

AN IMPROVEMENT OF HARMONIC CURRENT MEASUREMENT ALGORITHMS IN ACTIVE POWER FILTERING

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Abstract: The paper deals with measurement and control aspects of active power filtering in ship systems. A main focus of the paper is concentrated on improvement of harmonic current measurement algorithms based on ip-iq method with application of LPF module and, alternatively, on ip-iq method with application of mean value module.

Keywords: Harmonic current measurement, active power filtering.

1. INTRODUCTION

One of the ways for improving electrical power quality in ships systems, especially loaded by non-linear and non-stationary consumers is an application of the correcting and filtering systems. An exemplary solution consisting of parallel active power filter with power factor correction, series active power filter and set of passive power filters (so - called Combined APFCC and SAPF/PF), dedicated to simultaneous reactive power compensation and mitigation of higher harmonics, has been described in [1]. Further research carried out under polish - chinese joint project led to conclusion, that a basic part of the analysed filtering and correcting system is active power filter and improvement of its properties has a critical importance for solving the analysed problem. Taking into account well known configuration of this filter and related procedures of its control [2], [3] authors proposed a progress on the way of more precise measurement of load harmonic current and the better APF control. The last problem is presented in the separate publication [4], concerning optimization on current tracing algorithm in active power filter based on SVPWM, it means paper dedicated to matter how to improve a compensating current waveform. In this paper a problem of detecting of harmonic current for APE control is considered.

2. MODEL OF THE SHIP ELECTRICAL POWER SYSTEM

Related block diagram of the physical model of ship power system equipped with shunt active power filter is illustrated in Fig.1.

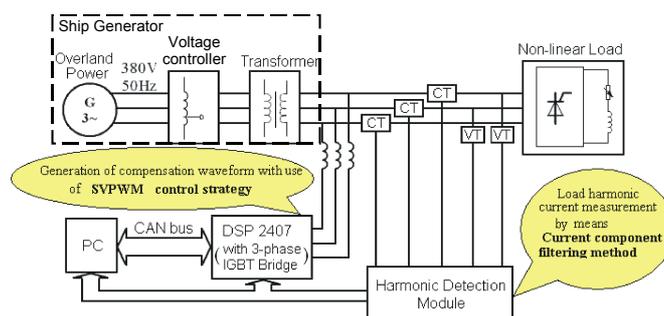


Fig.1. Physical model of ship electrical power system equipped with active power filtering system.

Application of active power filter in the configuration of the system shown in Fig.1 is connected with two basic problems: measurement of distorted load current (including an identification of its waveform) and generation of appropriate compensation current by active power filter. A supply side of the considered system was realized, by means of an appropriately chosen voltage controller and transformer as overland electrical power separator and that made the electric network connected to the transformer be an isolated small capacity network, together with a resistive-inductive character non-linear load. This physical model corresponds to an isolated power network, like ship network. In the preliminary research for solving the first problem the current component filtering method and alternatively wavelet transform method were considered. On the other hand, for solving the second problem the space vector pulse width modulation control strategy, or the fuzzy-sliding mode control strategy as an alternative possibility were carried out. Finally, for further investigations, taking into account the experimental research results a method of harmonic current measurement based on the current component filtering and active power filter control strategy based on the space vector pulse width modulation concept have been chosen. The designed shunt active power filter was able to fulfill the task of harmonic current suppression and keep the current of the network side approximately sinusoidal.

3. A CONCEPT OF IMPROVEMENT OF HARMONIC CURRENT MEASUREMENT ALGORITHMS

In this part of the paper a new solution of harmonics measurements for shunt APF is proposed. It applies a mean value module to the APF instead of the commonly used low-pass filter (LPF) module in the algorithms based on i_p - i_q method [2], [5]. In a marine electric network with considerable load, like an electric propulsion ship, usually asymmetric three-phase voltage occurs. And the application of a mean value module to the APF can make the accuracy of harmonic detection greatly improved, if compared with the application of commonly used LPF module. The last solution leads to the deterioration of harmonic measurement precision, which is mainly due to the phase shift and amplitude variation of the distorted voltage. Simultaneously, the application of a mean value module can significantly reduce the response time of harmonic measurement of a three-phase asymmetrical voltage.

3.1. Measurement of harmonic current with traditional i_p - i_q algorithm [5,6]

The method applied to measure the fundamental active current with traditional i_p - i_q algorithm is shown in Fig. 2.

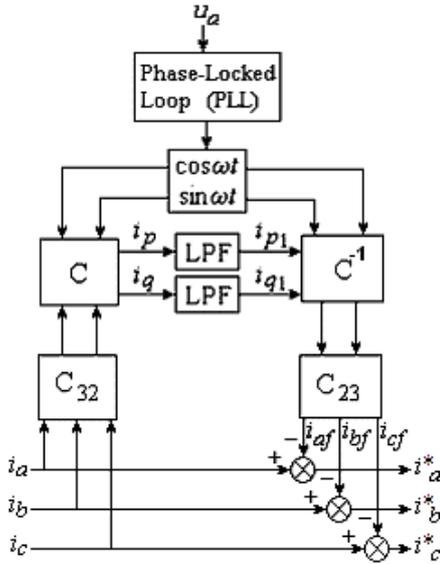


Fig. 2 Block diagram of basic principle of traditional i_p - i_q algorithm.

Where, u_a is network phase “a” voltage. The currents i_a , i_b , i_c are three phase detected load currents respectively, and i_a^* , i_b^* , i_c^* are three phase harmonic currents respectively. The currents i_p , i_q stand for active current and reactive current respectively, and i_{p1} , i_{q1} stand for fundamental active current and reactive fundamental current respectively. The currents i_a^* , i_b^* , i_c^* are the difference of three phase line currents i_a , i_b , i_c and three phase fundamental currents i_{af} , i_{bf} , i_{cf} respectively. Their mathematical relationship is:

$$\begin{bmatrix} i_p \\ i_q \end{bmatrix} = CC_{32} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (1)$$

$$C_{32} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \quad (2)$$

$$C = \begin{bmatrix} \sin \omega t & -\cos \omega t \\ -\cos \omega t & -\sin \omega t \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} i_{af} \\ i_{bf} \\ i_{cf} \end{bmatrix} = C_{23} C^{-1} \begin{bmatrix} i_{p1} \\ i_{q1} \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} i_{af} \\ i_{bf} \\ i_{cf} \end{bmatrix} \quad (5)$$

3.2 Measurement of harmonic current with improved i_p - i_q algorithm

In this part, a new solution of harmonics measurements for shunt APF is proposed. It applies a mean value module to the APF instead of the commonly used low-pass filter (LPF) module (Fig. 2) in the algorithms based on i_p - i_q method [7, 8, 9], as shown in Fig. 3.

It is supposed that the unbalanced 3-phase voltage is u_a , u_b , u_c . At this time, to obtain the synchronization rotation angle ϕ_u using traditional single phase PLL, and to act this synchronization rotation angle as the standard vector phase will make the measurement precision much lower. In this paper, an improved solution is applied to obtain the synchronization rotation angle of 3-phase voltage.

Firstly, using balanced component method to decompose u_a , u_b , u_c into 3 sets balanced fundamental components of positive sequence.

$$\begin{bmatrix} U_{a1} \\ U_{b1} \\ U_{c1} \end{bmatrix} = \begin{bmatrix} U^+ \sin(\omega t + \phi_u^+) \\ U^+ \sin(\omega t + \phi_u^+ - \frac{2}{3}\pi) \\ U^+ \sin(\omega t + \phi_u^+ + \frac{2}{3}\pi) \end{bmatrix} \quad (6)$$

and negative sequence components,

$$\begin{bmatrix} U_{a2} \\ U_{b2} \\ U_{c2} \end{bmatrix} = \begin{bmatrix} U^- \sin(\omega t + \phi_u^-) \\ U^- \sin(\omega t + \phi_u^- - \frac{2}{3}\pi) \\ U^- \sin(\omega t + \phi_u^- + \frac{2}{3}\pi) \end{bmatrix} \quad (7)$$

zero sequence component: U_0

where, $\phi_u^+ = \phi_u^-$, $U_a = U_{a1} + U_{a2} + U_0$; $U_b = U_{b1} + U_{b2} + U_0$; $U_c = U_{c1} + U_{c2} + U_0$,

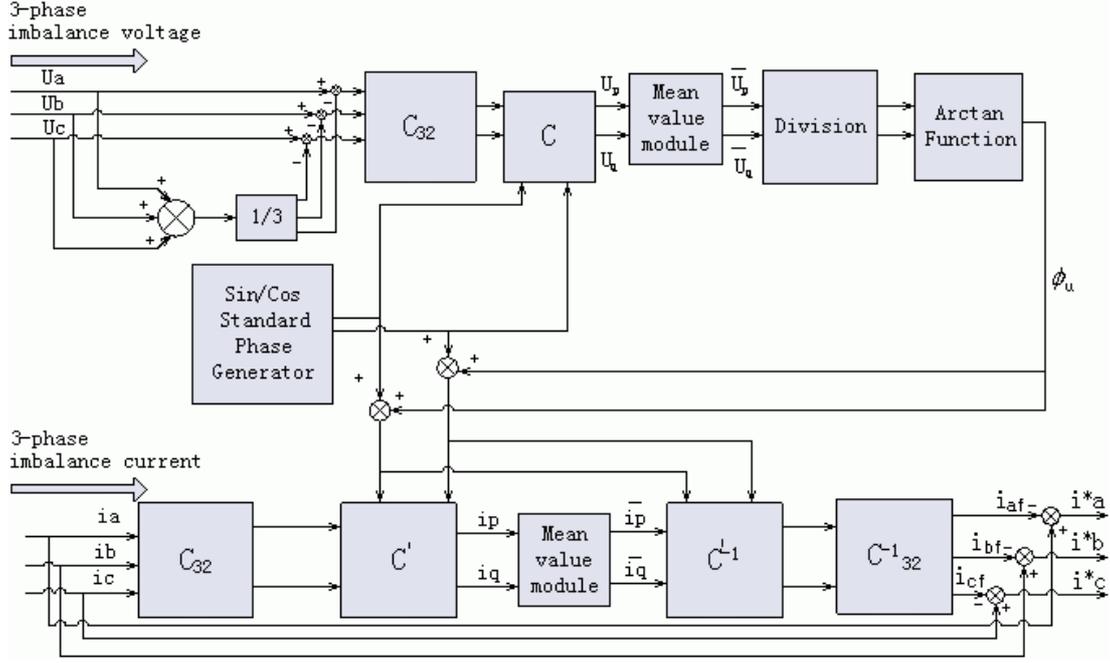


Fig. 3. Block diagram of harmonics measurement algorithm with application of a mean value module for shunt active power filter in ship network

So that $U_0 = 1/3(U_a + U_b + U_c)$.

u_a^*, u_b^*, u_c^* are the sum of positive sequence component and negative sequence component. To make transform similar as i_p - i_q transform, then to be filtered with a mean value module, the DC component can be obtained.

$$\begin{bmatrix} \overline{U_p} \\ \overline{U_q} \end{bmatrix} = \begin{bmatrix} \sqrt{3}U^+ \cos \phi_u^+ \\ -\sqrt{3}U^+ \sin \phi_u^+ \end{bmatrix} \quad (8)$$

Then, $\frac{\overline{U_q}}{\overline{U_p}} = \tan \phi_u^+$, and to obtain ϕ_u^+ through

$\arctan \frac{\overline{U_q}}{\overline{U_p}}$. The ϕ_u is obtained.

i_a, i_b, i_c , are 3-phase load current, and the active component i_p and reactive component i_q are,

$$\begin{bmatrix} i_p \\ i_q \end{bmatrix} = C' C_{32} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (9)$$

$$\text{where, } C_{32} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \quad (10)$$

$$C' = \begin{bmatrix} \sin(\omega t + \phi_u) & -\cos(\omega t + \phi_u) \\ -\cos(\omega t + \phi_u) & -\sin(\omega t + \phi_u) \end{bmatrix} \quad (11)$$

$\sin(\omega t + \phi_u)$ and $-\cos(\omega t + \phi_u)$ are all in-phase with source voltage which are obtained through 3-phase voltage phase lock module.

Through a mean value module, fundamental active current $\overline{i_p}$ and reactive fundamental current $\overline{i_q}$ are obtained respectively. Then,

$$\begin{bmatrix} i_{af} \\ i_{bf} \\ i_{cf} \end{bmatrix} = C_{32}^T C'^{-1} \begin{bmatrix} \overline{i_p} \\ \overline{i_q} \end{bmatrix} \quad (12)$$

And afterwards,

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} i_{af} \\ i_{bf} \\ i_{cf} \end{bmatrix} \quad (13)$$

It is supposed that the measured 3-phase current is,

$$\begin{cases} i_a = \sum_{k=1}^{\infty} I_{km} \sin(k\omega t + \phi_{ku}) \\ i_b = \sum_{k=1}^{\infty} I_{km} \sin[k(\omega t - \frac{2}{3}\pi) + \phi_{ku}] \\ i_c = \sum_{k=1}^{\infty} I_{km} \sin[k(\omega t + \frac{2}{3}\pi) + \phi_{uk}] \end{cases} \quad (14)$$

where, I_{km} , ϕ_u are the amplitude and initial phase of the k th harmonic current respectively.

According to figure 3, and based on formula (14), i_p , i_q are described as,

$$\begin{cases} i_p = \sqrt{\frac{2}{3}} \sum_{k=1}^{\infty} I_{km} \left[\sqrt{3} \sin \frac{2}{3} k\pi \cos \omega t \cos(k\omega t + \phi_{ku}) \right. \\ \quad \left. + (1 - \cos \frac{2}{3} k\pi) \sin \omega t \sin(k\omega t + \phi_{ku}) \right] \\ i_q = \sqrt{\frac{2}{3}} \sum_{k=1}^{\infty} I_{km} \left[\sqrt{3} \sin \frac{2}{3} k\pi \cos \omega t \cos(k\omega t + \phi_{ku}) \right. \\ \quad \left. - (1 - \cos \frac{2}{3} k\pi) \sin \omega t \sin(k\omega t + \phi_{ku}) \right] \end{cases} \quad (15)$$

Generally the above currents (15) are composed of the AC and DC components. But since the network has no even order harmonics, the mean value of the AC component in 1/6 period is 0. Then the DC component \bar{i}_p , \bar{i}_q can be obtain by using the mean value module, as listed in the formula (16).

$$\begin{cases} \bar{i}_p = \frac{6}{T} \int_{t-\frac{T}{6}}^t i_p dt \\ \bar{i}_q = \frac{6}{T} \int_{t-\frac{T}{6}}^t i_q dt \end{cases} \quad (16)$$

From formula (16), when a mean value module is applied, only 1/6 fundamental period is delayed in obtaining \bar{i}_p and \bar{i}_q . It shows that the response time is reduced.

4. RESULTS OF SIMULATION RESEARCH

This has been mentioned above that two version of ip-iq method have been chosen for this paper purpose. First version is based on application of the commonly used low-pass filter as harmonic detection module. Second version implements mean value module for the very same aim. In both cases the resulting distortions of load currents have been analyzed and compared. This is justified by the fact that the whole solution is to improve the very current quality. Further, voltage distortion in ship systems are due to mutual interaction of load current as well as present configuration of ship electric power plant. It means that level of voltage distortions can vary depending on actual load and power plant configuration. Nevertheless, this it seems certain that the more distorted current the worse effect for voltage in whole ship system.

Finally, the current waveforms for both considered cases completed by their respective spectra are presented in Fig. 4.

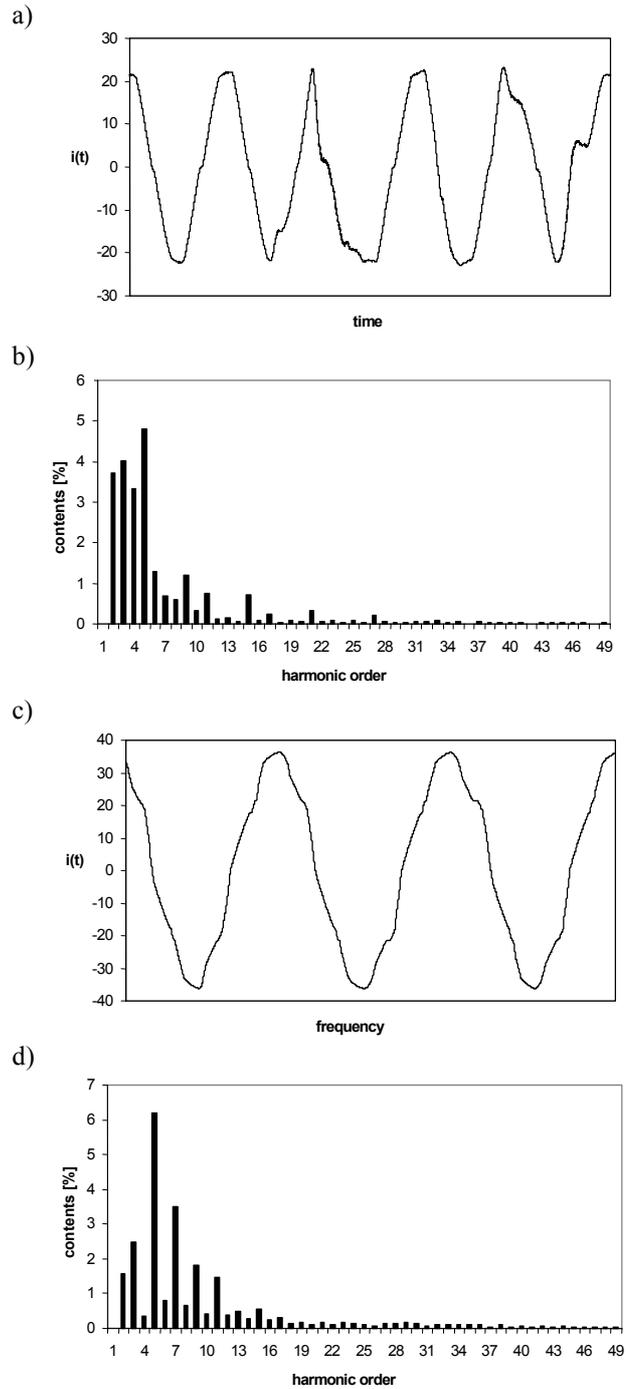


Fig.4. The current waveforms after compensation for two version of algorithm based on ip-iq method, with use LPF module (a) and mean value module (c) and their harmonic analysis (b) and (d).

Next problem to solving has been criterion for the methods comparison. There are quite a number indices for assessment of signal waveform distortions. Arguably, the most commonly used is total harmonic distortion factor, designated as THD. This is calculated as a square root of sum of squares of harmonic r.m.s values related to the r.m.s value of fundamental component [10]. This factor is expressed in percentage. In real power systems there are voltage magnitude fluctuations and its frequency changes. The impact of such a voltage parameters variations on results of harmonics measurements is hardly negligible. The

partial solution would be concept of harmonics subgroups laid in related IEC 61000-4-7 Standard [10]. This concept consists in calculation of square root of the sum of squares of r.m.s. value of harmonic component and r.m.s. values of two spectral components immediately adjacent to it. The result is considered as rms value of harmonic subgroup G [10] (formula for 50-Hz systems):

$$G_{sg,h} = \sqrt{\sum_{i=-1}^1 C_{h-10+i}^2} \quad (17)$$

where: h – order of frequency bin, C – r.m.s. value of frequency bin calculated by Discrete Fourier Transform (DFT) on the basis of ten cycles rectangular window.

Finally, THD is designated as THDS and calculated as follow [10]:

$$THDS = \frac{\sqrt{\sum_{h=2}^n G_h^2}}{G_1} \cdot 100 \quad (18)$$

where: G_1 – r.m.s. value of subgroup of fundamental component.

However, there are standards, which define THD factor in other way as the ratio of rms value of the residue (after elimination of the fundamental) to the rms value of the fundamental expressed in percentage [11], [12], [13]. The distortion index calculated according to this definition is sometimes designated as total waveform distortion TWD [14]. After incorporating the concept of harmonic subgroups the factor can be designated as TWDS and defined as [15]:

$$TWDS = \frac{\sqrt{A_{rms}^2 - G_1^2}}{G_1} \cdot 100 \quad (19)$$

where: A_{rms} – r.m.s. value of whole signal, e.g. current.

The advantages and disadvantages of above presented factors for assessment of waveform distortions have been profoundly discussed in ref. [15] on the basis of real ship signals.

For the paper purpose both above described factors, namely THDS and TWDS, have been calculated. The results of the calculation are laid in Table 1.

Table 1. Measurement results of selected indexes of current distortion for algorithm based on $ip-iq$ method with application of LPF module (a) and mean value module (b).

	a)	b)
THDS [%]	8.34	8.20
TWDS [%]	27.12	12.23

Analysis of the results shown in Table 1 leads to the conclusion that application of mean value module instead of low-pass filter possess clear advantage if TWDS factor is considered. Its value is more than two times lower for the former case. Moreover, there is huge difference between values of THDS and TWDS factors, especially if LPF module is analyzed. This confirms conclusion laid in ref.

[15] that application of THDS factor for rough assessment of waveform distortions in ship systems is at least doubtful. If only THDS would be analyzed, the existing difference between obtained results for both methods would be overlooked.

Finally, this should be added that total harmonic or waveform distortion factors seem the best but not only criteria for the methods assessment. In many cases the content of respective harmonics are to be considered. This can be noted that maximum value of the content of fifth harmonic is below 5% for LPF module and slightly above 6% for mean value module (see Fig. 2b and Fig. 2d, respectively). Nevertheless, comparison of THDS and TWDS as well as analysis of Fig. 2 lead to conclusion that in the case of LPF module the lower value of fifth harmonic is accompanied by higher values of other harmonics and, even worse, interharmonics. Especially, high values of interharmonics are to be pointed out since some authors recommends limiting their respective content to 0.1% (concerns voltage waveform), independently of their frequency [16]. So, the advantage of mean value module is still unchallenged.

5. FINAL REMARKS

The problem of power quality in marine networks have gained its due significance over last few years. This results from some accidents, like malfunctions of important systems, black-outs or even fire. The accidents were due to inappropriate level of power quality in ship systems. The solution is to control and improve the level of power quality.

In this paper a new concept of harmonics measurements for shunt APF has been proposed that uses a mean value module instead of the traditional low-pass filter (LPF) module. The method, if applied to an electric network with asymmetric three-phase voltage, e.g. an electric network of electric propulsion ship, is able to significantly reduce the response time of harmonic detection for the three-phase asymmetrical voltage. The simulation results under the environment of Matlab/simulink show that, compared with the commonly used i_p-i_q method with LPF, this method is faster in detection response and more accurate in harmonic control. The new method based on mean value module also makes the accuracy of harmonic detection greatly improved when the three-phase voltage is asymmetry. This visible for TWDS factor in particular. The difference is huge and must not be neglected.

6. REFERENCES

- [1] Xiao-Yan Xu, Janusz Mindykowski, C.L.Philip Chen, Study on Hybrid Filtering Solution for Marine Electric Network, Polish Maritime Research, Vol.17, No2, 2010, pp.72-78.
- [2] Salmeron, P., Herrera, R. S., and Vazquez, J. R.: 'A new approach for three-phase loads compensation based on the instantaneous reactive power theory', Electric Power Systems Research, 78, (4), pp. 605-617, 2008
- [3] Yang, J., and Wang, Z.: 'A study on the comparison of two methods used to detect the harmonic currents of three-phase circuits', Trans. China Electrotechnical Society, 10, (5), pp. 43-48, 1995

- [4] Xiao-Yan Xu, Yang Caijian, Janusz Mindykowski, Optimization on current tracing algorithm in power filter based on SVPWM, *Automatic and Electric Power Systems*, Vol. 36, N^o 4, 2012, pp. 80-84
- [5] Akagi, H., Kanazawa, Y., and Nabae, A.: 'Instantaneous reactive power compensators comprising switching devices without energy storage components', *IEEE Trans. Industry Applications*, 20, (3), pp. 625-630, 1984
- [6] Peng, F. Z., Akagi, H., and Nabae, A.: 'A new approach to harmonic compensation in power systems – a combined system of shunt passive and series active filters', *IEEE Trans. Industry Applications*, 1990, 26, (6): 983-990.
- [7] Jiang Hai-ya, Li Wen-juan, Du Jian-hua. A comparative analysis of three kinds of fundamental wave extraction on APF[J]. *Techniques of automation and applications*, 2010, 29, (1): 97-100.
- [8] Qi Ming-jun, Luo An, Liu Ding-guo. New method of harmonic currents detection for unbalanced power system[J]. *Power electronics*, 2008, 42, (4): 12-14.
- [9] Li Peng, Gao Jin-feng, Liu Shao-feng. Simulation study in current-average harmonic detection approach using simulink[J]. *Microcomputer information*, 2004, 28, (8): 245-247.
- [10] IEC Standard 61000-4-7, General guide on harmonics and interharmonics measurements for power supply systems and equipment connected thereto, 2002.
- [11] IEC Standard 60092-101, Electrical installations in ships. Definitions and general requirement, 2002.
- [12] IEC Standard 60533, Electrical installations in ships. Electromagnetic compatibility, 2002.
- [13] IEEE Standard 1459-2010, IEEE Standard definitions for the measurement of electric power quantities under sinusoidal, nonsinusoidal, balanced or unbalanced conditions.
- [14] M. Bollen, I. Gu, Signal processing of power quality disturbances, Wiley-Interscience, 2006.
- [15] T.Tarasiuk, J.Mindykowski.: An extended interpretation of THD concept in the wake of ship electric power systems research, *Measurement (Elsevier)*, vol. 45, no 2, 2012, pp. 207-212.
- [16] Fuchs E., Roesler D., Masom M., Are harmonic recommendations according to IEEE and IEC too restrictive?, *IEEE Transactions on Power Delivery*, vol. 19, No. 4, 2004, s. 1775-1786.