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The improvement of compensating current generation 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 will be concentrated on the analysis of the ways of improvement of compensating current generation algorithms. Two aspects of improvement will be discussed: a choice of an appropriate algorithm and an assessment of the quality of compensation by analysis of resulting waveform distortions on power supply side.

I. Introduction

One of the solution for improving electrical power quality in ship systems, usually loaded by non-linear and non-stationary consumers is an application of the correcting systems. These non-linear consumers cause distorted line load currents, which through the voltage drop on the generator and the line impedances are subsequently transferred into distorted voltage supply on the bus bars of main and auxiliary switchboards in the ship electrical power systems [1]. A fundamental condition for effective operation of the ship electric systems is to control and limit of the distorted (mainly by harmonics and interharmonics) current impact on the whole system operation, e.g. by active power systems (APF) [1], [2], [3], [4], [5], [6]. A concept of ship electric power system equipped with the power quality improvement modules is shown in Fig.1. This results in necessity of, firstly, fast and adequate detection of analysed, usually significantly distorted load current waveforms, and secondly a precise control of active power filter with the use of appropriate algorithms for compensating current generation. The first problem, is presented in the separated publication [2], concerning a new concept of harmonic current detection for shunt active power filters control. The last one will be discussed in this paper, based on the research results carried out under Polish-Chinese joint research project.

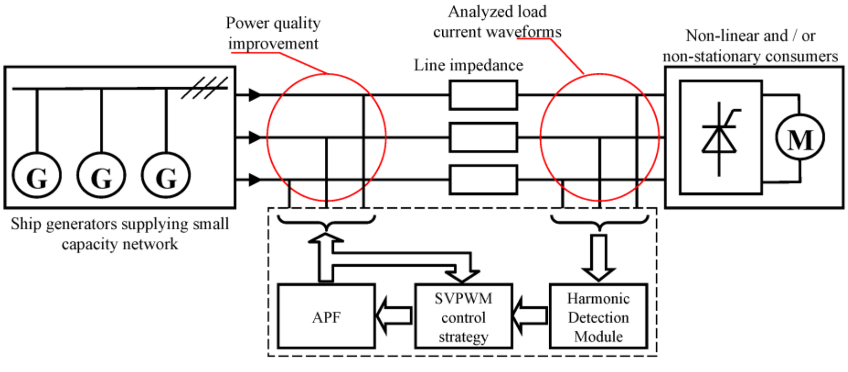

Figure 1. Ship electrical power network with shunt APF as power quality correction system

Within this research two concepts, how to improve the quality of compensation current generated by APF were considered: the first method, which adopts quasi - resonant control algorithm, and the second one based on traditional method of SVPWM (Space Vector Pulse Width Modulation) current tracing algorithm, developed as optimized method of SVPWM current tracing algorithm. Some aspects of the optimized method mainly related to the design and structure of the new algorithm, versus traditional version has been presented in paper published in Chinese [2]. The novum of this paper is in-depth comparative analysis of resulting waveforms distortions on power supply side, based on the THDS (IEC 61000-4-7) and TWDS (IEEE45:2002) definitions and the other complementary criteria [7].

II. A concept of improvement of compensating current generation algorithms in active power filtering

In this part of the paper a new solution of compensating current generation algorithm for shunt APF called by the authors optimized method of SVPWM current tracing algorithm, which adopts the error of three-phase phase-to-phase current to decide the district of space instruction voltage vector [2], [5], is presented. Compared with the traditional current tracing algorithm, the detection of three phase network voltage is avoided, as well as the complex calculation for deciding the scope of space instruction voltage vector is significantly reduced. This approach simplifies hardware circuit and related algorithm.

II.1. Traditional method of SVPWM current tracking algorithm

Current control methods of active power filter commonly use tracking PWM [8], [9] control algorithms, but one of the most frequently applied options of algorithmization of compensating current generation is SVPWM method. In Fig.2 three-phase the ship power supply with the inverter circuit as a basic module of active power filter is presented.

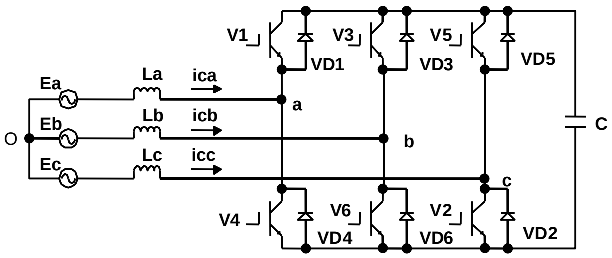

Figure 2. Inverter circuit of active power filter

Paper [10] shows that difference between space instruction (reference) and space-voltage vector is:

$$\boldsymbol{u}_{\boldsymbol{r}}^{*}(t_n)-\boldsymbol{u}_{\boldsymbol{k}}(t_n)=L\frac{d\Delta\boldsymbol{i}(t_n)}{dt} \qquad (1)$$

where: $\boldsymbol{u}_{\boldsymbol{r}}^{*}(t_n)$ - space reference voltage vector, $\boldsymbol{u}_{\boldsymbol{k}}(t_n)$ - space-voltage vector, $\Delta\boldsymbol{i}(t_n)$ - error current vector, and $\Delta\boldsymbol{i}(t_n)=\boldsymbol{i}^{*}(t_n)-\boldsymbol{i}(t_n)$.

From (1), when the space-voltage vector $\boldsymbol{u}_{\boldsymbol{k}}(t_n)$ is tracking the reference voltage vector $\boldsymbol{u}_{\boldsymbol{r}}^{*}(t_n)$, the changing ratio of the error current vector $d\Delta\boldsymbol{i}(t_n)/dt$ can be controlled. Then, one can control the error current vector $\Delta\boldsymbol{i}(t_n)$ to realize the purpose of current tracking. The detailed description of this algorithm and related designations can be found in [10].

Other exemplary description of this method [4] shows that the reference voltage vector $\boldsymbol{u}_{\boldsymbol{r}}^{*}$ is the sum of the grid voltage $\boldsymbol{E}(t_n)$ and vector $Ld\boldsymbol{i}_{\boldsymbol{r}}^{*}(t_n)/dt$. The value of $Ldi_a^{*}(t_n)/dt$, $Ldi_b^{*}(t_n)/dt$, and $Ldi_c^{*}(t_n)/dt$ can be obtained by the value of $E_a(t_n)$, $E_b(t_n)$ and $E_c(t_n)$ measured and substituted into equation (2). Then, the value of u_a^{*}, u_b^{*} and u_c^{*} is obtained as:

$$\boldsymbol{u}_{\boldsymbol{r}}^{*}(t_n)=L\frac{d\boldsymbol{i}_{\boldsymbol{r}}^{*}(t_n)}{dt}+\boldsymbol{E}(t_n) \qquad (2)$$

where the index r corresponds the phases a, b and c, respectively.

There are two drawbacks in this algorithm of determining area which $\boldsymbol{u}_{\boldsymbol{r}}^{*}$ belongs to: the first thing one must do the measurements of three-phases grid voltages $E_a(t_n)$, $E_b(t_n)$ and $E_c(t_n)$ from the physical circuits, and then, the several complex operations must be taken to determined finally which area $\boldsymbol{u}_{\boldsymbol{r}}^{*}$ belongs to. It makes both software and hardware so complex. In theory, the value of $\boldsymbol{u}_{\boldsymbol{r}}^{*}$ can be given by $Ld\boldsymbol{i}_{\boldsymbol{r}}^{*}(t_n)/dt$, but the harmonic

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wave is changing so fast that the value of $L d\boldsymbol{i}_r^*(t_n)/dt$ is hard to obtain [11-14].

II.2. The design of optimized algorithm

As it was mentioned in subchapter II.1, traditional method of SVPWM application in APF control was based on the reference space voltage vectors $\boldsymbol{u}_r^*$ and error current vector $\Delta\boldsymbol{i}$ concepts. Having above mentioned quantities a system of the current tracking control choose the appropriate switching states. Instead of this solution the authors propose to use only error current vectors $\Delta\boldsymbol{i}$ in the tracking control algorithm. The improved algorithm uses three-phase error current vector $\Delta\boldsymbol{i}$ to judge which area $\boldsymbol{u}_r^*$ belongs to directly. For the convenience of description, space voltage vector would be located in the three-phase symmetrical coordinate system transformed from three-phase abc coordinate system with 30° clockwise rotation, shown in Fig.3 below.

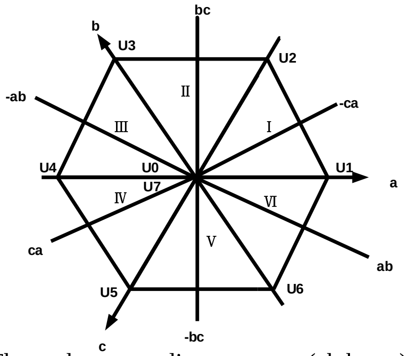

Figure 3. Three phase coordinate system (ab,bc,ca)

Table 1. Relationship of space instruction voltage vectors $\boldsymbol{u}_r^*$ and error current vector $\Delta\boldsymbol{i}$

Area $\boldsymbol{u}_r^*$ located	error current vector
I	$\Delta i_{ab} > 0$, $\Delta i_{bc} > 0$, $\Delta i_{ca} < 0$
II	$\Delta i_{ab} < 0$, $\Delta i_{bc} > 0$, $\Delta i_{ca} < 0$
III	$\Delta i_{ab} < 0$, $\Delta i_{bc} > 0$, $\Delta i_{ca} > 0$
IV	$\Delta i_{ab} < 0$, $\Delta i_{bc} < 0$, $\Delta i_{ca} > 0$
V	$\Delta i_{ab} > 0$, $\Delta i_{bc} < 0$, $\Delta i_{ca} > 0$
VI	$\Delta i_{ab} > 0$, $\Delta i_{bc} < 0$, $\Delta i_{ca} < 0$

In the case of $\Delta i_{ab} > 0$ (because of $\Delta i_{ab} = i_{ab}^* - i_{ab}$), the value of i_{ab} should be increased to make Δi_{ab} tend to zero controlling instruction voltage vector $\boldsymbol{u}_r^*$. So one can increase i_{ab} by means of controlling $u_{ab}^*\left(u_{ab}^* > 0\right)$. In the case of $\Delta i_{bc} > 0$ (because of $\Delta i_{bc} = i_{bc}^* - i_{bc}$), the value of i_{bc} should be increased to make Δi_{bc} tend to zero controlling instruction voltage vector $\boldsymbol{u}_r^*$. So one can increase i_{bc} by means of controlling $u_{bc}^*\left(u_{bc}^* > 0\right)$. In the case of $\Delta i_{ca} < 0$ (because of $\Delta i_{ca} = i_{ca}^* - i_{ca}$), the value of i_{ca} should be decreased to make Δi_{ca} tend to zero controlling instruction voltage vector $\boldsymbol{u}_r^*$. So one can decrease i_{ca} by means of controlling $u_{ca}^*\left(u_{ca}^* < 0\right)$. From the analysis above, when $\Delta i_{ab} > 0$, $\Delta i_{bc} > 0$ and $\Delta i_{ca} < 0$, one should make sure $u_{ab}^* > 0$, $u_{bc}^* > 0$ and $u_{ca}^* < 0$. And at this time, the instruction voltage vector $\boldsymbol{u}_r^*$ is located in space **I**. The corresponding conclusions can be drew when it comes to the other 5 situations. In the Tab.1 the optimized relationship of space instruction voltage $\boldsymbol{u}_r^*$ and error current vector $\Delta\boldsymbol{i}$ is presented. Afterwards a principle block diagram of SVPWM current tracking algorithm before and after optimization is shown in Fig.4.

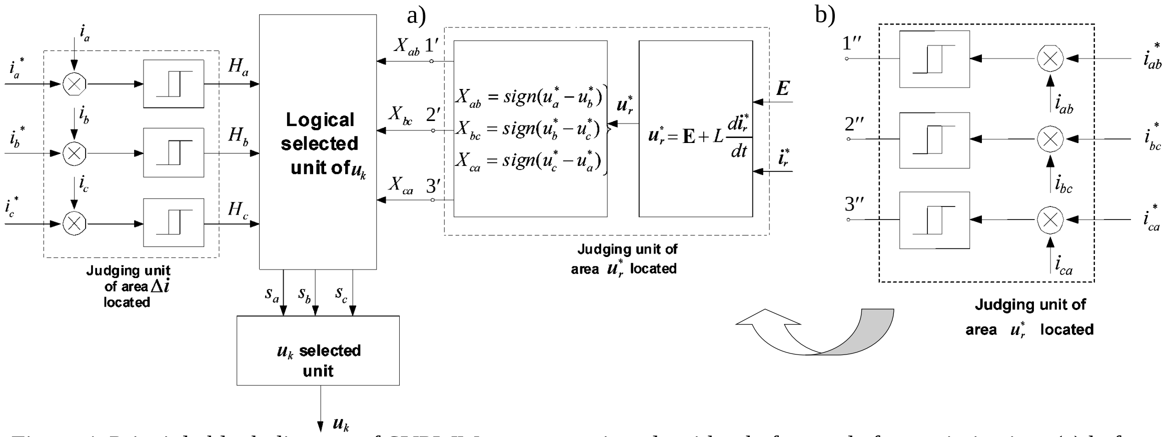

Figure 4. Principle block diagram of SVPWM current tracing algorithm before and after optimization, (a) before optimization, (b) after optimization

After the contrast between (a) and (b) of Fig.4, we can notice that SVPWM current tracing algorithm after optimization does not contain the signal of grid voltage.

III. Results of simulations research - analysis of waveforms distortion

A three-phase uncontrolled bridge rectifier with resistive and inductive load is adopted as harmonic source, of which the parameters are set as below: R=15Ω, L=1mH, C=0.001F, Ls=1mH. The reference voltage u_{dr} of the DC-side is 800V. Presented below curves (Figure 5) have been elaborated for the both cases of compensating current generation, for shunt APF based on traditional and optimized method of SVPWM current tracing algorithms, respectively. The analysis of simulation results has been carried out for both cases of compensating current generation for shunt APF, namely traditional method and optimized SVPWM current tracing algorithm. For the assessment of both cases following indices of waveform distortions have been assumed:

$$THD = \frac{\sqrt{\sum_{h=2}^{n} I_h^2}}{I_1} \cdot 100 \tag{3}$$

$$TWD = \frac{\sqrt{I_{rms}^2 - I_1^2}}{I_1} \cdot 100 \tag{4}$$

where: I_h - r.m.s. value of h-order harmonic, I_1 - r.m.s. value of fundamental component, I_{rms} - r.m.s. value of whole current.

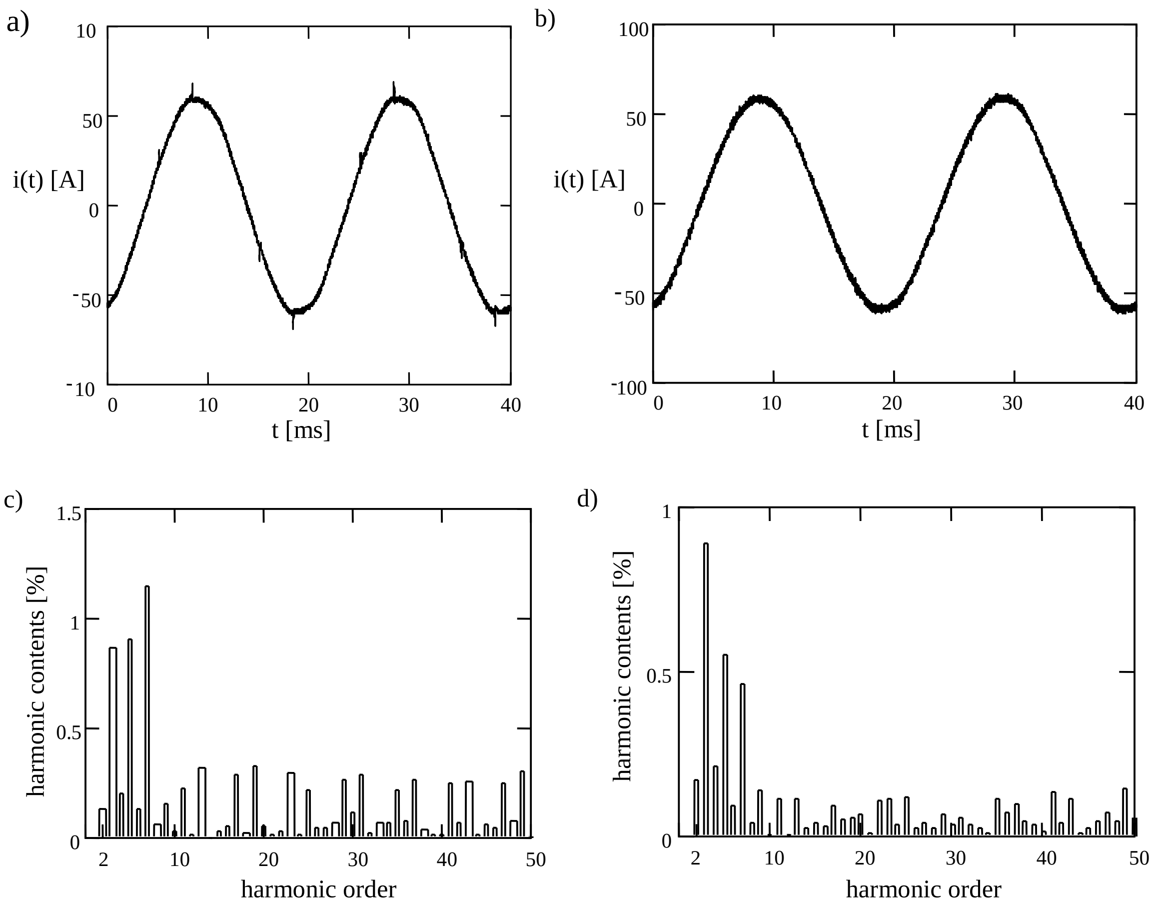

Figure 5. Network current waveform and its harmonic analysis before (a, c) optimization and after optimization (b, d)

As complementary factors, the content of a few lower order harmonic has been used for both methods comparison:

$$I_h^{\%} = \frac{I_h}{I_1} \cdot 100 \tag{5}$$

where: $I_h^{\%}$ - content of harmonic of h-order.

It was assumed that investigated currents fundamental frequency equaled to 50 Hz and the sampling frequency was 200 kHz. Analysis has been carried out for chosen period of both signals. The exact width of measurement window has been determined by analysis of signal zero crossing after low-pass filtration, in order to avoid adverse impact of multiple zero crossings. Finally, the TWD factor represents distortions at whole frequency band, whereas THD factors represents distortions at limited frequency band (lower frequencies), depending on chosen *n* value. For the considered research the following n values have been assumed: 50, 100 and 200. The first value results from highest harmonic order typically used in power quality analysis (and implemented by manufacturers of power quality analyzers). The second value represents harmonic of 100th order and this has been recommended by American Bureau of Shipping for distortion analysis onboard of ships with AFE PWM drives [15]. At last, the third value is equal to 10 kHz (for 50 Hz fundamental frequency, exactly the considered case). The very value is considered as maximal for low-frequency conducted disturbance at ship systems [16]. Finally, the waveforms for both above mentioned cases have been shown in Fig. 5, together with their respective spectra up to 50th harmonic. The results of calculation of the chosen distortion indices have been laid in Table 2.

Table 2. Results of calculation of TWD and THD factors and chosen harmonics content for both considered cases

Factor	Traditional method	Optimized method
TWD [%]	3.04	2.81
THD *n*=50 [%]	1.83	1.27
THD *n*=100 [%]	1.87	1.34
THD *n*=200 [%]	1.95	1.43
$I_3^{\%}$ [%]	0.87	0.89
$I_5^{\%}$ [%]	0.90	0.55
$I_7^{\%}$ [%]	1.15	0.46
$I_{11}^{\%}$ [%]	0.23	0.12
$I_{13}^{\%}$ [%]	0.32	0.12

The analysis of the results laid in Table 2 leads to conclusion that overall improvement of current distortions is rather limited (considering comparison of traditional versus optimized method). Nevertheless, some components contents is reduced significantly. The observation concerns lower order harmonic, particularly 7th harmonic. The analysis of values of THD factors confirm the observation. So, the optimized method is to be implemented, if lower order harder harmonics would be a concern.

IV. Final remarks

The optimized SVPWM current tracking algorithm determines the area of the space command voltage vector u_r^* through the three-phase interphase error current. Compared with the traditional algorithm, proposed SVPWM current tracking algorithm could eliminate the need for detection of the three-phase grid voltage and simplify the complex calculations of determining the area. The filtering effect using the optimized SVPWM current tracking algorithm is better than the original algorithm, but an overall improvement of current distortions is rather limited. It is worth adding, that under considered conditions the current THD values were reduced more significantly than TWD value, moreover, the 5th and 7th harmonics were highly mitigated. On the other hand, a simplification of the SVPWM current tracking algorithm makes the hardware circuit simplified, reduces the computing time, improves the speed of operation and reduces the compensating delay, so the compensation accuracy can be improved.

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