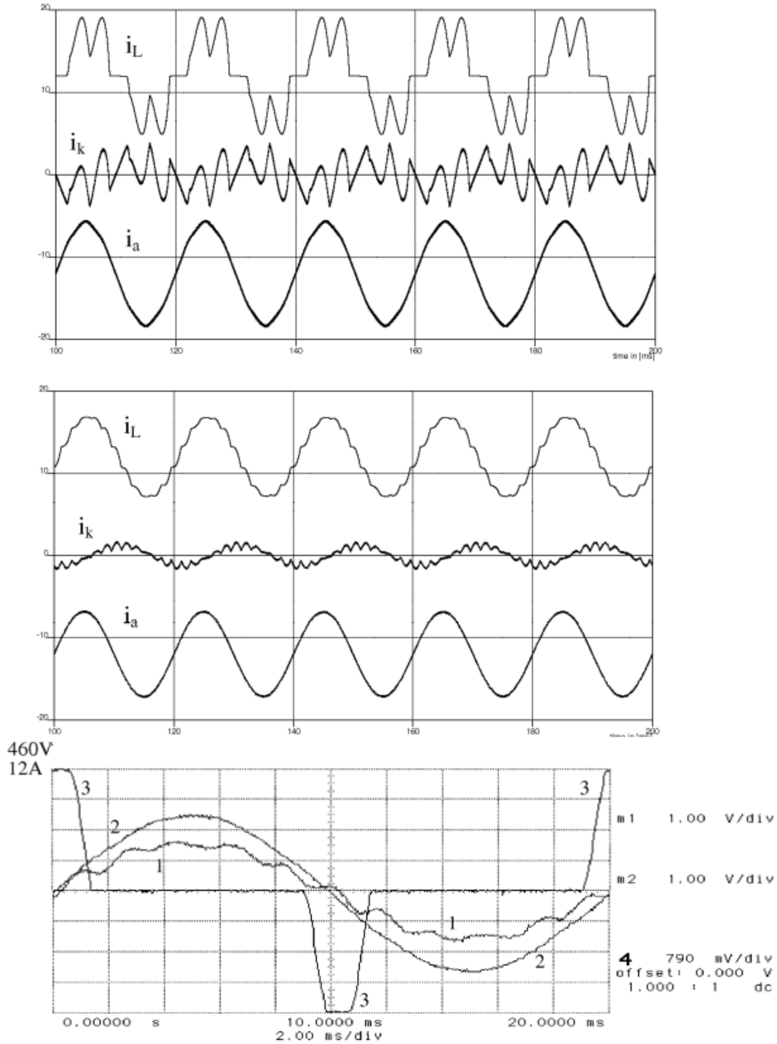

Fig. 4. Research results: a) simulation research, 6-pulse 50 kW rectifier with active filter, b) simulation research, 12-pulse 50 kW rectifier with the TDSλ system and active filter, c) laboratory research, 12-pulse 2 kW rectifier with TDSλ system only; 1 – current i_k, 2 – current i_a, 3 – current i_L

Figure 5 presents the block diagram of the non-controlled 24-pulse rectifier, supplied from the 3-phase power grid with phase voltage U_n (n = a, b, c). The following presents the simulation and laboratory research results of the 24-pulse converter system with a power of 2 kW.

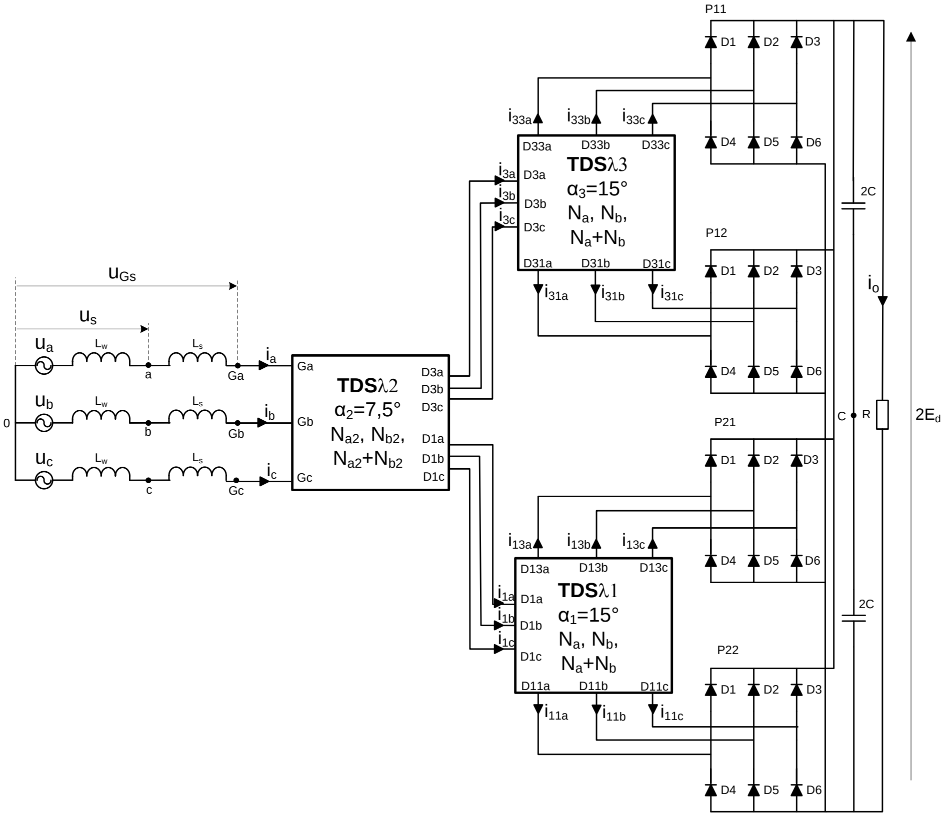

Fig. 5. Block diagram of the uncontrolled 24-pulse rectifier with a coupled TDSλ reactors system

Figure 6 presents the waveforms of the voltage U_a and current i_a in the power supply path at the rated load of the 24-pulse rectifier.

The curves show the shapes that slightly differ from a sine wave, while maintaining a phase shift angle close to 12°.

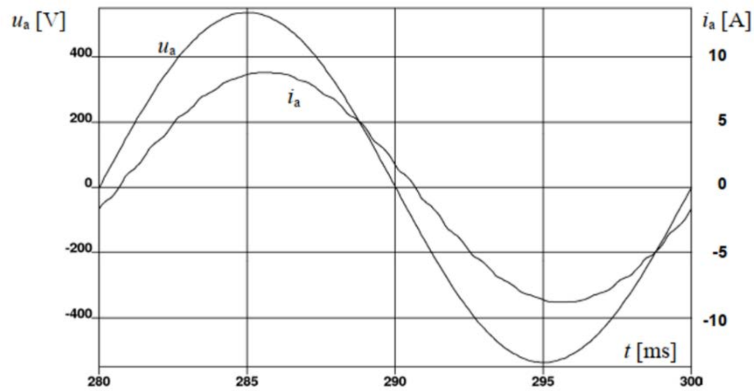

Fig. 6. Waveforms of the voltage U_a and current i_a in the power supply line

Figure 7 presents the spectrum current analysis in the power supply line of the 24-pulse converter. The most important fact is that the higher harmonics of the order of 5, 7, 11, 13, 17, 19 are practically not recorded, while the harmonics of the order of 23 and 25 constitute not more than 2% of the basic harmonic value.

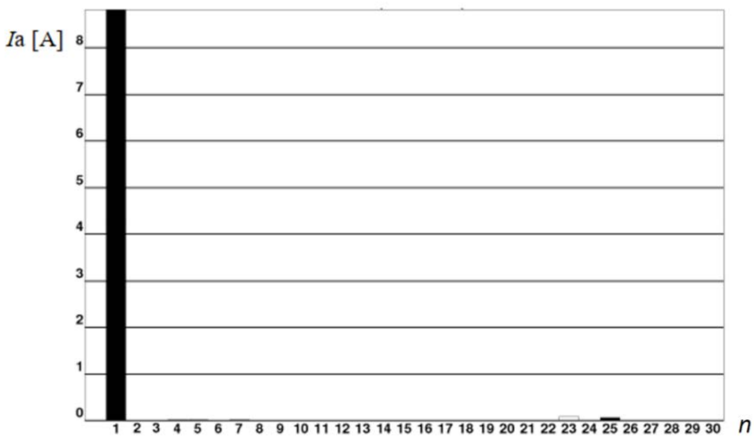

Fig. 7. Spectrum of the current i_a in the power supply path; n – harmonics order

In Figure 8, the presented voltage and current oscillogram in the power supply line of the 24-pulse rectifier operating under rated load conditions, which points to a small distortion of the power supply line current.

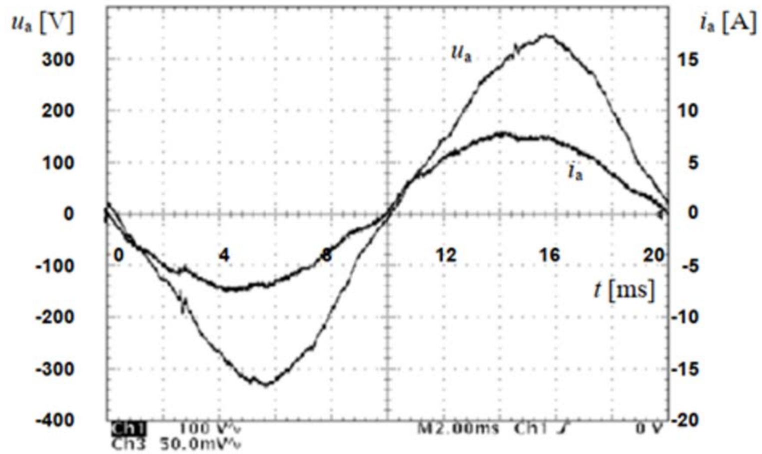

Fig. 8. Voltage and current oscillogram in the power supply line of the 24-pulse rectifier

The THD calculated from the formula (1) for the current drawn from the power grid

$$W_{hI} = \frac{1}{I_1}\sqrt{\sum_{n\rangle 1}^{\infty} I_{hn}^2}\cdot 100\%\,, \tag{1}$$

was 4.88%, which can be regarded as very good.

4. COOPERATION OF MULTI-PULSE RECTIFIERS WITH APF – RESULTS OF LABORATORY TESTS

Based on the relationships presented in [Mysiak 1996], a series of parameters were calculated to prepare laboratory models of 12- and 24-pulse rectifier systems to cooperate with the APF filter. The results of the research involving the developed models are shown in Figure 9 as waveforms of the selected values. The laboratory research was conducted in the Power Electronics Laboratory of C&T Elmech Sp. z o.o. in Pruszcz Gdański.

The results of the experimental research on the 12-pulse and 24-pulse rectifier with APF are presented below. Figures 9 and 10 compare the waveforms of the currents flowing in the grid before and after filtering.

Figure 9 presents the results for the 12-pulse rectifier, of which the overall power of the TDSλ system was equal to 13% of the DC input power (Pd) and the APF power was approx. 20% of Pd.

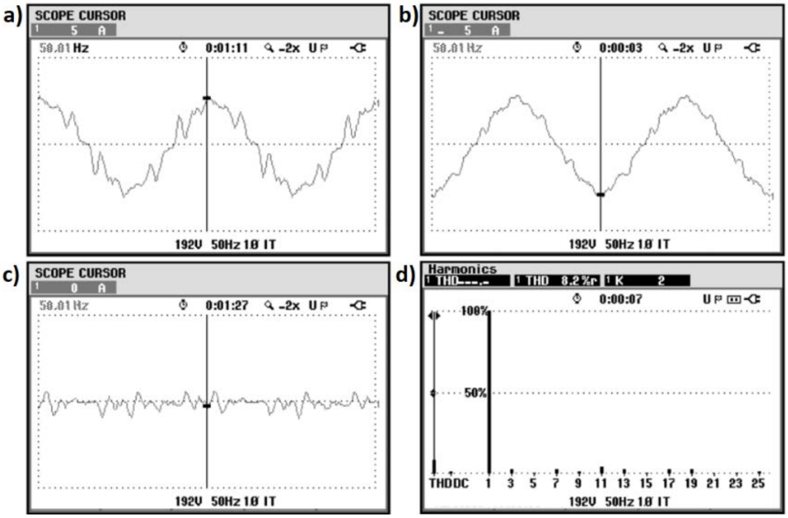

Fig. 9. Waveform of the current flowing in the grid before filtering: a) and after filtering, b) with the harmonics spectrum, c) for the 12-pulse rectifier, d) and waveform of the compensation current

In contrast, Figure 10 presents the results for the 24-pulse rectifier, of which the size power of the TDSλ system was equal to 21% of Pd and the APF power was approx. 20% of Pd.

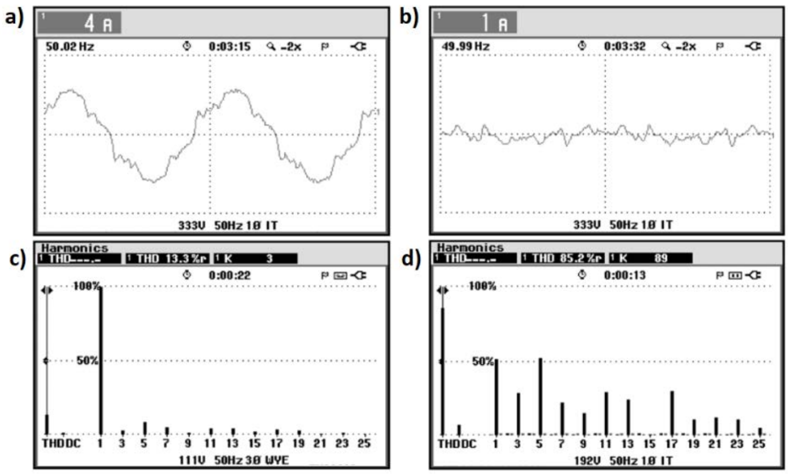

Fig. 10. Waveform of the current flowing in the grid before filtering: a) and its amplitude, b) and its harmonics spectrum spectrum, c) with the waveform of the compensation current, d) for the 24-pulse rectifier

The effective cooperation of the presented multi-pulse rectifier systems with APF enables omitting the use of linear reactors L_d and thus reducing the costs of construction. The system of the multi-pulse rectifier cooperating with the active filter produces a power supply current with only minimal distortion. At the same time, it should be noted that the coupled reactors system in use and the active filter are characterised by low power, which could mean that such a system will be relatively inexpensive. The practical use of the system can be considered relative to local grids, for example on ships, which often supply a non-linear load.

5. CONCLUSIONS

The concept of the rectifier system with coupled reactors and the active filter is an approach to the problem of improvement of the quality of energy drawn from the power grid. In particular, this approach enables developing inexpensive power supply systems with increased reliability under difficult environmental conditions, for example on a ship.

To discuss the examined systems in terms of reliability and practical applications in the existing power supply systems with high quality requirements (EMC) is a major challenge for the presented concept with the simultaneous application of the TDSλ reactors system and APF.

The advantageous solution seems to be the application of the system consisting of the coupled TDSλ reactor for the multi-pulse rectifier with APF, due to the compromise between the reduction of the reactor and filter power and the level of reduction of the harmonics of the power supply line. The proposed solution enables simplifying the system by eliminating the reactor L_d and reducing the costs of the produced system.

REFERENCES

Akagi, H., Watanabe, E.H., Aredes M., 2007, *Instantaneous Power Theory and Applications to Power Conditioning*, John Wiley&Sons.

Aredes, M., 1996, *Active Power Line Conditioners*, the doctor engineer dissertation, Technical University of Berlin, Berlin.

Depenbrock, M., 1990, *A new 18-Pulse Rectifier Circuit with Line-Side Interphase Transformer and Nearly Sinusoidal Line Currents*, IAS.

Iwaszkiewicz, J., Mysiak, P., 2019, *Supply System for Three-Level Inverters Using Multi-PulseRectifiers with Coupled Reactors*, Energies, https://www.mdpi.com/1996-1073/12/17/3385, (25.04.2021).

Iwaszkiewicz, J., Muc, A., Mysiak, P., 2019, *A 12-pulse Rectifier Using Couled Reactors for Supplying Three-Inverters*, Renewable Energy & Power Quality Jurnal, http://www.icrepq.com/E&Q/papers-19/382-19-iwaszkiewicz.pdf (25.04.2021).

Iwaszkiewicz, J., Muc, A., Mysiak, P., 2019, *18-pulse Rectifier in Arrangement with Couled Three-Phase Reactors*, Renewable Energy & Power Quality Jurnal, http://www.icrepq.com/E&Q/papers-19/383-19-iwaszkiewicz.pdf (25.04.2021).

Miyairi, S., 1986, *New Method for Reducing Harmonics Involved in Input and Output of Rectifier with Interphase Transformer*, IEEE Transactions on Industry Applications.

Muc, A., Iwaszkiewicz, J., Mysiak, P., Piechowski, L., 2021, *System zasilania falowników wielopoziomowych wykorzystujący wielopulsowe prostowniki z dławikami sprzężonymi magnetycznie*, Przegląd Elektrotechniczny, http://pe.org.pl/articles/2021/2/18.pdf (25.04.2021).

Mysiak, P., 1996, *The DC-output Multipulse Converter in the Low Voltage Power Network Supply Conditions*, the doctor's thesis dissertation, Warsaw Technical University, Warsaw.

Mysiak, P., 2005, *A Multi-Pulse Diode Rectifier with a Coupled Three-Phase Reactor – the Design Method and Results of the Simulation and Laboratory Tests*, Electrical Power Quality and Utilisation Journal, vol. XI, no. 1.

Strzelecki, R., Supronowicz, H., 1997/1999, *Filtration of the Harmonic in AC Supply Systems*, Adam Marszałek Publishing House, Toruń.

Supronowicz, H., Strzelecki, R., 2000, *The Power Factor in AC-power Supplying Systems and Its Improvement Methods*, Publishing House of Warsaw Technical University, Warsaw.

Śleszyński, W., Cichowski, A., Mysiak, P., 2020, *Suppression of Supply Current Harmonics of 18-pulse Diode Rectifier by Series Active Power Filter with LC Coupling*, Energies, https://www.mdpi.com/1996-1073/13/22/6060/htm (25.04.2021).

Tunia, H., Barlik, R., Mysiak, P., 1998, *The Coupled Reactors System for Current Higher Harmonics Reducing in Three-Phase Loads Supplying from VSI (in polish)*, Electrical Power Quality and Utilisation, Cracow.

Wojciechowski, D., 2005, *Novel Estimator of Distorted and Unbalanced Electromotive Force of the Grid for Control System of PWM Rectifier with Active Filtering*, EPE, Dresden.

Wojciechowski, D., 2006, *Grid Voltages Sensorless Control of PWM Rectifier with Active Filtering*, Electrical Power Quality and Utilisation Journal, vol. XII, no. 1, pp. 43–48.