Michał KRYSTKOWIAK[1], Michał GWÓŹDŹ[2]

Poznan University of Technology (1), Poznan University of Technology (2)

Simulation and experimental models of 3-phase diode rectifier with current modulation in DC circuit

***Abstract**. In the paper the diode rectifier with current modulation in DC output circuit is presented. The power circuit of this converter and structure of control system of power electronics current modulator are described. With aid of such solution, power grid current of presented rectifier is almost sinusoidal. Different structures of current regulator – part of control circuit – are considered. Chosen results of simulation and experimental researches are shown also.(**Model symulacyjny i doświadczalny 3-fazowego prostownika diodowego z modulatorem prądu w obwodzie prądu stałego**).*

***Streszczenie.** W artykule zaprezentowano prostownik diodowy z modulacją prądu w stałoprądowym obwodzie wyjściowym. Opisano sposób realizacji części silnoprądowej przekształtnika i części sterującej energoelektronicznego modulatora prądu. Modulacja prądów wyjściowych umożliwiła uzyskanie prądu sieci pobieranego przez prostownik bardzo dobrze zbliżonego do sinusoidalnego. Przedstawiono wybrane struktury regulatora prądu zastosowanego w torze sterowania. Zaprezentowano również wybrane wyniki badań symulacyjnych i eksperymentalnych.*

Keywords: rectifier, current modulator, filter, harmonics.
Słowa kluczowe: prostownik, modulator prądu, filtr, harmoniczne.

Introduction

The rectifiers belong to very usefully group of power electronics devices. Unfortunately the classical solutions of diode and thyristor rectifiers have disadvantageous harmonic spectrum of source current [1]. One of the ways, which corrects the waveform of current, depends on use a current modulation in DC output circuits of these rectifiers [2]. These converters are built with two 6-pulse diode rectifiers, which are supplied by two 3-phase transformers about connection: star-star and star-delta. In this way we get shift phase about 30 electrical degrees of voltage sources for each of diode rectifier. Additionally, in DC output circuit, a current modulator must be placed. Block scheme of this converter is shown on Fig. 1.

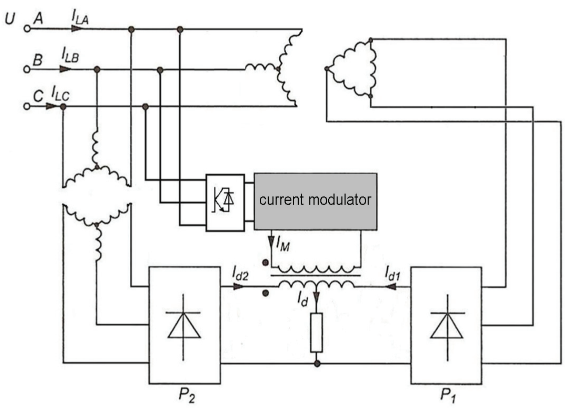

Fig.1. The diode rectifier with current modulator in output circuit

Presented above solution is used to obtaining almost sinusoidal source current. The current modulator is a kind of power electronics current source, which is connected to main circuit by a special wide-band pulse transformer with two taps on secondary site. The current of modulator is adding or subtracting to output currents of each 6-pulse diode rectifiers with aid of this transformer. In this way we can change the shape of input currents of these two diode rectifiers and also resultant source (power grid) current. In aim of getting almost sinusoidal current of power grid, the modulator must generate triangular signal with fundamental frequency, which is equal to 300 Hz. Thus, the control system of current modulator, decides about the effectiveness of energy quality transformation and about the waveform of source current.

So, the optimal selection of control system structure and parameters is really important. During researches different solutions of filters, which were used as current regulators in control circuit, were analysed. Some of these are presented in this article. These special filters must fulfil particular conditions, which are described also.

Simulation model of power circuit

The elaborated simplified simulation model of power circuit of diode rectifier with current modulator is presented on Fig. 2. This model was build with help of Orcad PSpice software.

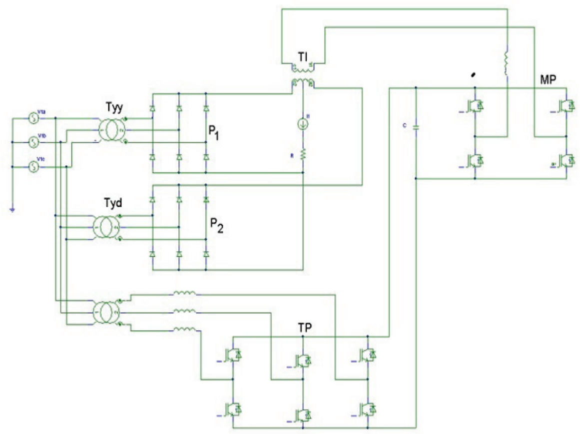

Fig.2. The simulation model of power circuit of rectifier

The additional 3-phase transistor rectifier (TP) was used to control the value of capacitor voltage in DC circuit of power electronics current modulator. The power of this additional converter is only about 2% to 3% of total DC load power. With help of this transistor rectifier, which works in inverter mode, we can achieve improvement of efficiency.

Simulation model of control system and current modulator

Fig. 3 presents a simulation model of described above power electronic current source [3]. This converter works as a current modulator. The current modulator is built with IGBT full bridge inverter with passive serial inductive filter at the output. This converter is connected to DC output circuits of each diode rectifiers via wide-band pulse transformer.

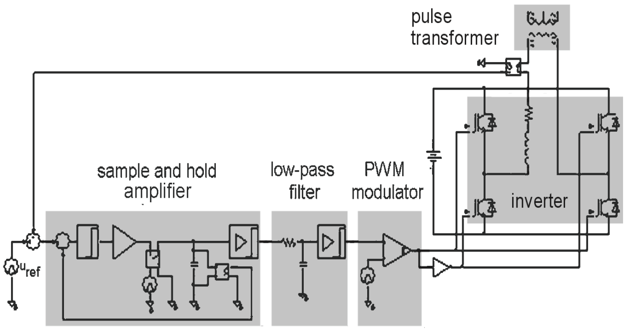

Fig.3. The simulation model of control circuit and current modulator

The elaborated signal model of current modulator with control system is shown on Fig. 4.

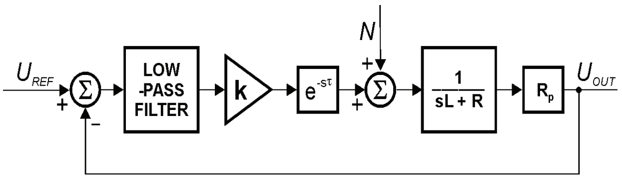

Fig.4. The small signal (linear) model of current modulator with control system

Direct behind the low-pass filter (which works as a current regulator), block K is placed. This block represents resultant gain of control system with current modulator, which is equal to product of low-pass filter gain and gain of inverter with PWM modulator. Delay block represents PWM modulator together with inverter. Parameters R and L represent short-circuit inductances and resistances of star-stat and star-delta transformers on secondary windings terms and also resistance and inductance of output filter of current modulator. The short-circuit parameters of pulse transformer were disregard, because the values of these parameters are much smaller than the values of shot-circuit parameters of energy transformers (about connection star-star and star-delta). The resistance R_p represents the sensor, which is used to measure the output signal. The signal N represents voltage, which is induced on pulse transformer.

If amplitude of u_{ref} is much larger than amplitude of n signal, the transfer function can be reduced to following form:

$$U_{out}(s) = \frac{F(s) k R_p e^{-s\tau}}{sL + R + F(s) k R_p e^{-s\tau}} U_{ref}(s) \tag{1}$$

where: *F(s)* – transfer function of filter.

This case has been mainly introduced in researches of simulation and experimental models.

To assure correct work of presented converter, filter utilized in control circuit must fulfil particular conditions. The three following criterions of filter structures and parameters selection were elaborated [4].

The first of analyzed criterions, was the limitation of slew rate value of PWM modulator input signal. Fulfilment of this condition is necessary to assure the correct switching frequency, which must be equal to frequency of carrying signal. This condition is described by following equation:

$$\frac{d}{dt}\left[\mathrm{L}^{-1}\left(\frac{k_F F(s)(R + sL)}{R + sL + kF(s) R_p e^{-s\tau}} U_{ref}(s)\right)\right] < \frac{d}{dt}\left[s_n(t)\right] \tag{2}$$

where: k_F – gain of low-pass filter, $s_n(t)$ – carrying signal.

The second criterion depends on assurance of the largest gain value of open-circuit transmittance in useful bandwidth, as well as the smallest value of this gain in bandwidth, where the shift phase is close to –180 el. deg.

The last criterion, which has been analyzed during the researches, is the limitation of output signal spectrum due to aliasing effects risk. This limitation is obtained thanks low-pass filter implementation in control system and passive serial inductive filter at the output of current modulator.

During the simulation and experimental researches, several parameters of low-pass filter were analyzed. Also different additional structures of filters were elaborated. One of these has been filter about structure like on Fig. 5. This block is based on differentiator [4]. With help of this additional structure, minimization of delay effect in power electronics inverter with PWM modulator has been achieved. Thus, we can increase the resultant gain value of open-circuit transfer function, while the closed feedback loop circuit is still stable. In this way we can improve the quality of output signal of current modulator.

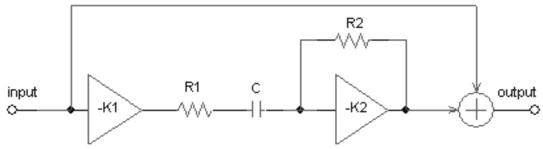

Fig.5. The simulation model of additional high-pass filter

On Fig. 6 and 7 the reference and output signals for two structures of filters used in control system (for low-pass filter and low-pass filter with additional high-pass filter) are shown.

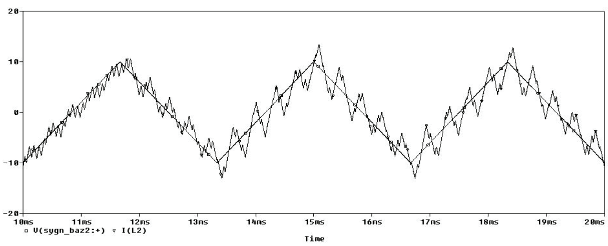

Fig.6. Output and reference signal of current modulator – for low-pass filter

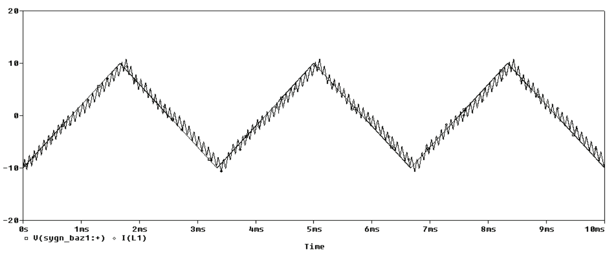

Fig.7. Output and reference signal of current modulator – for combination of low-pass and high-pass filters

Value of resultant gain of open-loop circuit for both investigated cases shown on Fig. 6 and 7 has been the same.

Experimental model of rectifier with current modulator

The power circuit of power electronics current modulator has been built with utilization of laboratory inverter P3-5.0/550MFE LABINVERTER with passive filter (inductor) at the output. This converter is connected to output circuits of both diode rectifiers via a special pulse transformer.

This transformer is an important element of presented circuit. From its transforming ability, depends the effectiveness of energy transformation and the quality (THD) of power source current. The signal generated by current modulator contains higher harmonics, so the transformer should have wide bandwidth. This magnetic element should also assure the smallest losses of energy and symmetry of both windings of secondary side. These requirements cause, that the pulse transformer should be approximate to ideal transformer. The power of the current modulator is equal to 2-3% of DC load power, so the power of transformer can be also much smaller than power of load. In case of presented prototype of rectifier the power of load is about 6 kW and the power of transformer (with safety margin) is about 300 VA. For reducing values of leakage inductances, the toroidal core has been utilized. The windings has been built with the litz wire. Symmetry of both secondary sides was assured in result of suitable connection, which was used to keep the same distance of secondary site windings from toroidal core.

In aim of building the simulation model of presented experimental transformer, the replacing parameters must be calculated [5]. The unconventional calculation method of these parameters was elaborated. To measure some values the circuit, which is shown on Fig. 8, was used. The pulse transformer is supplied by inverter, which generates rectangular signal

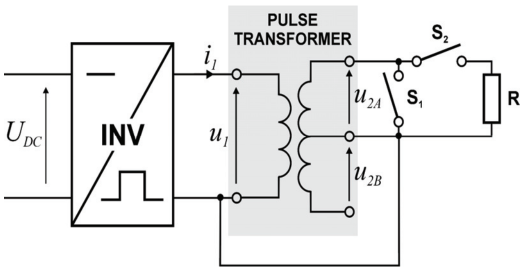

Fig.8. Circuit diagram for pulse transformer parameters calculating

The open-circuit inductance (switches S_1 and S_2 are opened), which represents mutual inductance, was calculated according to following equations:

(3) $$L_u = U_1 \frac{\Delta T}{\Delta I_1}$$

The waveforms of voltage and current for open-circuit state are shown on fig. 9. In this state also the resistance, which represents power losses of core, was calculated (in this aim the power of open-circuit state was also measured).

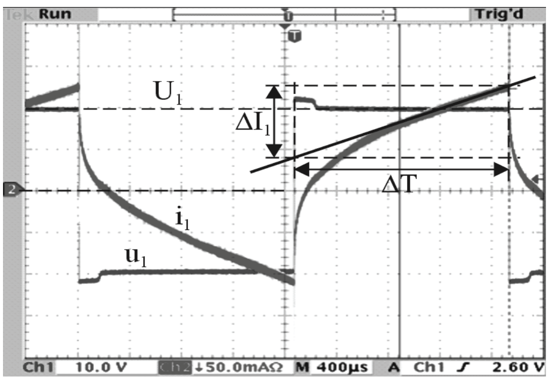

Fig.9. Waveforms for open-circuit state

In the short-circuit state (switch S_1 is closed and switch S_2 is opened), the time-constant of current waveform, approximated by exponential function, has been measured. On that way we have got values of leakage inductance, according to following equation:

(4) $$L'_r = \left(R_{CU1} + R'_{CU2}\right)\tau$$

The resistances have been measured with Kelvin Bridge.

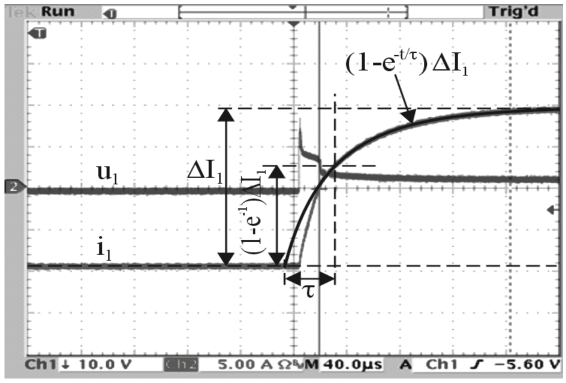

Fig.10. Waveforms for short-circuit state

For Orcad PSpice simulation purposes, the equivalent circuit of real pulse transformer has been utilized (Fig. 11). The values of all R and L components have been calculated on experimental way. All parasitic capacitors, existing in every real transformer, have been omitted due their very small influences on circuit, what has been verified during tests.

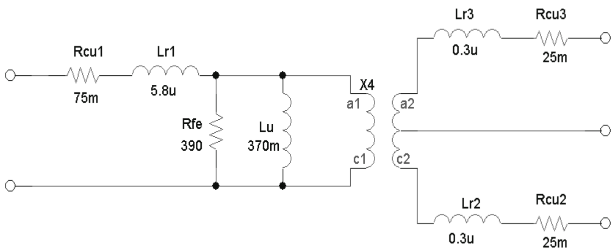

Fig.11. The simulation model of carried out pulse transformer

The digital control system is realized with aid of ALS-G3-1369 DSP evaluation board, which has been delivered by ALFINE-TIM. This system is equipped with modern floating point signal processor ADSP-21369 [6]. The block scheme of system is shown on Fig. 12. The wideband filter used as an unconventional current regulator, has been implemented by elaborated algorithm of digital IIR filter.

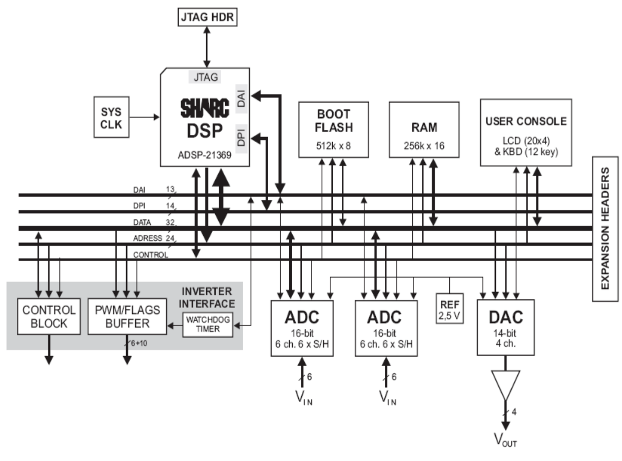

Fig.12. The block scheme of digital control system

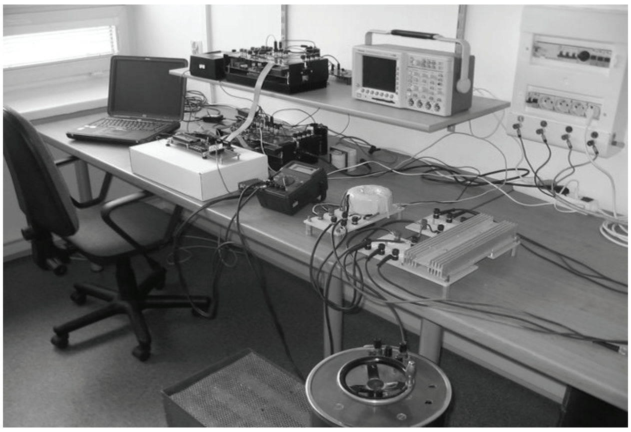

Fig.13. General view of experimental model of rectifier with current modulator in DC circuit

On Fig. 13 the elaborated experimental model of rectifier with power electronics current modulator is shown.

Chosen results of simulation and experimental researches

Chosen results of simulation researches are presented below. On Fig. 14 and 15 the waveform and harmonic spectrum (in logarithmic scale) of power grid current for nominal working conditions are shown.

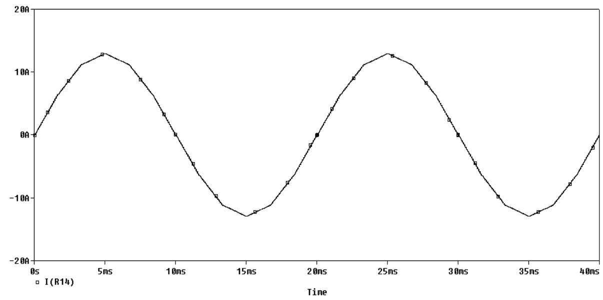

Fig.14. The waveform of power grid current of diode rectifier with current modulation

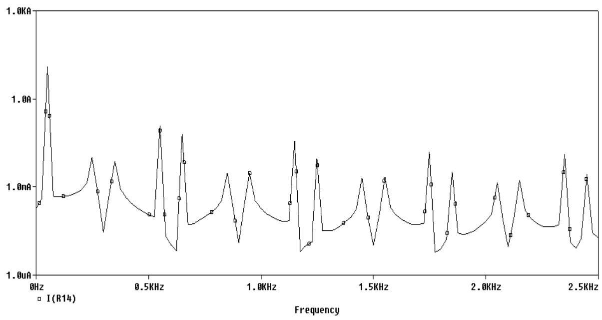

Fig.15. The harmonic spectrum of power grid current of diode rectifier with current modulation (THD=1,1%)

The simulation researches of desribed rectifier have been investigated also for phase and amplitude asymmetry of supplied voltage sources. The waveforms of source currents of each phase for amplitude and also phase asymmetry of supplied voltages are shown on Fig.16 and 17. In spite of disadvantegous condition of supply, the rectifier works still correctly – the current modulator corrects the waveforms of source currents. For amplitude asymmetry about –10 % to 5% of nominal value, the largest THD of source current is about 1.7%. Also for phase asymmetry about –10° to 10° of nominal value shift phase the rectifier works correctly – the largest THD of source current is about 4.6%.

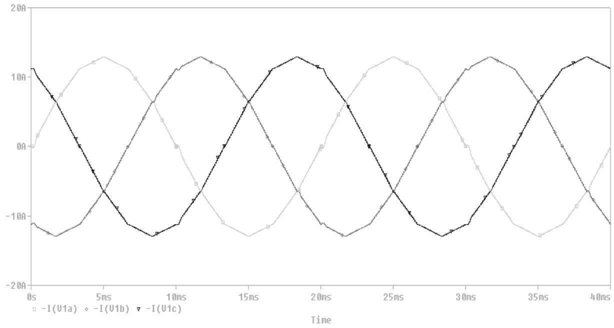

Fig.16. The waveforms of power grid currents of diode rectifier with current modulation for amplitude asymmetry of voltage sources

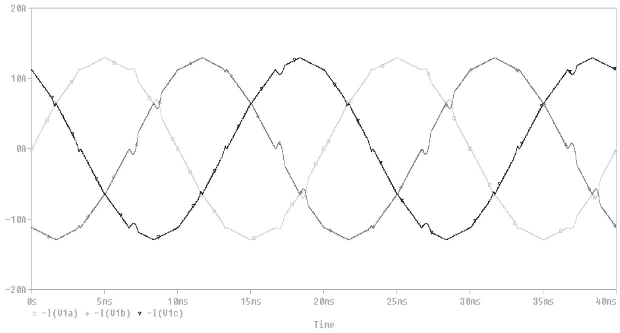

Fig.17. The wave forms of power grid currents of diode rectifier with current modulation for phase asymmetry of voltage sources

On Fig. 18 and Fig. 19 the waveforms and harmonic spectrum of power grid currents (for the same nominal working conditions) of experimental diode rectifier with current modulation and classical 12-pulse diode rectifier are shown. In case of current modulation, this signal has been almost sinusoidal.

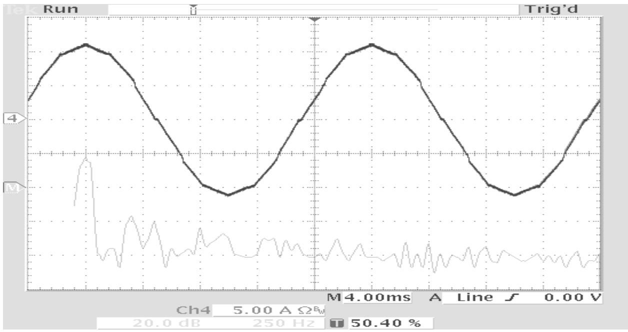

Fig.18. The waveform and harmonic spectrum of power grid current of diode rectifier with current modulation (THD=2,4%)

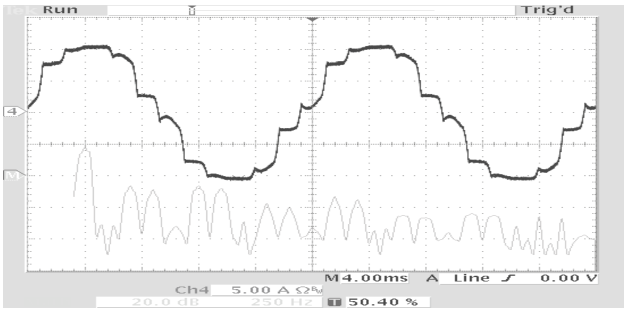

Fig.19. The waveform and harmonic spectrum of power grid current of classical 12-pulse diode rectifier (THD=11,6%)

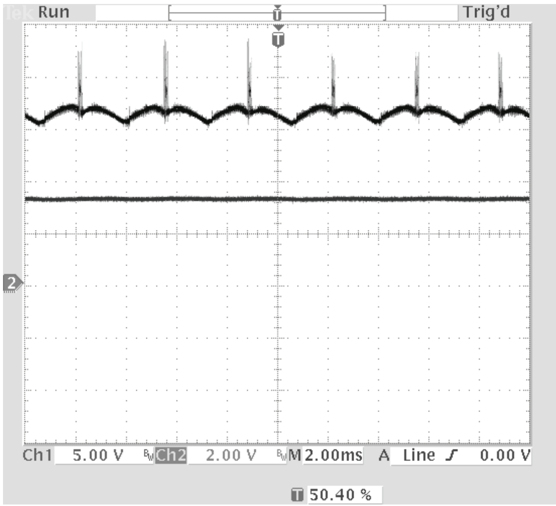

Fig.20. The waveforms of load current (red line) and load voltage (blue line)

On Fig. 20 the waveforms of load current and load voltage for case rectifier with modulator are presented. In case of voltage waveform, periodic overvoltages caused by leakage inductance of pulse transformer can be noticed.

Summary

In the paper, one of the ways leading to increasing the quality of power grid current of traditional rectifiers is presented. In this aim, a current modulator in DC output circuit of two 6-pulses rectifiers has been utilized. In result the current of power grid is almost sinusoidal. This solution is special attractive in case of higher power of load value, because the power of the current modulator is only about 2% to 3% of total DC load power.

The control circuit of current modulator, which is based on wide-band filters, is presented. The criterions of filter parameters selection are described also. The structure with additional high-pass filter in control system was analysed. With aid of this additional block we have achieved partial compensation of delay effect. So, we could increase the resultant gain of open-circuit transfer and keep stability of converter. In this way we can improve the quality of power grid current.

REFERENCES

1. [1] Tunia H., Power Electronics, WNT, Warsaw 1994.
2. Strzelecki R., Supronowicz H., "The power factor of AC circuits and correction method," *OWP*, Warsaw 2000, p. 120–135.
3. Gwóźdź M., Krystkowiak M., "Control system of power electronics current modulator utilized in diode rectifier with sinusoidal source current," *EPE-PEMC 2008*, ID 667.
4. Gwóźdź M., Krystkowiak M., "Control system of power electronics current modulator utilized in diode rectifier with sinusoidal power grid current," *Electrotechnical Review*, No7, 2009.
5. Krystkowiak M., Gwóźdź M., "Calculation of Parameters of Equivalent Circuit of Pulse Transformer," *EPNC*, Lille, Francja, 2-4.07.2008, p. 139-140.
6. http://www.analog.com

***Authors**: dr inż. Michał Krystkowiak, Politechnika Poznańska, Instytut Elektrotechniki i Elektroniki Przemysłowej, ul. Piotrowo 3a, 60-965 Poznań, E-mail: Michal.Krystkowiak@put.poznan.pl; dr inż. Michał Gwóźdź, Politechnika Poznańska, Instytut Elektrotechniki, i Elektroniki Przemysłowej, ul. Piotrowo 3a, 60-965 Poznań, E-mail: Michal.Gwozdz@put.poznan.pl.*