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AC/DC line-side converter, PWM rectifier, Voltage Oriented Control, decoupled current control, nonlinear DC-link voltage control, feedforward load compensation

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HIGH-PERFORMANCE DECOUPLED CONTROL OF PWM RECTIFIER WITH LOAD COMPENSATION

The paper presents the decoupled vector control of the PWM rectifier with the nonlinear DC-link voltage regulation and the load compensating feedforward. The concept of the proposed control system is based on Voltage Oriented Control with Space-Vector Pulse Width Modulation (SV-PWM). For the high-performance operation of the PWM rectifier and the satisfactory current tracing the decoupled current control has been introduced. The performance of the linear PI controller of the DC-link voltage is strictly dependent on its settings and it may introduce a disadvantageous voltage overshoot under a heavy load impact. In order to improve the transient response of the DC-link voltage control loop a load compensation has been proposed. The different approach to the control of the DC-link voltage based on the regulation of the square power of the DC voltage has been introduced. The algorithm of the proposed nonlinear control system of the PWM rectifier has been implemented on a fixed-point 150MHz DSP evaluation board of an experimental setup with a power converter. The selected experimental results have been presented and discussed.

1. INTRODUCTION

Nowadays the adjustable speed drives with the squirrel-cage induction motors are intensively developed. In these drives the angular velocity and the electromagnetic torque are precisely controlled using mostly the voltage source inverters. For years most of the electrical drives with the voltage inverters have been supplied from the power distribution line through the thyristor rectifiers. Such frequency converters were supposed to provide the smooth control of the amplitude of the basic harmonic of the output voltage neglecting the influence of the line-side rectifier on the grid. The frequency converters supplied by the thyristor and diode rectifiers are characterized by the disadvantageous

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properties as the lack of the possibility of the regenerative braking of the induction motor, the intake of the non-sinusoidal distorted currents from the grid at the power factor different from the unity. The flow of the non-sinusoidal currents in the power distribution line causes the distorted voltage drops over the other power devices being supplied from the grid. The distorted voltages are also inappropriate for the line transformers since more heat is produced especially in case of the high power ratings.

The growth of the use of the frequency converters and other electrical devices that require the AC to DC conversion has considerably increased the electrical power consumption. Due to these facts the specific rules concerning the electrical power utilization have been determined through the establishment of the detailed laws (IEC 61000-3 – European Standards). These regulations impose the requirements towards the electronic and power electronic devices connected to the grid in order to provide high standards of the power quality. Referring to the most important determinations, the modern line-side converters should draw sinusoidal currents from the mains without the intake of the reactive power. The power converters should also have the possibility of the returning of the electrical energy back to the mains. In order to adapt the modern power electronics devices to the valid standards the special topologies of the line-side rectifiers are being developed. Comparing to the diode and thyristor rectifiers more advantageous in respect of the technical and economical reasons are AC/DC line-side converters named also PWM rectifiers or synchronous rectifiers.

Unlike the diode rectifiers the AC/DC line-side converters provide the sinusoidal line currents at the unity power factor condition. Simultaneously the DC-link voltage is kept constant at the reference level during the control process regardless the converter load variations. Some topologies of the AC/DC line-side converters provide the bidirectional power flow. The possibility of the regeneration of the mechanical kinetic energy and its return in the form of the electrical energy back to the grid is especially important in the drive systems with the active load torque as the cranes, lifts, winches, downhill belt conveyors and in the heavy inertia drive systems operating at the frequent stops, varying values of the shaft velocity or changes of the direction of the rotation as the electrical traction propulsions or the mill scale drives [7,8].

The control strategies for the AC/DC line-side converters have been adapted from the methods elaborated for the vector control of the induction motors. The classical control techniques require the strict knowledge of the values of the line and load parameters since the PI control performance is strictly dependent on the proper identification of the line chokes inductance and the DC-link capacitance.

Recently more stress has been put on the elaboration of the nonlinear control algorithms for the PWM rectifiers in order to eliminate the disadvantageous influence of the variations of the line and load parameters on the converter operation [4,6,9]. In this paper a method of the compensation of the load impact and the efficient control of the DC-link voltage has been proposed. The presented method has been implemented and verified on the hardware application of the DSP-based controlled PWM rectifier.

2. MATHEMATICAL MODELS OF PWM RECTIFIERS

The PWM rectifier can be designed as a voltage-source or current-source converter depending on its particular application. The following subsections present the topologies and the strict mathematical descriptions of the typical three-phase two-level PWM rectifiers being in the widespread use in industry.

2.1. MODEL OF VOLTAGE-SOURCE PWM RECTIFIER

The voltage-source PWM rectifier has the topology presented in Fig.1 [10]. The converter's bridge consists of the six fully-controllable power switches (IGBTs, MOSFETs, GTOs) connected to the three-phase grid voltages e_{gA}, e_{gB}, e_{gC} via the three symmetrical line chokes of the resistance R_g and the induction L_g.

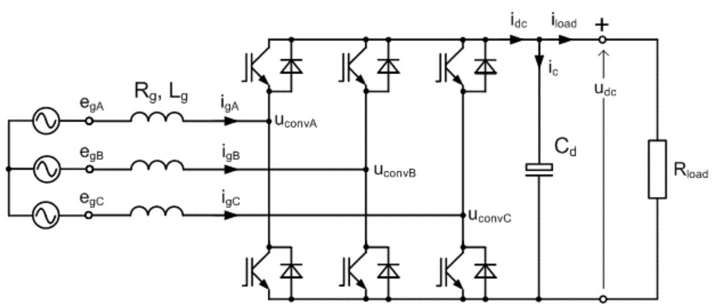

Fig.1. Three-phase voltage-source PWM rectifier

During the operation of the AC/DC line-side converter its transistors are being switched by the rectifier's control system producing the pulse-width modulation scheme based on the principles of a chosen control strategy. In order to reach the sufficient quality of the line currents in case of the voltage-source PWM rectifier the high switching frequency has to be provided. The switching signals are denoted as K_a, K_b and K_c for the particular phases respectively. The relationship between the converter input voltages u_{convA}, u_{convB}, u_{convC} and the DC-link voltage u_{dc} depends on the instantaneous states of the power switches and can be described in a form of equations (1).

$$u_{convA} = \frac{K_a \cdot u_{dc}}{2}, \qquad u_{convB} = \frac{K_b \cdot u_{dc}}{2}, \qquad u_{convC} = \frac{K_c \cdot u_{dc}}{2} \tag{1}$$

The control design of a PWM rectifier is often performed in a synchronous frame rotating with the angular velocity corresponding to the grid pulsation ω. Thus the mathematical model of the voltage-source PWM rectifier in the *d-q* coordinates can be formulated in the set of the differential equations (2).

$$
\begin{aligned}
\frac{d}{dt}u_{dc} &= -\frac{u_{dc}}{R_{load}C_d} + \frac{3}{2C_d}K_d i_{gd} \\
\frac{d}{dt}i_{gd} &= -\frac{R_g}{L_g}i_{gd} + \omega i_{gq} - \frac{1}{2L_g}K_d u_{dc} + \frac{1}{L_g}e_{gd} \\
\frac{d}{dt}i_{gq} &= -\frac{R_g}{L_g}i_{gq} - \omega i_{gd} - \frac{1}{2L_g}K_q u_{dc}
\end{aligned} \tag{2}
$$

Assuming that the power conversion is lossless the power balance of the PWM rectifier can be described by the nonlinear differential equation (3).

$$
\frac{3}{2}e_{gd}i_{gd} = u_{dc}C_d\frac{d}{dt}u_{dc} + \frac{u_{dc}^2}{R_{load}} \tag{3}
$$

2.2. MODEL OF CURRENT-SOURCE PWM RECTIFIER

The current-source PWM rectifier has the topology presented in Fig.2 [10]. The two-level converter consists of the six power switches connected in series with the free-wheeling diodes. The power bridge is interfaced with the three-phase grid voltages e_{gA}, e_{gB}, e_{gC} via the LC filter of the series induction L_g and the parallel capacitance C_g.

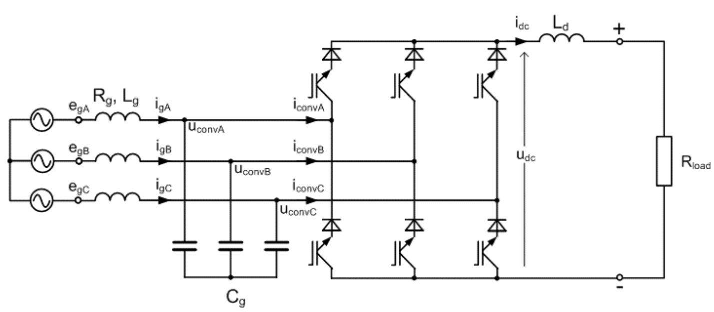

Fig.2. Three-phase current-source PWM rectifier

Unlike the voltage-source converter which produces the PWM input voltage under the control process the current-source PWM rectifier produces the pulse-width modulated input currents. The relationship between the converter input currents i_{convA}, i_{convB}, i_{convC} and the DC-link current i_{dc} depends on the instantaneous states K_a, K_b and K_c of the power switches and can be formulated into the equations (4).

$$i_{convA} = \frac{K_a \cdot i_{dc}}{2}, \qquad i_{convB} = \frac{K_b \cdot i_{dc}}{2}, \qquad i_{convC} = \frac{K_c \cdot i_{dc}}{2} \tag{4}$$

It is also convenient to perform the model of the current-source PWM rectifier in the *d*-*q* coordinates. Hence the mathematical description of the converter is represented by the five differential equations for the converter's state-space variables (5).

$$\begin{aligned}
\frac{d}{dt} i_{dc} &= -\frac{R_{load}}{L_d} i_{dc} + \frac{3}{2L_d} K_d u_{convd} \\
\frac{d}{dt} i_{gd} &= -\frac{R_g}{L_g} i_{gd} + \omega i_{gq} - \frac{1}{L_g} u_{convd} + \frac{1}{L_g} e_{gd} \\
\frac{d}{dt} i_{gq} &= -\frac{R_g}{L_g} i_{gq} - \omega i_{gd} - \frac{1}{L_g} u_{convq} \\
\frac{d}{dt} u_{convd} &= \frac{1}{C_g} i_{gd} + \omega u_{convq} - \frac{1}{C_g} K_d i_{dc} \\
\frac{d}{dt} u_{convq} &= \frac{1}{C_g} i_{gq} - \omega u_{convd} - \frac{1}{C_g} K_q i_{dc}
\end{aligned} \tag{5}$$

Similarly as in case of the methodology of the modeling of the voltage-source converter the power balance condition (6) is based on the equality of the instantaneous values of the power at the AC and the DC side of the current-source PWM rectifier at any load condition by the assumption of the lossless power conversion.

$$\frac{3}{2} e_{gd} i_{gd} = i_{dc} L_d \frac{d}{dt} i_{dc} + i_{dc}^2 R_{load} \tag{6}$$

The current-source PWM rectifiers are preferably used in the high power industrial applications. This is due to the fact that the high quality of the line currents can be achieved at the very low switching frequency and thus much slower high power GTO thyristors or Silicon-Controlled Rectifiers can be applied in the converter's topology.

3. VOLTAGE ORIENTED CONTROL OF PWM RECTIFIERS

The Voltage Oriented Control technique for the AC/DC line-side converters originates from Field Oriented Control for the induction motors. It provides the fast dynamic response since the current control loops are applied. The properties of the control systems based on the VOC strategy are different depending on the involved PWM technique. The hysteresis pulse-width modulation method provides the on-line current tracking thus the influence of any disturbances is minimized and the better robustness of the control system is achieved. On the other hand the varying switching frequency introduces an additional stress in the power switches and requires the higher values of the parameters of the input filter. The Space-Vector PWM technique reduces the higher harmonics content in the line currents since the constant switching frequency of the power transistors is provided [3]. Fig.3 presents Voltage Oriented Control with SV-PWM for the AC/DC line-side converters.

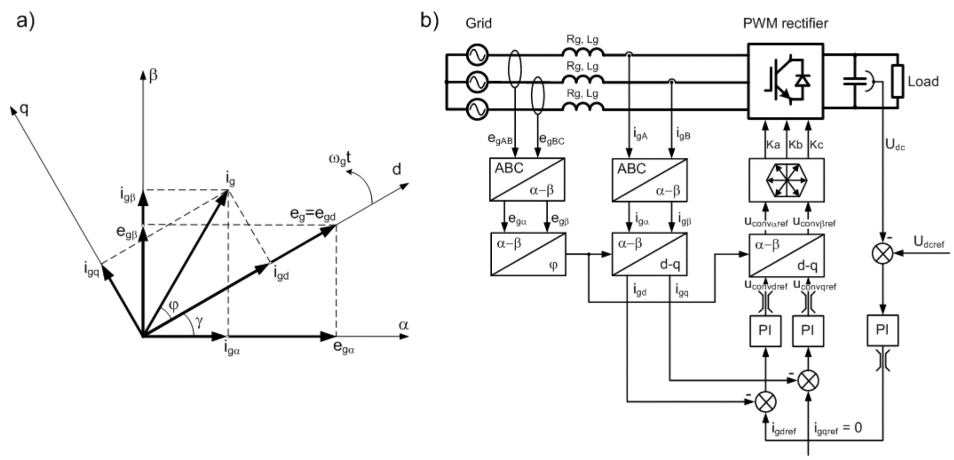

Fig.3. Voltage Oriented Control of PWM rectifiers: a) vector layout, b) block diagram

Due to the vector transformation to the *d-q* reference frame the AC-side control variables are hence the DC signals. Thus the steady-state errors are easily eliminated via the PI controllers. The reference values of the converter input voltages are computed in the current controllers based on the values of the current tracking errors (7).

$$
\begin{aligned}
u_{convd} &= k_p\left(i_{gdref} - i_{gd}\right) + k_i \int \left(i_{gdref} - i_{gd}\right)dt \\
u_{convq} &= k_p\left(i_{gqref} - i_{gq}\right) + k_i \int \left(i_{gqref} - i_{gq}\right)dt
\end{aligned}
\tag{7}
$$

4. NONLINEAR DECOUPLED CONTROL OF PWM RECTIFIERS WITH LOAD COMPENSATION

The Voltage Oriented Control-based system for the PWM rectifier has the cascaded structure. The line current control is realized in the inner loop while the DC-link voltage control proceeds in the outer loop. Referring to the equations (2) the control system is coupled and the performance of the PI control may not be satisfactory.

In order to provide the high-performance operation of the line current control loop the PI line current controllers have to be decoupled according to the equations (8) [5].

$$\begin{aligned} u_{convd} &= \omega L_g i_{gq} + e_{gd} + k_p\left(i_{gdref} - i_{gd}\right) + k_i \int \left(i_{gdref} - i_{gd}\right) dt \\ u_{convq} &= -\omega L_g i_{gd} + k_p\left(i_{gqref} - i_{gq}\right) + k_i \int \left(i_{gqref} - i_{gq}\right) dt \end{aligned} \tag{8}$$

The signals described by (8) after the α-β transformation are sent to the modulator.

The power balance equation (3) represents the nonlinear differential equation and reveals the nonlinearity included in the formal description of the PWM rectifier. In this case the design of the PI linear controller is troublesome. This inconvenience may be overcome by the linearization of the DC-link voltage dynamics. Hence the new state variable $(u_{dc})^2$ is considered instead of u_{dc} in the power balance condition (9) [1].

$$\frac{3}{2} e_{gd} i_{gd} = \frac{1}{2} C_d \frac{d}{dt} \left(u_{dc}\right)^2 + \frac{u_{dc}^2}{R_{load}} \tag{9}$$

The reference value of the i_{gd} is derived from the modified equation of the power balance condition (9) and can be presented as (10).

$$i_{gdref} = \frac{1}{k_1 k_2}\left(p_{Cd}(t) + p_{load}(t)\right) = \frac{1}{k_1 k_2}\left(p_{Cd}(t) + u_{dc} i_{load}\right) \tag{10}$$

The k_1 constant includes the coefficient dependent on the assumed matrix of the transformation from the three-phase coordinates into the rectangular frame. The k_2 constant stands for the difference between the e_{gd} and u_{dc} since the boost-type voltage-source PWM rectifiers operate with $u_{dc} > e_{gd}$. Thus k_2 should be individually selected to provide the equality of (10). The power of the load $p_{load}(t)$ can be calculated either with the help of the DC-link voltage and load current transducers or a state-space load observer [1]. The instantaneous values of the capacitor power $p_{Cd}(t)$ are computed in the PI controller that regulates the state variable u_{dc}^2. Fig.4 demonstrates the proposed nonlinear decoupled vector control system of the PWM rectifier with the feedforward compensation of the load impact.

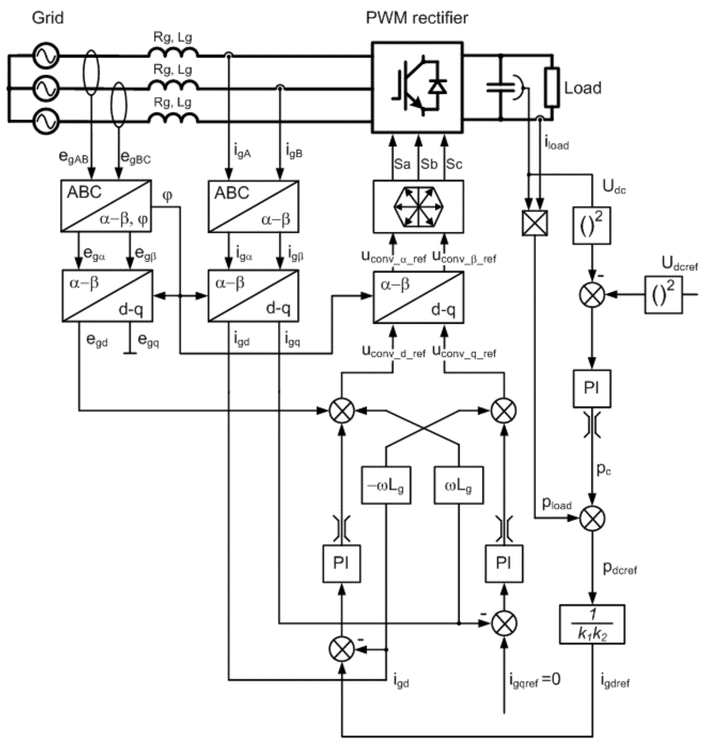

Fig.4. Decoupled vector control of PWM rectifier with load compensation

5. EXPERIMENTAL STUDIES OF PROPOSED CONTROL TECHNIQUE

The experimental verification of the proposed control method has been carried out on the laboratory prototype with the power converter and the fixed-point DSP. The power unit of the proposed prototype of the AC/DC line-side converter is based on the 3.3 kW IGBT power module by EUPEC® with the electronic interface EiceDRIVER™ 6ED003E06-F [2]. As the control unit the evaluation board eZdsp™ R2812 based on the 150 MHz TMX320R2812 DSP has been chosen. Fig.5 demonstrates an overview of the laboratory setup with the PWM rectifier.

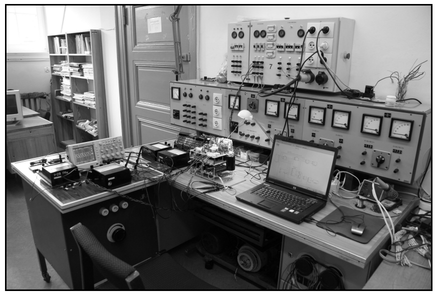

Fig.5. Overview of experimental setup of the PWM rectifier

Fig.6 shows the grid phase current at unity power factor by the step change of the converter load and the fast transients at the DC-side of the PWM rectifier.

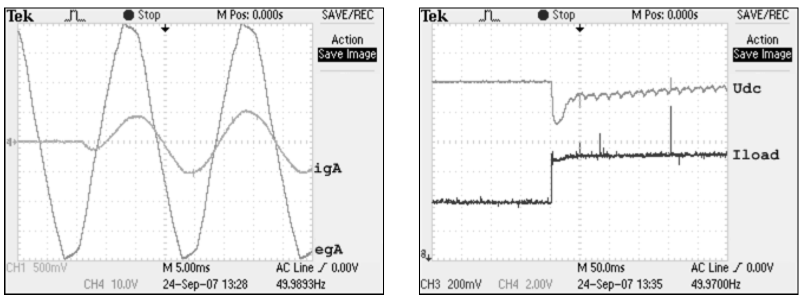

Fig.6. (left) grid phase voltage and respective grid phase current,
(right) transient of DC-link voltage and measured load current from feedforward

Fig.7 presents the grid phase current in the synchronous *d-q* frame by the step change of the converter load and the input PWM voltage of the AC/DC line-side converter.

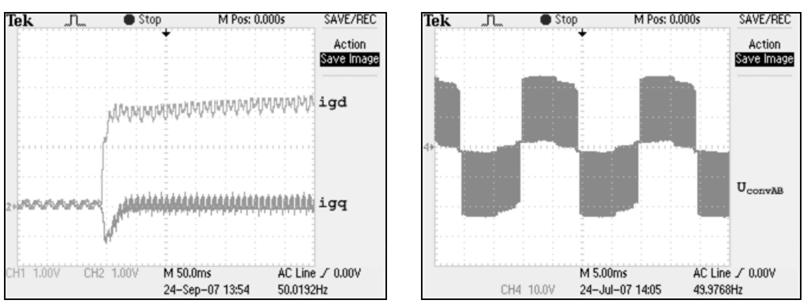

Fig.7. (left) grid currents in synchronous frame, (right) rectifier's input PWM line-to-line voltage

For the reliable confirmation of the excellent dynamic performance of the proposed nonlinear control system of the PWM rectifier the comparative analysis has been carried out. The Voltage Oriented Control of the PWM rectifier without the load compensation and the current decoupling system from Fig.3b has been examined. The experimental results have been obtained at the same grid and load conditions as well as the computational rates of the control system. Fig.8 demonstrates the transient of the grid currents in the *d-q* coordinates and the response of the DC-link voltage control loop to the step change of the converter load.

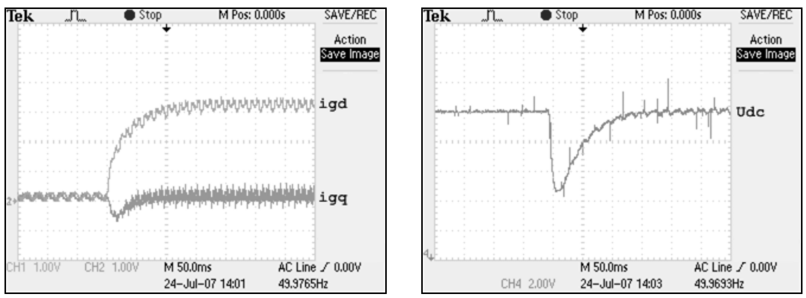

Fig.8. Selected results of Voltage Oriented Control of PWM rectifier without load compensation and current decoupling (from Fig.3b): (left) grid currents in *d-g* coordinates, (right) DC-link voltage

6. CONCLUSIONS

The paper presents the real-time application of the decoupled control system of the PWM rectifier based on the Voltage Oriented Control technique. The compensation of the load current has been introduced to provide the high-performance operation of the AC/DC line-side converter. For the effective PI control of the DC-link voltage the linearization of the rectifier's output voltage control loop has been carried out. Hence the control variable $(u_{dc})^2$ has been taken into account instead of the u_{dc}. This technique has eliminated the nonlinearity of the PWM rectifier and has made the linear PI voltage controller robust and independent of the operating point.

The disadvantageous influence of the rapid changes of the converter load has been minimized by the introduction of the feedforward of the load current based on the load current sensor. The feedforward information about the actual converter load has contributed to the considerable improvement of the transient response of the DC-link voltage. The high quality of the grid currents has been provided by the application of the Space-Vector Pulse Width Modulation with the switching frequency of 5kHz.

The operation of the proposed control method has been successfully examined on the laboratory setup of the PWM rectifier with the fixed-point digital signal processor.

REFERENCES

[1] BLASCO-GIMÉNEZ R., PENA R., CÁRDENAS R., CARTES J., *Load Compensated Non-linear Voltage Control of a Boost Type Rectifier*, 9th International Conference on Power Electronics and Motion Control-EPE-PEMC`00, Košice, 2000.

[2] KANELIS K., LORENZ L., STOLZE T., *New Low Cost IGBT-Modules*, Proceedings on International Conferences ZM Communications GmbH PCIM'01, Nuremberg, 2001.

[3] KNAPCZYK M., PIEŃKOWSKI K., *Analysis of Pulse Width Modulation Techniques for AC/DC Line-Side Converters,* Scientific Papers of the Institute of Electrical Machines, Drives and Metrology of the Wroclaw University of Technology, No. 59, Studies and Research, No. 26, Wroclaw, 2006.

[4] KNAPCZYK M., PIEŃKOWSKI K., *Robust Current Control Technique for Boos-Type AC-DC line-side Converter with Sliding-Mode Voltage Observer,* Scientific Papers of the Institute of Electrical Machines, Drives and Metrology of the Wroclaw University of Technology, No. 58, Studies and Research, No. 25, Wroclaw, 2005.

[5] KWON B. H., YOUM J. H., LIM J. W., *A Line-Voltage-Sensorless Synchronous Rectifier*, IEEE Transactions on Power Electronics, vol.14, no.5, September 1999.

[6] RIOUAL P., POULIQUEN H., LOUIS J. P., *Nonlinear control of PWM rectifier by state feedback linearization and exact PWM control*, IEEE PESC'94 Proceedings, June, 1994.

[7] RODRÍGUEZ J. R., DIXON J. W., ESPINOZA J. R., PONTT J., LEZANA P., *PWM Regenerative Rectifiers: State of the Art*, IEEE Transactions on Industrial Electronics, vol.52, no.1, February 2005.

[8] SINGH B., SINGH B. N., CHANDRA A., AL-HADDAD K., PANDEY A., KOTHARI D. P., *A Review of Three-Phase Improved Power Quality AC-DC Converters*, IEEE Transactions on Industrial Electronics, vol.51, no.1, June 2004.

[9] SOARES V., VERDELHO P., *Linear and Sliding-Mode Controllers for Three-Phase Four-Wire Power Converters*, International Symposium on Industrial Electronics IEEE-ISIE'05, Dubrovnik, 2005.

[10] YE Y., KAZERANI M., QUINTANA V. H., *Modeling, Control and Implementation of Three-Phase PWM Converters*, IEEE Transactions on Power Electronics, vol.18, no.3, May 2003.

ODSPRZĘŻONE STEROWANIE WEKTOROWE PROSTOWNIKIEM PWM O POLEPSZONYCH WŁAŚCIWOŚCIACH DYNAMICZNYCH

Artykuł prezentuje odsprzężone sterowanie wektorowe prostownikiem PWM z nieliniową regulacją napięcia stałego obwodu pośredniczącego i sprzężeniem wyprzedzającym od prądu obciążenia przekształtnika. W celu polepszenia właściwości dynamicznych układu sterowania prostownikiem PWM wprowadzono odsprzężenia prądów sieci w prostokątnym układzie współrzędnych, zsynchronizowanym z wektorem napięcia sieci. Aby poprawić dynamiczną odpowiedź liniowego regulatora napięcia stałego przekształtnika wprowadzono sprzężenie wyprzedzające od prądu obciążenia. Ponadto przedstawiono metodę linearyzacji dynamiki działania pętli sterowania napięciem stałym poprzez regulację drugiej potęgi napięcia stałego. Algorytm przedstawionej metody został zaimplementowany w układzie eksperymentalnym prostownika PWM opartym na stałoprzecinkowym procesorze sygnałowym sterującym modułem mocy przekształtnika. Przedstawiono i omówiono wybrane wyniki badań eksperymentalnych.