Electrical Power Quality and Utilisation, Journal *Vol. XII, No. 1, 2006*

Grid Voltages Sensorless Control of the PWM Rectifier with Active Filtering

Daniel WOJCIECHOWSKI

Gdynia Maritime University, Poland

***Summary*: The paper presents structure and experimental results of the control system of the PWM rectifier with active filtering function. Proposed control system was designed for maximum filtering performance in steady state. This task is realized by predictive algorithms applied for both control as well as calculation of grid currents. Accuracy of these algorithms strongly depends on precise information about future samples of equivalent electromotive force of the grid, which is in general distorted and unbalanced. For this purpose, a novel estimator and predictor is proposed. The control of DC voltage is realized with application of variable gain PI controller. It ensures high dynamics in transient states and low gain for steady state oscillations of DC voltage. Proposed control system is AC voltages sensorless and has excellent active filtering performance, even at presence of grid voltage distortions.**

Keywords:
*active filters,
power quality,
predictive control,
estimation techniques*

1. INTRODUCTION

Three phase PWM rectifier based on voltage source inverter topology is recognized as the best choice for front-end converter (Fig. 1a).

With proper control it is capable of bidirectional power conversion with unity power factor and controlled DC voltage [6, 10].

The same topology is used in widely developed shunt active power filter application [1, 2, 7] (Fig. 1b). It is desirable from economical point of view to join PWM rectifier and active filter into one single device, which is depicted on Figure 2.

PWM rectifier with active filtering can be used, for example, as a front-end converter in electrical drives, where it is rated for machine overload capability. Most of time electrical machines works in drive systems below its overload power capability, and even below its rated power, so power electronics converters work in these systems at a fraction of rated power. This surplus of rated power of converter can be utilized for active filtering, which can in consequence reduce overall demand for other harmonics or reactive power compensating devices. This solution requires more sophisticated control, but requires almost no extra hardware components. Some examples of control algorithms of PWM rectifier with active filtering are presented in the literature [3, 5, 9].

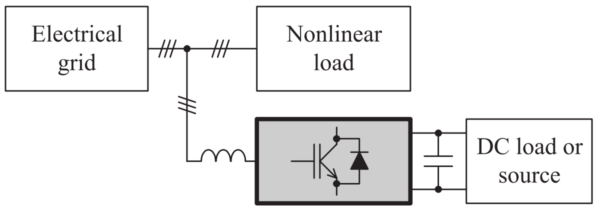

Fig. 2. Application diagram of front-end converter with active filtering

Continuous development and reduction of overall costs of microprocessor systems created a possibility to implement more sophisticated, sensorless control algorithms. The drawback of using processor based control systems is a time delay from measurements to control commands.

In the paper the grid voltages sensorless control system of PWM rectifier with active filtering is presented. Computation related delays are compensated using predictive algorithms and, additionally, the one sampling period prediction is applied for maximum filtering performance.

In all mentioned above applications of the PWM rectifier the control objectives are realized by grid currents shaping. Therefore, the most important part of the PWM rectifier control system is the grid currents inner controller. The accuracy and exactness of grid currents shaping are mostly dependent on quasi-steady state error and dynamics of applied current controller, where a controller's dynamics is

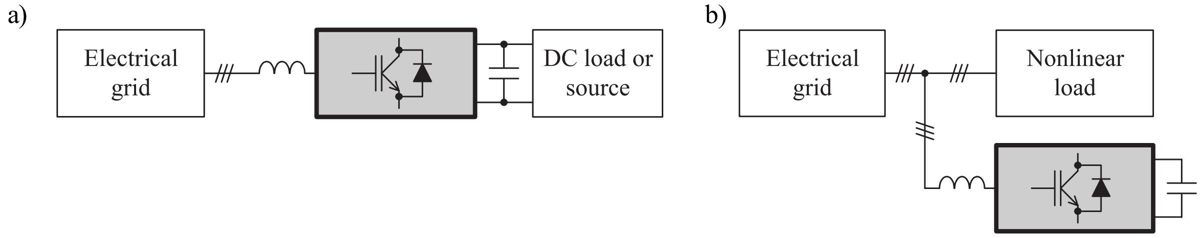

Fig. 1. Application diagram of front-end converter (a) and shunt active power filter (b)

especially important in PWM rectifier applications realizing active filtering. In control systems proposed in literature the importance of currents controller seems to be disregarded and PI [6, 2, 3] or hysteresis [6, 1, 3] controllers are commonly used. High dynamics can be achieved with use of a deadbeat current controller [10, 7], but this type of controller has property of operating in saturated state and has to be designed for particular set of circuit parameters.

In recent years, among promised and extensively developed control techniques are the predictive control algorithms. In the control system presented in the paper the model based predictive controller of grid currents is applied, which has been proposed in original form in [4]. This controller has dynamics which is limited only by circuit parameters of the converter, within of which it assures zero control error. Additionally, this controller is very easy to implement for particular PWM rectifier application and circuits parameters.

The second most important part of the PWM rectifier control system, regardless of its application and structure of the system, is the algorithm of calculation of set grid currents. In the paper, an algorithm is proposed, which is based on well known and commonly used instantaneous power theory. The computation delays are taken into account and predictive algorithm is proposed.

Both the model based grid currents controller and the grid currents calculation algorithm are based on information about past, present and future values of equivalent electromotive force (emf) of the grid. In presented control system this information is calculated in proposed novel sensorless algorithm. Algorithm provides estimation and prediction of in general distorted and unbalanced grid emf.

Another important part of the control system of PWM rectifier with active filtering is the DC voltage controller. In the control system of the PWM rectifier without active filtering function, this controller has to assure fast control of DC voltage during changes of DC load or source, so it has to provide high dynamics and low steady state error. This task can be easily realized by properly designed PI controller. In the control system of a shunt active filter, the DC voltage controller has to provide very low gain for steady state oscillations of DC voltage. These oscillations are the result of compensation of active components of nonlinear load supply harmonic currents. In the active filter application it is not necessary to ensure fast control of DC voltage, because of lack of DC load or source. In an active filter control systems presented in the literature a PI controllers of DC voltage are commonly used. In PWM rectifier with active filtering, the DC voltage controller has to provide both high dynamics in transients and low gain for steady state DC voltage oscillations. This requirements seems to be disregarded in the literature. In the control system presented in this paper the solution based on variable gain PI controller is proposed.

The paper presents experimental results of proposed control system of PWM rectifier with active filtering in steady state as well as in transient states, obtained for 7kVA prototype.

2. MATHEMATICAL DESCRIPTION OF THE SYSTEM

2.1. Representation of signals in three phase system

Instantaneous phase voltages and currents in three-phase system can be linearly transformed into orthogonal components $\alpha, \beta, 0$ using Clarke transform, which for power invariance is defined as:

$$\begin{bmatrix} f_\alpha(t) \\ f_\beta(t) \\ f_0(t) \end{bmatrix} = \mathbf{T} \begin{bmatrix} f_A(t) \\ f_B(t) \\ f_C(t) \end{bmatrix},$$

$$\text{where} \quad \mathbf{T} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ \sqrt{2}/2 & \sqrt{2}/2 & \sqrt{2}/2 \end{bmatrix} \tag{1}$$

In three phase, three wire system the sum of phase currents i_A, i_B, i_C is equal zero at any instant of time. According to (1), the zero component of current is also equal zero. Zero component of voltage is not equal zero, but it has no impact on currents because in three phase, three wire system the impedance for zero component is equal $Z_0 = \infty$, so it can be neglected. Phase voltages and currents in three phase, three wire system can be therefore denoted with orthogonal components α, β and next as a complex numbers, respectively $\underline{u} = u_\alpha + \mathrm{j}u_\beta$ and $\underline{i} = i_\alpha + \mathrm{j}i_\beta$. Signals are represented in a control systems with discrete time samples. Periodical, complex, discrete time signal can be expanded into Fourier series according to equation:

$$\underline{f}(k) = \sum_{n=0}^{N-1} \underline{F}_n \mathrm{e}^{\mathrm{j}2\pi nk/N},$$

$$\text{where} \quad \underline{F}_n = \frac{1}{N} \sum_{k=0}^{N-1} \underline{f}(k) \mathrm{e}^{-\mathrm{j}2\pi nk/N} \tag{2}$$

Particular complex harmonics represent symmetrical and asymmetrical components of distorted and unbalanced voltage or current in three phase, three wire system. Complex harmonics of order $n = 1 \pm 3k,\ k \in \mathbb{Z}$ represents symmetrical components, while remaining harmonics except of zero order represent asymmetrical components. Zero order harmonic is not present.

2.2. Mathematical model of PWM rectifier

Circuit model of PWM rectifier connected to the electrical grid is presented on Figure 3a. It is composed of six power switches with turn off capability, for example IGBTs, with capacitive filter on the DC side and inductive filter on the AC side. Assuming, that in each of three legs of converter there is always one and only one switch in on state and that power

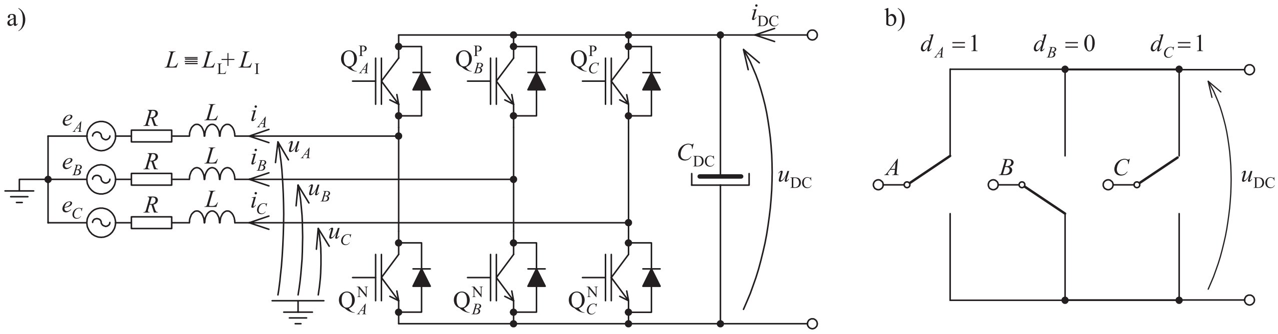

Fig. 3. Circuit model (a) and simplified switching model (b) of the PWM rectifier

switches are ideal, the model of the converter can be simplified as it is presented on Figure 3b. The state of switches in each of the leg can be described using switching function defined in the following way:

$$d_k(t) = \{0, 1\}, \quad k = A, B, C \tag{3}$$

There are six active states of converter for $d_A + d_B + d_C = \{1, 2\}$ and two passive states for $d_A + d_B + d_C = \{0, 3\}$. In each of the active state there exists a circuit for energy transfer between the DC and AC side. Using the switching function model, PWM rectifier connected to the grid can be described by equations:

$$\frac{\mathrm{d}\underline{i}}{\mathrm{d}t} = -\frac{R}{L}\underline{i} + \frac{1}{L}\left(u_{DC}\underline{d} - \underline{e}\right),$$
$$\frac{\mathrm{d}u_{DC}}{\mathrm{d}t} = \frac{1}{C_{DC}}\left[i_{DC} - Re\left(\underline{d}^*\underline{i}\right)\right] \tag{4}$$

where all the complex quantities in the above equations are obtained by Clarke transform defined by (1), and represented as a complex numbers. Neglecting switching functions and defining instantaneous powers:

$$\underline{s}_{conv} = \underline{u}^*\underline{i},\ p_{conv} = Re\left(\underline{u}^*\underline{i}\right),\ q_{conv} = Im\left(\underline{u}^*\underline{i}\right) \tag{5}$$

the linear, functional model of PWM rectifier can be formulated as:

$$\frac{\mathrm{d}\underline{i}}{\mathrm{d}t} = -\frac{R}{L}\underline{i} + \frac{1}{L}\left(\underline{u} - \underline{e}\right),\ \frac{\mathrm{d}u_{DC}}{\mathrm{d}t} = \frac{1}{C_{DC}}\left(i_{DC} - \frac{p_{conv}}{u_{DC}}\right) \tag{6}$$

3. CONTROL SYSTEM OF THE PWM RECTIFIER WITH ACTIVE FILTERING

3.1. Structure and implementation of proposed control system

The structure of proposed control system is presented on Figure 4. The control algorithm is computed with constant sampling period T_{sampl}. The last measured samples are denoted with $(k - 1)$. Voltages are assumed to be constant during each T_{sampl} and samples defined between $(n - 1)$ and (n) are denoted with $(n - 1| n)$. Values of voltages at instant of time denoted with (n) are approximated with average value

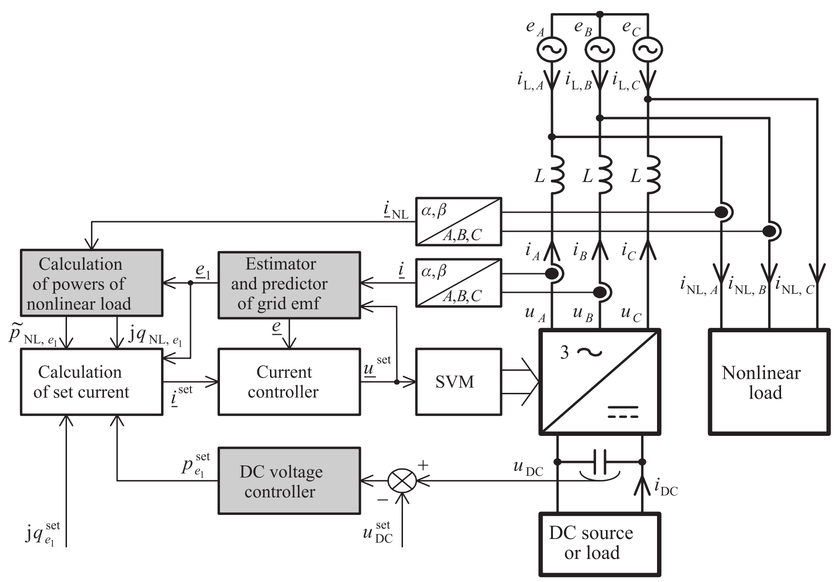

Fig. 4. Block diagram of proposed control system

defined between $(n) - 0.5\ T_{sampl}$ and $(n) + 0.5\ T_{sampl}$. On each sampling period, based on signals measured at instant $(k - 1)$, the grid voltage $u^{set}\ (k \mid k + 1)$ is computed in the control algorithm. On Figure 4, a samples denotations are neglected for simplicity. The control system can be divided into the following main parts:

- DC voltage controller,
- algorithm of calculation and prediction of compensated components of nonlinear load power,
- algorithm of calculation of set grid currents,
- predictor and estimator of distorted and unbalanced equivalent electromotive force of the grid,
- model based predictive controller of grid currents,
- Space Vector Pulse Width Modulator (SVM).

The proposed control system was implemented on digital controller with floating point digital signal processor ADSP-21065L and programmable logic device Altera FLEX 6000. Next, it was investigated on 7kVA laboratory prototype of PWM rectifier with IGBT power switches. The parameters of investigated system are listed in appendix.

3.2. Control of DC voltage

The objectives of DC voltage controller of the control system of PWM rectifier with active filtering can be formulated as follows:

- fast control of DC voltage u_{DC} in transients at changes of current i_{DC},
- low gain for oscillations of u_{DC} related with compensation of active components of nonlinear load current $\underline{i}_{NL}$.

These control objectives can be fulfilled by proposed variable gain PI controller (Fig. 5a). The algorithm of PI controller is described by following equation:

$$p_{e_1}^{set}(k-1) = k_p \delta u_{DC}(k-1) + \\ + \frac{1}{2} T_{sampl} k_i \sum_{n=1}^{k-1} \left[\delta u_{DC}(n-1) + \delta u_{DC}(n) \right] \quad (7)$$

The proportional gain of the applied controller is dependent on its input error δu_{DC} (Fig. 5b), and is described as follows:

$$k_p = \begin{cases} k_{p,min} & \Leftarrow \left|\delta u_{DC}\right| < \Delta U_{thr} \\ A_k \left(\left|\delta u_{DC}\right| - \Delta U_{thr} \right) + k_{p,min} & \Leftarrow \left|\delta u_{DC}\right| \geq \Delta U_{thr} \end{cases} \quad (8)$$

where $k_{p,min}$ is the minimal value of k_p, ΔU_{thr} denotes a threshold value of δu_{DC}, and A_k denotes is a slope of linear function $k_p = f(\delta u_{DC})$ for $|\delta u_{DC}|$ greater than ΔU_{thr}. This solution fulfils control requirements defined above. It is important to design the threshold value ΔU_{thr} to be not less than amplitude of filtering related oscillations of DC voltage. Based on (6), these oscillations are described as follows:

$$\tilde{u}_{DC} = \frac{1}{C_{DC}} \int_t \left(\tilde{i}_{DC} - \frac{\tilde{p}}{u_{DC}} \right) dt \quad (9)$$

On Figure 6 there are presented transients of u_{DC} and PWM rectifier's grid current i_A, measured during start-up of the control system. Figure 6a presents transients achieved for DC voltage control loop with constant gain PI controller, while Figure 6b — with proposed variable gain PI controller. The values of a controllers parameters were set up to $k_p = 30W/V$, $k_i = 3 \cdot 10^3 W/(V \cdot s)$, and $k_{p,min} = 10W/V$, $k_i = 3 \cdot 10^3 W/V \cdot s$, $A_k = 20$, $\Delta U_{thr} = 2V$, for constant and variable gain controller, respectively. The duration time of transient states for both controllers is the same, while for proposed variable gain controller the overshoot of u_{DC} was 2.5 times smaller and value of proportional gain was 3 times smaller.

On Figure 7, the transients measured during step change of DC load current from $i_{DC} = 0$ to $-4.6A$ are presented.

Proposed controller provides, in addition, low gain for oscillations of DC voltage which are present in case of impulse current of DC load or source and low gain for DC voltage measurement noise.

3.3. Estimator and predictor of distorted and unbalanced electromotive force of the grid

The task of proposed estimator and predictor is to precisely calculate the samples of the grid emf required in both set grid currents calculation algorithm and currents controller. In the set grid currents calculation algorithm, the samples $\underline{e}_1\ (k - 1)$ and $\underline{e}_1\ (k + 1)$ of emf fundamental harmonic are required, while in currents controller the samples $\underline{e}\ (k - 1 \mid k)$ and $\underline{e}\ (k \mid k + 1)$ of in general distorted and unbalanced emf are necessary. The grid emf is calculated based on (6) as follows:

$$\underline{e}_{calc}(k-2 \mid k-1) = L \frac{\underline{i}(k-2) - \underline{i}(k-1)}{T_{sampl}} + \underline{u}^{set}(k-2 \mid k-1) \quad (10)$$

The equivalent grid emf calculated according to (10) contains all of its complex harmonics components, but it is

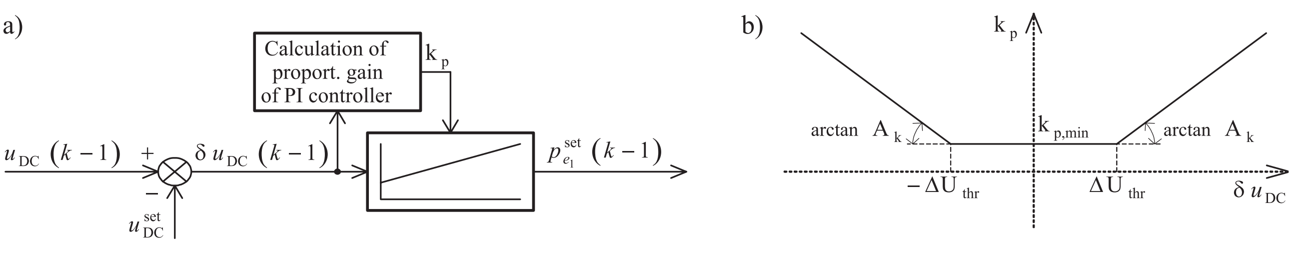

Fig. 5. Controller of DC voltage. Structure (a) and function of variable gain (b)

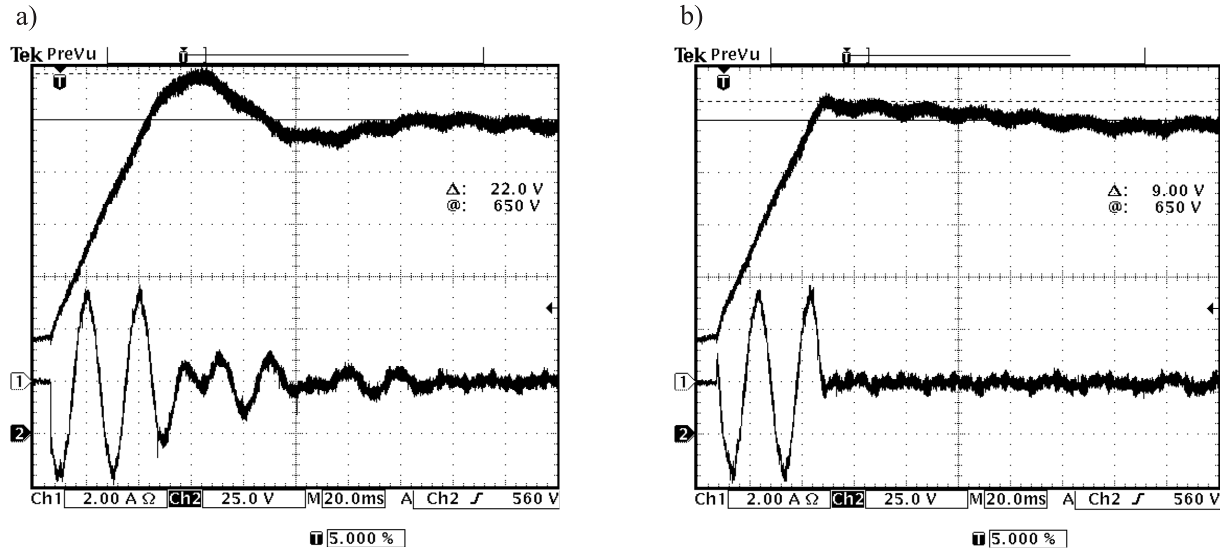

Fig. 6. Transients during start-up of the control system

significantly noised due to measurement errors multiplied by difference quotient which is present in (10). The phase diagram of $\underline{e}_{\mathrm{calc}}$ is presented on Figure 8. The signal has to be restored and predicted. It is realized in the following stages:

- calculation of fundamental harmonic of the grid emf,
- calculation of selected, non-fundamental harmonics of grid emf representing its distortion and unbalance,
- prediction of calculated harmonics of the grid emf,
- superposition of predicted harmonics.

The block diagram of proposed estimator is presented on Figure 9. For simplicity, on Figure 9 and in a consecutive text the sample index $(k-2 \mid k-1)$ is neglected.

The fundamental harmonic of the grid emf is calculated based on module and argument of $\underline{e}_{\mathrm{calc}}$, which are defined by equations, respectively:

$$\left|\underline{e}_{\mathrm{calc}}\right| = \sqrt{\left(Re\,\underline{e}_{\mathrm{calc}}\right)^2 + \left(Im\,\underline{e}_{\mathrm{calc}}\right)^2}$$

$$\measuredangle e_{\mathrm{calc}} = arctan\left(\frac{Im\,\underline{e}_{\mathrm{calc}}}{Re\,\underline{e}_{\mathrm{calc}}}\right) \tag{11}$$

The argument of fundamental harmonic of grid emf is restored in Phase Locked Loop (PLL), while the module is determined by 1st order Infinite Impulse Response (IIR) Low Pass Filter (LPF). In consequence, the fundamental harmonic is calculated as follows:

$$\underline{e}_1 = \left|\underline{e}_1\right| \mathrm{e}^{\mathrm{j}\measuredangle e_1} \tag{12}$$

The complex amplitudes of particular harmonics of grid emf are calculated by correlating noised signal of $\underline{e}_{\mathrm{calc}}$ with basis functions of these harmonics as follows:

$$\underline{E}_n = \overline{\underline{e}_{\mathrm{calc}} \mathrm{e}^{-\mathrm{j}n\measuredangle e_1}} \tag{13}$$

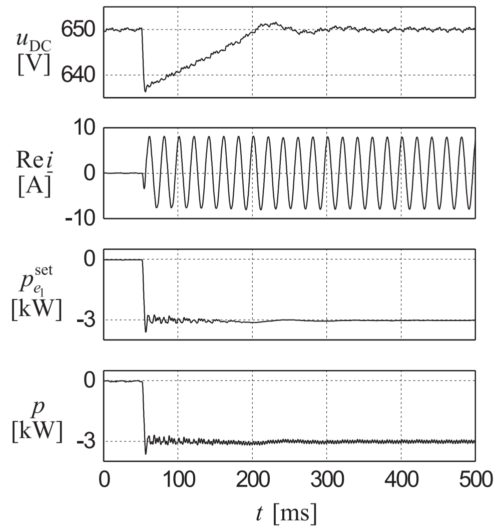

Fig. 7. Transients during step change of DC load from $i_{DC} = 0$A to $i_{DC} = -4.6$A

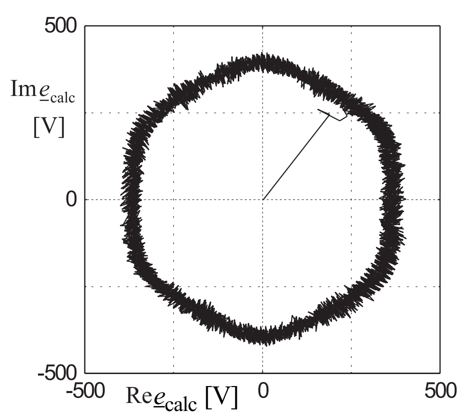

Fig. 8. Phase diagram of equivalent grid emf calculated according to (10)

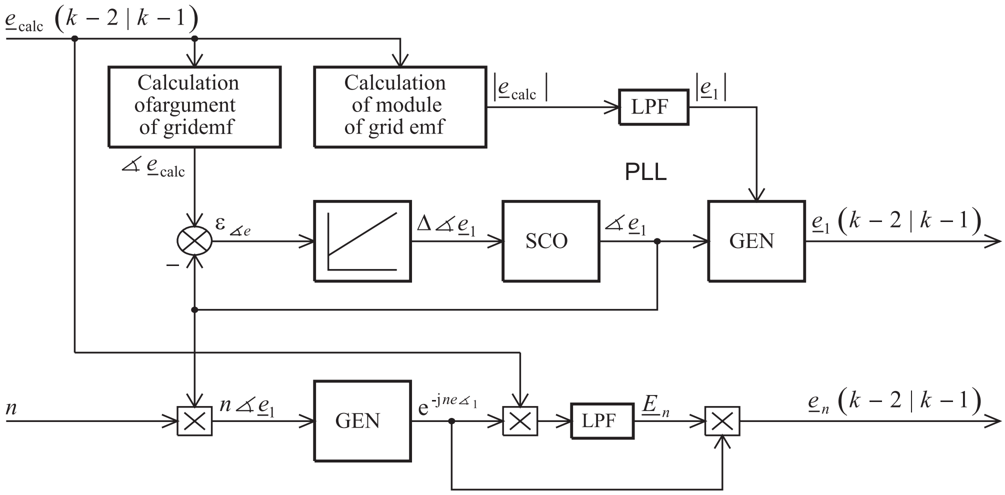

Fig. 9. Estimator of complex harmonics of grid emf

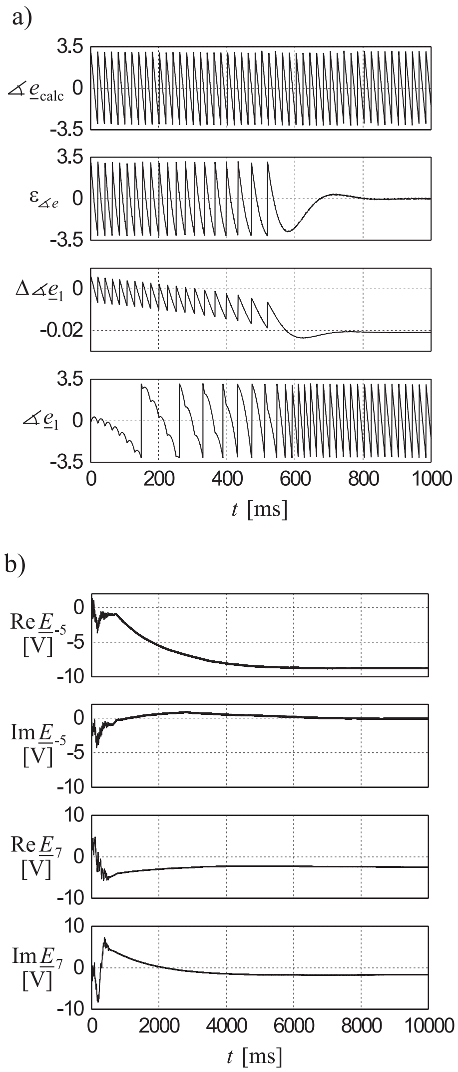

Fig. 10. Synchronization of PLL (a) and estimated amplitudes of the grid emf during start-up (b)

where average value in (13) is determined by 1st order IIR LPF. For ideal filtering, (13) is equivalent with Fourier Transform defined by (2). The particular complex harmonics of grid emf are calculated in the following way:

$$\underline{e}_n = \underline{E}_n e^{-\mathrm{j}n\measuredangle \underline{e}_1} \qquad (14)$$

Prediction of calculated harmonics is realized by incrementing its argument according to:

$$\underline{e}_n\left(k-2+l \mid k-1+l\right) = \underline{e}_n\left(k-2 \mid k-1\right)\mathrm{e}^{\mathrm{j}n\cdot l\cdot\Delta\measuredangle \underline{e}_1} \qquad (15)$$

where n is the harmonic order, l is the prediction horizon, and $\Delta\measuredangle\underline{e}_1$ denotes sampling period increment of argument of $\underline{e}_1$ and it is calculated in PLL. In (15) it is assumed, that amplitudes of particular harmonics are constant during one sampling period T_{sampl}, what is fulfilled in practise. The samples $\underline{e}_1$ $(k-1)$ and $\underline{e}_1$ $(k+1)$ are predicted for $n = 1$ and for $l = 0.5$ and $l = 2.5$, respectively. Superposition of predicted harmonics of the grid emf is realized according to equation:

$$\underline{e}\left(k-2+l \mid k-1+l\right) = \sum_m \underline{e}_m\left(k-2+l \mid k-1+l\right) \qquad (16)$$

On Figure 10a the transients of PLL measured during its synchronization are presented. On Figure 10b there are presented selected transients of calculated amplitudes of grid emf, measured during start-up of the control system and on Figure 11 there are presented transients of restored harmonics of grid emf, and restored distorted emf $\underline{e}$, measured in steady state. Restored signal of emf $\underline{e}$ is free of noise which is present on calculated emf $\underline{e}_{\mathrm{calc}}$.

3.4. Calculation of set grid currents

In the control system, calculation of set grid currents is performed by predictive, time domain algorithm. The PWM rectifier grid currents are calculated to obtain the supply current $\underline{i}_L$ proportional to the fundamental harmonic of grid emf $\underline{e}_1$ [8]. The block diagram of applied algorithm is presented on Figure 12. The predicted sample of the set grid current $\underline{i}^{\mathrm{set}}$ $(k+1)$ is calculated according to equation:

$$\underline{i}^{\mathrm{set}}\left(k+1\right) = \frac{p_{e_1,lim}\left(k+1\right) + \mathrm{j}q_{e_1,lim}\left(k+1\right)}{\underline{e}_1^*\left(k+1\right)} \qquad (17)$$

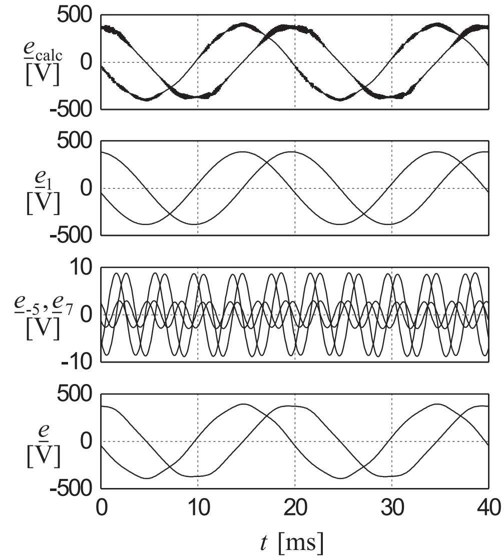

Fig. 11. Estimated harmonics of the grid emf during steady state

where the limited values of instantaneous powers $p_{e1,lim}$ and $q_{e1,lim}$ are related with fundamental component of the grid emf, and are calculated as follows:

$$p_{e_1,lim}(k+1) = min\left\{p_{e_1}^{set}(k+1) + \tilde{p}_{NL,e_1}(k+1),\ S_{e_1,max}\right\} \quad (18)$$

$$\begin{aligned} q_{e_1,lim}(k+1) &= \\ &= min\left\{\left[q_{e_1}^{set}(k+1) + q_{NL,e_1}(k+1)\right],\ \sqrt{S_{e_1,max}^2 - p_{e_1,lim}^2(k+1)}\right\} \end{aligned} \quad (19)$$

The value of limitation of PWM rectifier's apparent power $S_{e1,max}$ is related with maximum permissible current of applied power switches. The limitation defined by (18) and (19) preserves unlimited value of active power at expense of additional limitation of value of reactive power in case, when:

$$S_{e_1,max} \geq p_{e_1}^{set}(k+1) + \tilde{p}_{NL,e_1}(k+1) \ \wedge$$

$$\begin{aligned} S_{e_1,max}^2 < &\left[p_{e_1}^{set}(k+1) + \tilde{p}_{NL,e_1}(k+1)\right]^2 + \\ &+ \left[q_{e_1}^{set}(k+1) + q_{NL,e_1}(k+1)\right]^2 \end{aligned} \quad (20)$$

Predicted samples of power components of nonlinear load in (17), (18), (19) are calculated based on sample of instantaneous apparent power defined for the previous period of the grid emf. Prediction algorithm is based on circular buffer and its structure is depicted in detail on Figure 13. The length of buffer is determined on-line based on detection of zero crossing of grid emf argument. The compensated variable component of active power of nonlinear load is determined by using 1st order IIR LPF.

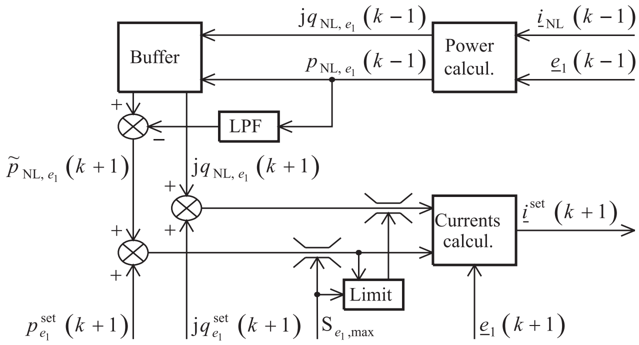

Fig. 12. Set grid current calculation algorithm

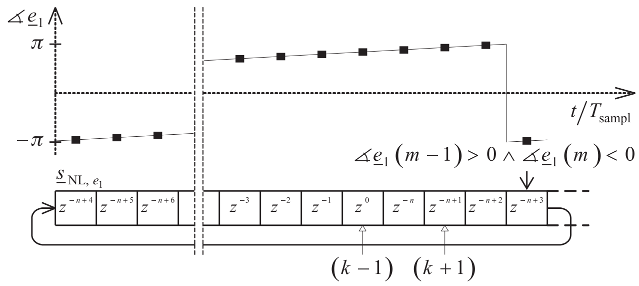

Fig. 13. Circular buffer for prediction of compensated power components

3.5. Currents controller

In the control system of PWM rectifier, grid currents are controlled by model based predictive controller introduced in original form in [4]. The task of this controller on each sampling period T_{sampl} is to calculate set grid voltage $\underline{u}^{set}(k \mid k+1)$ based on measured samples of grid current and predicted samples of grid emf. Set grid voltage is calculated based on (6) according to equation:

$$\underline{u}^{set}(k \mid k+1) = L\frac{\underline{i}^{set}(k+1) - \underline{i}(k)}{T_{sampl}} + \underline{e}(k \mid k+1) \quad (21)$$

where current $\underline{i}(k)$ is predicted as follows:

$$\underline{i}(k) = \underline{i}(k-1) + T_{sampl}\frac{\underline{u}^{set}(k-1 \mid k) - \underline{e}(k-1 \mid k)}{L} \quad (22)$$

The output of the controller constitutes the limited value of set grid voltage and is defined by equation:

$$\underline{u}_{lim}^{set}(k \mid k+1) = min\left\{\begin{array}{l} \underline{u}^{set}(k \mid k+1), \\ \dfrac{\left|\underline{u}_{max}\right|}{\left|\underline{u}^{set}(k \mid k+1)\right|}\underline{u}^{set}(k \mid k+1) \end{array}\right\} \quad (23)$$

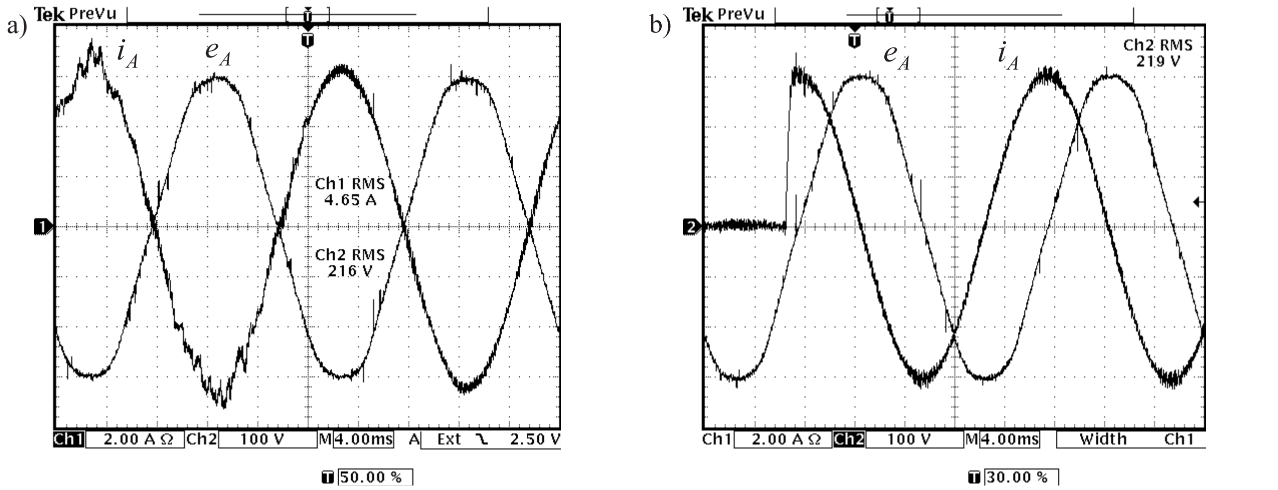

Fig. 14. Transients of grid current i_A during activation of estimator and predictor of the grid emf (a) and step change of set reactive power from $q_{e_1}^{set} = 0$ to 3kVAr (b)

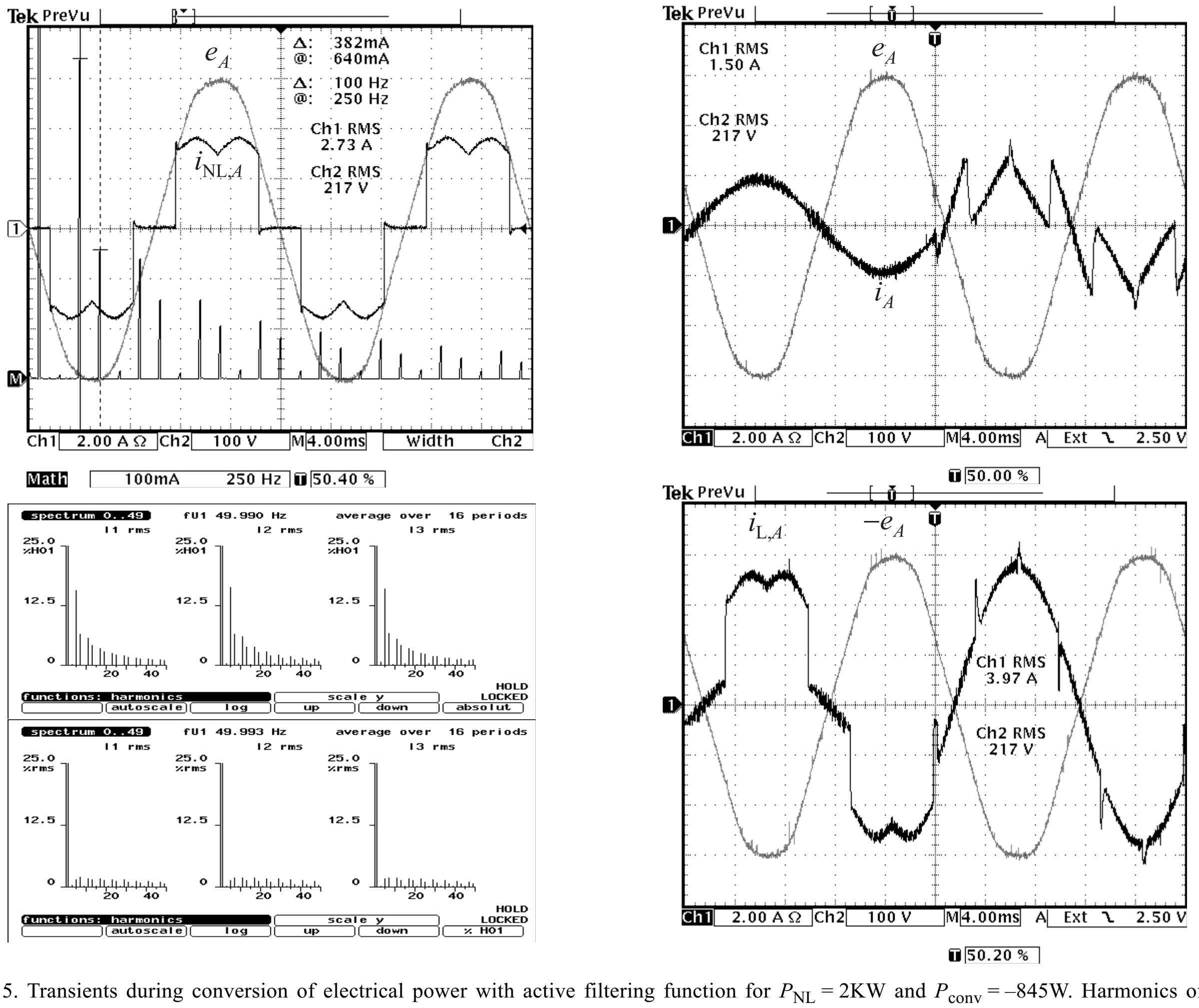

Fig. 15. Transients during conversion of electrical power with active filtering function for $P_{NL} = 2$KW and $P_{conv} = -845$W. Harmonics of grid currents without and with compensation

On Figure 14a there is presented an influence of accuracy of grid emf estimation on quality of current control. From $t = 0$ms to $t = 20$ms, the current controller operates based on noised and unpredicted values of grid emf $\underline{e}_{calc}$ calculated according to (10). From instant $t = 20$ms the estimator and predictor is activated. Total harmonic distortion of current after activation of the predictor and estimator is equal $THD_i = 0.97\%$. On Fig. 14b the dynamics of the controller is presented for instance of transients measured during step change of set reactive power of PWM rectifier.

3.6. Generating of grid voltages

In the control system the grid voltage of the PWM rectifier are generated by using the Space Vector Pulse Width

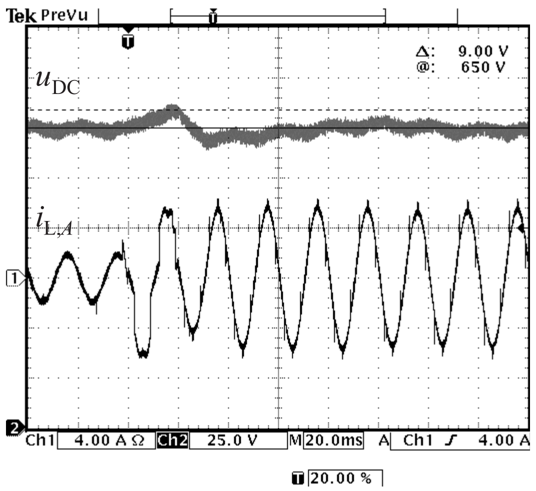

Fig. 16. Transients during step change of active power of compensated nonlinear load from P_{NL} = 0 to 2kW

Modulation (SVM) with implemented compensation for both dead time and power switches voltage drop [9]. The applied compensation algorithms assure precise generation of the grid voltage.

4. OPERATION OF PWM RECTIFIER WITH ACTIVE FILTERING FUNCTION

On Figure 15 there are presented transients measured for operation of control system with active filtering. As a compensated nonlinear load the full bridge three-phase diode rectifier without AC filter and with resistive load was used. Harmonic distortion of supply currents $i_{L,A}$, $i_{L,B}$, and $i_{L,C}$ in case of operation of PWM rectifier without compensation is equal THD_i = 20.5% and in case of operation with compensation — THD_i = 6.7%. The harmonic distortion remaining in the compensated supply currents is the result of circuit parameters dependent power limits of PWM rectifier [9] and not of the control system itself. On Figure 16, the transients measured during step change of active power of nonlinear load are presented. During transient state the supply currents are not fully compensated and there is an instantaneous error of DC voltage. It is related with principle of operation of the predictive calculation algorithm of set grid currents.

5. CONCLUSION

Presented results of experimental investigation confirm excellent active filtering performance and fast DC voltage control of proposed control system. Control tasks are realized correctly without measurements of AC voltages and also in case of presence of AC voltages distortion. Applications of proposed control system include:
— bi-directional AC/DC conversion of electrical energy,
— parallel active filtering,
— reactive power compensation,
and it is possible to arbitrary combine these applications in a single PWM rectifier.

APPENDIX

Table 1. Parameters of electrical circuits and control system

Quantity	Value
Grid voltage – 1st, 5th, and 7th harmonic	220 V, 5 V, 1.75 V
Grid voltage frequency	50 Hz
DC voltage	650 V
Serial inductance on AC side	17.5 mH
Serial resistance on AC side	100 mΩ
Capacitance on DC side	1 mF
PWM carrier frequency	7.5 kHz
Sampling frequency	15 kHz

REFERENCES

1. Aredes M.: *Active power line conditioners*. Ph.D. dissertation, Dept. Elect. Eng., Tech. Univ. of Berlin, Berlin, 1996.
2. Chattopadhyay S., Ramanarayanan V.: *Phase angle balance control for harmonic filtering of a three phase shunt active filter system*. Proc. of APEC 2002, Dallas, Texas, 2002.
3. Cichowlas M.: *PWM Rectifier with Active Filtering*. Ph.D. dissertation, Faculty of Elect. Eng., Warsaw Univ. of Tech., Warsaw, 2004.
4. Krzemiński Z., Guziński J.: *Controller of output current of voltage source inverter with prediction of electromotive force*. Proc. of ED&PE 1999, Kosice, 1999.
5. Lin B., Tsay S., Liao M.: *Integrated power quality compensator based on sliding mode controller*. Proc. of EPE 2001, Graz, 2001.
6. Malinowski M.: *Sensorless control strategies for three-phase PWM rectifiers*. Ph.D. dissertation, Faculty of Elect. Eng., Warsaw Univ. of Tech., Warsaw, 2001.
7. Mossoba J., Lehn P.: *A controller architecture for high bandwidth active power filters*. IEEE Transactions on Power Electronics, vol. 18, no. 1, Jan. 2003.
8. Strzelecki R., Supronowicz H.: *The power factor in AC power distribution systems and methods of its correction*. OWPW, Warsaw, 2000, (in Polish).
9. Wojciechowski D.: *Control of PWM rectifier with prediction of electromotive force*. PhD dissertation, Faculty of Elect. Eng., Gdansk Univ. of Tech., Gdansk, in press, (in Polish).
10. Zhou K., Wang D.: *Digital repetitive controlled three-phase PWM rectifier*. IEEE Trans. Power Electron., vol. 18, Jan. 2003.

Daniel Wojciechowski
was born in Walbrzych, Poland, in 1976. He received the M.Sc. Eng. and PhD degrees in field of electrical drives and power electronics from Gdansk University of Technology, Gdansk, Poland, in 2000 and 2005, respectively. In 2005, he joined Department of Ship Automation at Gdynia Maritime University, Gdynia, Poland, where he is currently an Adjunct. His research interests include modelling and control of high power factor converters, active filters and uninterruptible power systems.
e-mail address: dwojc@am.gdynia.pl

This paper is based on paper "Grid Voltages Sensorless Control System of the PWM Rectifier with Active Filtering Function" presented at the conference Compatibility in Power Electronics CPE 2005, Gdynia, 2005. The paper has been recommended for pubilcation in EPQU Magazine by CPE 2005 Scientific Committee.