Selective Estimation of Three-Phase Mains Current for Shunt Active Power Filter

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Abstract—**In the paper a method of the three phase current harmonics observers configuration for selective detection of the distortions is proposed. The relationship between the observer tuning gains and the speed of the estimation preserving the selectivity properties is obtained. Simulation and experimental results confirm the theoretical findings and demonstrate the effectiveness of the proposed solution for shunt active power filters with selective harmonics compensation.**

Keywords— active power filter, higher-order harmonics, observer, selectivity

I. INTRODUCTION

The operation of modern electrical equipment is closely related to the fact that its functioning leads to harmonics distortions in the power supply mains. The issue of harmonic distortion has been extensively studied at present, and various approaches have been proposed to compensate for these distortions [1], [2], including those implemented in industrial active power filters. However, the development of an active power filter is still characterized by high complexity, because the detection of harmonic distortions and their subsequent compensation require high computing performance of the controller, significant requirements for power electronics, measuring devices, which, as a consequence, leads to an increase in the overall dimensions of the product and the final cost.

Electrical power quality is characterized by certain permissible values of electrical parameters according to specialized regulations, for example [3]. One approach to improving the quality of electricity in the mains aimed at providing electrical parameters to these standards, as well as achieving this goal using as few resources as possible, is selective harmonic compensation [4], [5]. According to this approach, only the most critical harmonic components have to be compensated, which greatly simplifies the implementation of the active power filter.

The use of state observers allows the selective detection of higher order current harmonics of the three-phase mains. However, in [6] and [7] it is shown that the natural tuning of this observer, that is, based on the selection of a suitable damping factor, has a following contradiction. Decreasing the damping factor value leads to improvement of selectivity properties with the loss of estimation speed. On the other hand, the increasing the damping factor value results in the loss of selectivity properties, while the estimation speed increases. The critical issue from the digital implementation point of view is also the presence of "weakly" damped poles of the observer for the significantly "small" values of the damping factor, needed to ensure selectivity [6] – [8]. Finding a compromise between the speed and the selectivity of estimation using analytical methods, such as optimization of linear systems, is complicated by the high order of the observer (200 to estimate 50 harmonics) and the resonance mode of harmonics estimation.

The goal of this work is to develop a new harmonic observer tuning method, which is compromise between speed of estimation and selectivity properties leading to significant augmentation of the required estimator`s damping factor values and thereby simplifies their real-time implementation.

II. HARMONICS ESTIMATOR

It is shown in [8], that according to Fortescue's symmetrical components method a load current consisted of N harmonics may be presented as $\mathbf{i}_L = (i_{Ld}, i_{Lq})^T$ in mains voltage oriented reference frame (d-q):

$$i_{Ld} = x_{d0} + \sum_{i=1}^{N}(x_{dpi} + x_{dni}),\ i_{Lq} = x_{q0} + \sum_{i=1}^{N}(x_{qpi} + x_{qni}) \quad (1)$$

where $\mathbf{x}_i = (x_{dpi}, x_{qpi}, x_{dni}, x_{qni})^T$ – positive (p) and negative (n) sequences projections on d and q axes vector of i harmonic of load current, x_{d0}, x_{q0} - dc current components which corresponds to active and reactive current. In order to provide estimation of harmonic components in (1) the following observer is proposed [8]:

$$\dot{\hat{\mathbf{x}}} = \mathbf{A}_h\hat{\mathbf{x}} - \mathbf{K}_h\left[\mathbf{i}_L - \mathbf{C}_h\hat{\mathbf{x}}\right] \quad (2)$$

where: $\hat{\mathbf{x}} = (\hat{\mathbf{x}}_1^T, ..., \hat{\mathbf{x}}_N^T)^T$, $\hat{\mathbf{x}}_1 = (\hat{x}_{dp1}, \hat{x}_{qp1}, \hat{x}_{dn1}, \hat{x}_{qn1})^T$, $\hat{\mathbf{x}}_N = (\hat{x}_{dpN}, \hat{x}_{qpN}, \hat{x}_{dnN}, \hat{x}_{qnN})^T$, $\mathbf{K}_h = \left[\mathbf{K}_{h1}, ..., \mathbf{K}_{hN}\right]^T$, $\mathbf{A}_h = \text{blockdiag}\left[\mathbf{A}_{h1}, ..., \mathbf{A}_{hN}\right]$,

$$\mathbf{C}_h\left[2,4N\right] = \begin{bmatrix} 1 & 0 & 1 & 0 & ... & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & ... & 0 & 1 & 0 & 1 \end{bmatrix},$$

$$\mathbf{K}_{h1} = \begin{pmatrix} -k_{1h} & -k_{2h} \\ k_{2h} & -k_{1h} \\ -k_{1h} & k_{2h} \\ -k_{2h} & -k_{1h} \end{pmatrix}, \mathbf{K}_{hN} = \begin{pmatrix} -k_{1N} & -k_{2N} \\ k_{2N} & -k_{1N} \\ -k_{1N} & k_{2N} \\ -k_{2N} & -k_{1N} \end{pmatrix},$$

$$\mathbf{A}_{h1} = \begin{pmatrix} 0 & -\omega_m & 0 & 0 \\ \omega_m & 0 & 0 & 0 \\ 0 & 0 & 0 & \omega_m \\ 0 & 0 & -\omega_m & 0 \end{pmatrix}, \mathbf{A}_{hN} = \begin{pmatrix} 0 & -N\omega_m & 0 & 0 \\ N\omega_m & 0 & 0 & 0 \\ 0 & 0 & 0 & N\omega_m \\ 0 & 0 & -N\omega_m & 0 \end{pmatrix},$$

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where ω_m – mains voltage frequency, k_{11} … k_{1N} – correction matrix $\mathbf{K}_h$ gains, computed as $k_{1h} = \delta\omega_n$, $k_{2h} = [\omega_n^2 - (h\omega_m)^2]/2h\omega_m$ in order to establish the natural frequency of the oscillations $\omega_n = (1-2\delta^2)^{-1/2} h\omega_m$ and damping factor δ.

Estimator (2) guarantees the asymptotic estimation of all N harmonics or any selected quantity with performance provided by proper tuning of correction matrix $\mathbf{K}_h$ on the base of the chosen damping factor δ.

A. Observer`s performance

In order to investigate the dynamic behavior of the harmonics observer we consider the load current (1) which is given by the sum of first 20 harmonics with the same unity amplitudes and phase shift equal to $\pi/(i+1)$. The estimated load current with $x_{d0} = x_{q0} = 0$ is computed according to

$$\hat{i}_{Ld} = \sum_{i=1}^{N} (\hat{x}_{dpi} + \hat{x}_{dni}),$$
$$\hat{i}_{Lq} = \sum_{i=1}^{N} (\hat{x}_{qpi} + \hat{x}_{qni}). \qquad (3)$$

From (1) and (3) the current estimation errors are defined as $\tilde{i}_{Ld} = i_{Ld} - \hat{i}_{Ld}$, $\tilde{i}_{Lq} = i_{Lq} - \hat{i}_{Lq}$.

Fig. 1 and Fig. 2 show poles location, dynamics of the current estimation errors, and amplitude frequency characteristics of the error estimation vector modulus computed as $\left|\tilde{i}_L\right| = \sqrt{\tilde{i}_{Ld}^2 + \tilde{i}_{Lq}^2}$ for $\delta = 0.001$ and $\delta = 0.005$. From frequency characteristics the selectivity of harmonic estimation is observed in both cases. Higher values of damping factor δ provide faster convergence of the estimation errors to zero. However further increase of damping leads to the degradation of estimator selectivity From the comparison of Fig.1 and Fig.2 one can find out the dependence between estimation speed and estimator`s poles placement. From the linear control theory is well known: as far poles from the imaginary axis – as faster estimation goes on.

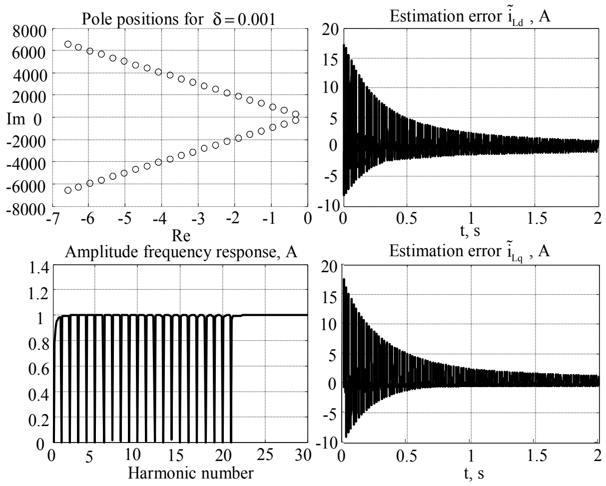

Fig. 1. Poles location, dynamics of the current estimated errors and amplitude frequency characteristics for δ=0.001

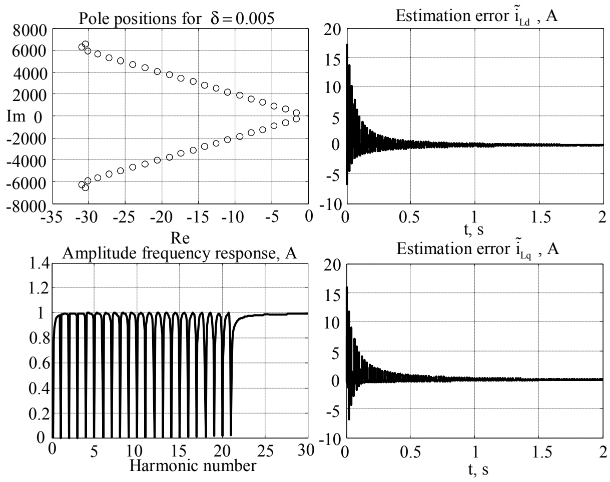

Fig. 2. Poles location, dynamics of the current estimated errors and amplitude frequency characteristics for δ=0.005.

B. Selectivity properties of observer

In order to investigate selectivity properties of the harmonics observer (2) the amplitude-frequency responses, shown in Fig.3, were obtained for the following set of damping factors $\delta = 0.02$, $\delta = 0.01$, $\delta = 0.001$. To build the frequency responses the input current of the observer were applied as $i_{Ld} = 1 \cdot \sin(\omega_n t)$, $i_{Lq} = 1 \cdot \cos(\omega_n t)$, with frequency ω_n slowly changing in time. Then the obtained values $\left|\tilde{i}_L\right| = f(t)$ were normalized as $\left|\tilde{i}_L\right| = f(\omega_n / \omega_N)$, where ω_N – frequency of the harmonic to be estimated.

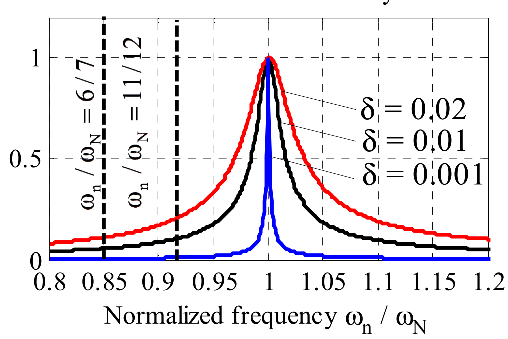

Fig. 3. Frequency response for observer sensitivity analysis

From Fig.3 it follows, that increasing of the damping factor δ leads to expanding of the resonance band, and thereby results in uprising of estimation error. On the other hand, for the same damping factor δ, increasing of the frequency, to be estimated, causes the increasing of the estimator sensitivity to the presence of the closest harmonics, in particular – to the neighboring ones. This leads to increase the estimation error values caused by nearest harmonics. As result a narrower observer resonance band for higher order harmonics is required, since the observer resonance band can cover frequencies even further than the neighboring ones. Lower-order harmonics (up to 5th), as it follows from Fig. 3, do not require a narrow resonance band, since they are weakly sensitive to the presence of neighboring harmonics in the spectrum. For example, for the damping factor $\delta = 0.01$ of the 12th harmonic observer, the presence of the 11th harmonic in the load current spectrum ($\omega_n / \omega_N = 0.91$ in relative units) will lead to an estimation error approximately 10%, while for the value of the damping factor $\delta = 0.001$ the estimation error is less than 2%.

Based on the lack of analytical methods for investigation of such resonance observer behavior we found that frequency analysis is the most suitable tool to define the relationship between observer poles placement, selectivity properties and estimation speed.

III. Harmonics Observer Tuning

The next stage of research was conducted to determine the damping factors that would allow estimation of given harmonics with errors from neighboring harmonics that do not exceed the specified values. In order to avoid the estimation errors caused by the presence of neighboring harmonics, while preserving the acceptable dynamic properties of the harmonics observer and the selectivity properties, let us consider the existing harmonics of the three-phase network and their belonging to symmetrical sequences. According to [9], the harmonics of a three-phase network can be harmonics of positive, negative or zero sequences.

The observer (2) is constructed on the basis of an internal model approach [10], according to which the positive and negative sequence signals are considered as generated by a harmonic oscillators. The internal model for 5-th and 7-th two phase harmonics generation is presented in Table I. Thus, one observer (2) can estimate two harmonics simultaneously – the positive and negative sequence harmonics, since it consists of two equations for estimation the components of the positive sequence, and two equations for the negative sequence. Park transformation of the load current signals (from the (a-b) coordinate system) to the coordinate system (d-q)), causes a shift of the harmonics order, but the harmonics sequence during the transformation remains the same. The correspondence of the three-phase system sequences to the harmonics represented in the coordinate system (d-q) are presented in Table I, where the symbol "+" indicates the harmonic belonging to the positive sequence, while the symbol "-" to the negative one.

TABLE I. Internal Model of Positive and Negative Sequences

3-phase mains harmonics	(d-q) harmonics	Internal model of positive and negative sequences in (1)
7+	6+	$\begin{pmatrix} \dot{x}_{dp} \\ \dot{x}_{qp} \\ - \\ \dot{x}_{dn} \\ \dot{x}_{qn} \end{pmatrix} = \begin{bmatrix} 0 & -6\omega_m & 0 & 0 \\ 6\omega_m & 0 & 0 & 0 \\ - & - & - & - \\ 0 & 0 & 0 & 6\omega_m \\ 0 & 0 & -6\omega_m & 0 \end{bmatrix} \begin{pmatrix} x_{dp} \\ x_{qp} \\ - \\ x_{dn} \\ x_{qn} \end{pmatrix}$ positive sequence — — — negative sequence
5-	6-	

Therefore, according to (2), as well as Table I, the observer for harmonic $6\omega_m$, constructed in the coordinate system (d-q), allows to provide simultaneously evaluation of the 7-th harmonic of a three-phase mains, since it is a positive sequence harmonic, and the 5-th harmonic, since it is a negative sequence harmonic.

A. Case of no even and multiple-three harmonics

Let us consider the balanced three-wire three-phase mains, where, according to [4], [5], the presence of pair harmonics and harmonics of multiple three is negligibly small. Under these assumptions such harmonics are not present in the load current spectrum, and therefore will not cause estimation errors. In particular, as shown in [11], three-phase power consumers based on 6-pulse rectifiers are sources of $6k \pm 1, k \in Z$ order harmonics. Modern variable frequency electrical motor drives built on the basis of the 6-pulse rectifier with an intermediate direct current link are the typical and wide spread consumers of the electric power. Following this consideration the selective detection and subsequent compensation of the 5-th, 7-th, 11-th, 13-th, 17-th and 19-th order harmonics will ensure that the quality of electrical energy meets the requirements of the regulatory documents.

When searching for the damping factors for the observer of the k-order harmonic, this harmonic is assumed as not present in the spectrum, while the neighboring harmonics are present. The k-order harmonics observer damping factor is considered acceptable if the observer's estimation error, generated by neighboring harmonics, does not exceed 5%. Table II presents the obtained damping factors for each observer. Based on the obtained damping factor, an observer feedback matrix $\mathbf{K}_h$ is constructed.

Simulation of the 6th, 12th and 18th order harmonics observer behavior, based on the damping factors presented in Table II, was performed in the following conditions. The harmonic composition of the load current is given in the 3-phase coordinate system by the harmonics of the positive (7, 13, 19) and negative (5, 11, 17) sequences with unit amplitude. Fig. 4 presents the FFT of the three-phase load current, the FFT of the observed current (in (a-b) and (d-q)), as well as the transient of the estimation errors, from where we establish the estimation with negligible small errors. Important to note that in this configuration, the poles of the harmonics observers are located at the nearby the same distance $r \in (75-85)$ from the imaginary axis on the complex plane. This makes it possible to study the selectivity of the observer and to calculate the tuning coefficients based on the predetermined, namely equidistant, arrangement of the observer poles on the complex plane, since the matrix $\mathbf{K}_h$ of the observer (2) is freely configurable.

This equidistant location of the poles (relative to the imaginary axis in the complex plane) ensures that convergent rate of each harmonic is the same, while the value of the damping coefficient decreases with increasing order of the harmonic. Having formed the given position of the observer poles as

$$\mathbf{P} = \begin{pmatrix} -r - j\omega_{nh} \\ -r + j\omega_{nh} \\ -r + j\omega_{nh} \\ -r - j\omega_{nh} \end{pmatrix} \quad (4)$$

the gains k_{1h}, k_{2h} of the observer matrix $\mathbf{K}_h$ are computed.

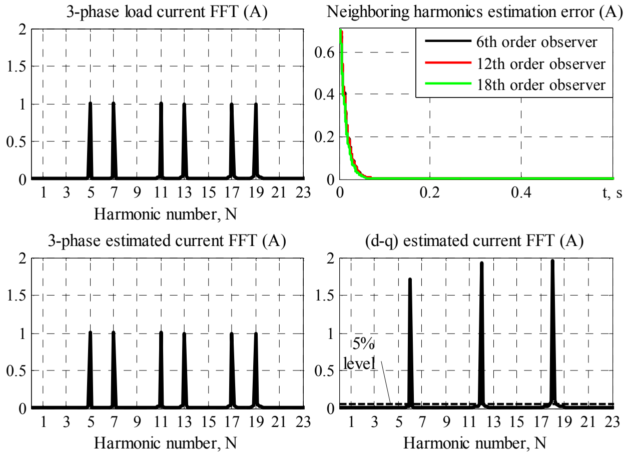

Fig. 4. Observer performance characteristics for 6th, 12th and 18th order harmonics estimation for $\delta_6 = 0.04$, $\delta_{12} = 0.02$, $\delta_{18} = 0.015$.

B. *Maximally distorted three-phase mains case*

However, in the case when there are another harmonics in the load current spectrum, there may arise a question of the sensitivity of the harmonic observer to the nearest harmonics in the spectrum. Let us consider the load current harmonic stuff is given by the 5-th, 7-th, 11-th, 13-th, 17-th, 19-th order harmonics with unit amplitude and the neighboring 4-th and 14-th order harmonics with amplitude equal to 0.5. Observer tuning is the same as in the previous test. From the comparison of load current FFT, estimated current FFTs and estimation errors, presented in Fig.4 and Fig.5 one can find out that some degradation of the observer accuracy is present when observer matrix $\mathbf{K}_h$ gains are calculated according to Table II.

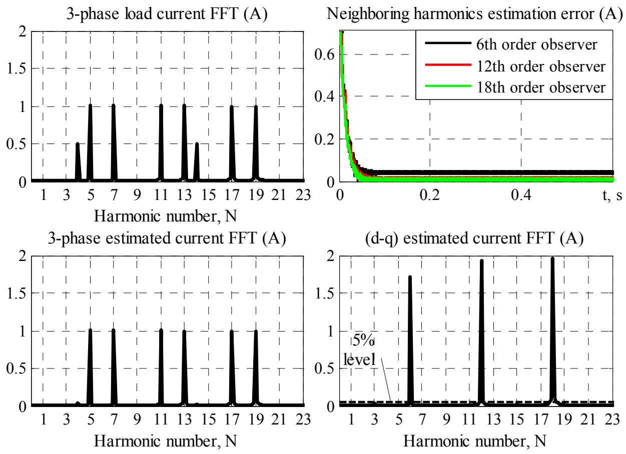

Fig. 5. Observer performance under neighboring harmonics perturbation for $\delta_6 = 0.04$, $\delta_{12} = 0.02$, $\delta_{18} = 0.015$.

As it follows from the results on Fig.5, in order to keep the selectivity properties for more distorted case one have to find out damping factors taking into account the presence of all possible current harmonics.

Harmonics with order of multiple three are zero sequence harmonics and they are considered to be not present in three wire mains. Let us consider the even harmonics of a three-phase mains, namely harmonics of order 2 and 4. The second-order harmonic is the harmonic of the negative sequence, and the harmonic of order 4 is the harmonic of the direct sequence. Both of these harmonics can be estimated using the 3rd harmonic observer, designed in the coordinate system (d-q), similar to the method presented above. The same considerations can be applied for the estimation of harmonics of order 8 and 10, 12 and 14, 16 and 18, 20 and 22. Therefore, to estimate the all harmonic spectrum of a three-phase mains up to 22th, it is necessary to design harmonic observers of order 3, 6, 9, 12, 15, 18, 21 in the coordinate system (d-q).

Further study and search for acceptable values of damping factors for each observer for harmonics k+6 and k–6 (in (a-b) frame) was carried out in the conditions of maximally distorted three-phase mains, that is, in the signal to be estimated, the whole spectrum of harmonics, which theoretically can occur in the three-phase mains, is presented.

The neighboring harmonics in the spectrum can cause an estimation errors, according to Fig. 5, so the research objective can now be paraphrased as follows: find the maximum permissible damping factors of the harmonics observer with order 6, 12, and 18, which provide the estimation with an accuracy, which is not exceed the specified level of 5%. The obtained damping factors and their corresponding to the harmonics order are presented in Table II. Fig.6 shows the load current FFT, estimated current FFT and estimation errors dynamics.

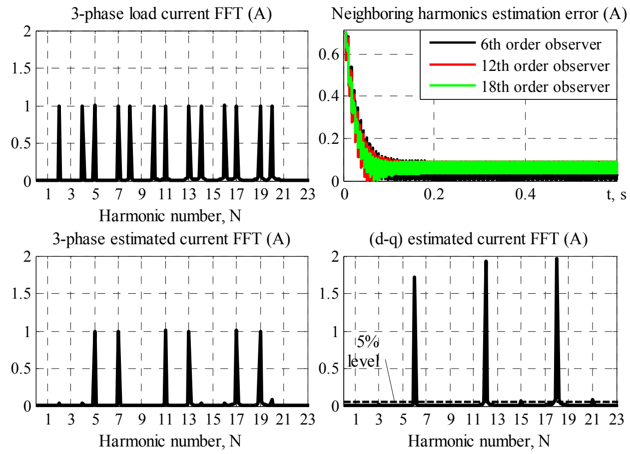

Fig. 6. Observer performance in case of strong distortions for $\delta_6 = 0.022$, $\delta_{12} = 0.012$, $\delta_{18} = 0.008$.

From Fig.6 one can find out, that 6th, 12th, 18th order harmonics observers tuned on the base of obtained damping factors provide estimation with errors, that not exceed the predefined 5% level. In this test observer poles are placed at the distance $r \approx 45$ from the imaginary axis.

From the obtained results it was found out the dependence between observer poles placement, observer selectivity properties and estimation speed. According to (4) there is possibility to compute a matrix $\mathbf{K}_h$ gains on the base of desired pole placement. Calculation of matrix $\mathbf{K}_h$ gains is conducted in MatLab by the function place() for $r \approx \text{const}$. As follows from the Table II, matrix $\mathbf{K}_h$ gains on base of desired poles position with $r \approx \text{const}$ and on the base of determined damping factor δ for every observer are almost equal.

Important to note that selection of the matrix $\mathbf{K}_h$ gains is general for all harmonics observers having structure given by (2).

TABLE II. OBSERVERS TUNING GAINS DEPENDING ON THE APPROACH OF CALCULATION

Tuning conditions	$\mathbf{K}_h$ gains	6th order estimator	12th order estimator	18th order estimator
The same value of δ for all observers (test in Fig.1)				
$\delta = 0.001$	k_{1h}	1.88	3.76	5.65
	k_{2h}	0.001	0.003	0.005
	$p_{1,2,3,4} = -1.88 \pm 1884.96i$, $p_{5,6,7,8} = -3.76 \pm 3769.20i$, $p_{9,10,11,12} = -5.65 \pm 5654.85i$			
Different values of δ for all observers (case of no even and multiple-three harmonics, test in Fig.4)				
$\delta_6 = 0.04$, $\delta_{12} = 0.02$, $\delta_{18} = 0.015$	k_{1h}	75.51	75.42	84.84
	k_{2h}	3.02	1.5	1.27
	$p_{1,2,3,4} = -75.51 \pm 1886.46i$, $p_{5,6,7,8} = -75.42 \pm 3770.66i$, $p_{9,10,11,12} = -84.84 \pm 5655.50i$			
Different values of δ for all observers (maximally distorted three-phase mains case, test in Fig.6)				
$\delta_6 = 0.022$, $\delta_{12} = 0.012$, $\delta_{18} = 0.008$	k_{1h}	41.48	45.24	45.24
	k_{2h}	0.91	0.54	0.36
	$p_{1,2,3,4} = -41.48 \pm 1885.41i$, $p_{5,6,7,8} = -45.24 \pm 3770.18i$, $p_{9,10,11,12} = -45.24 \pm 5655.04i$			

IV. EXPERIMENTAL RESULTS

Harmonics observer (2) is implemented on floating-point 32-bit DSP TMS320F28335 and verified experimentally. Load current shape, FFT and estimated current FFT in (d-q) reference frame and 3-phase system are presented in Fig.7.

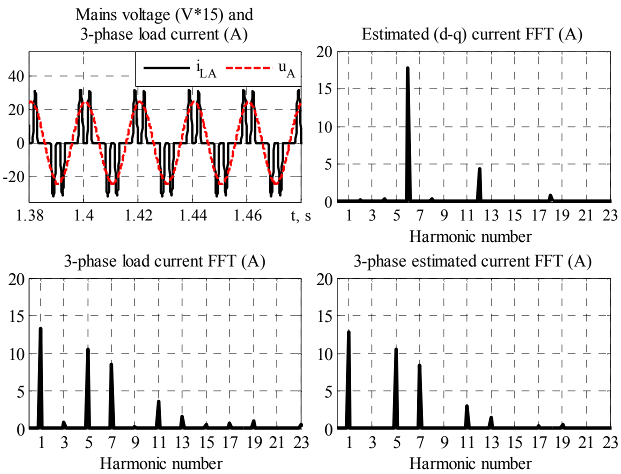

Fig. 7. Experimental investigation of the observer.

The non-linear load is represented by a bridge rectifier with capacitance filter and chopper for dc-load current regulation. Load currents are measured by Hall effect current sensors. Observer is tuned according to (4) with $r \approx 28$. Sampling time during experiment is set to $T_s = 75$ µs. From Fig.7 one can conclude that the designed observer provides estimation of the load current 5-th, 7-th, 11-th, 13-th, 17-th and 19-th harmonics. The main harmonic components in (d-q) reference frame are estimated by means of low-pass filtering of the load currents.

From comparison of the load and estimated currents FFT analysis, presented in a-b stationary reference frame, we conclude that observer based on proposed tuning guarantees selective estimation with respect of the existing neighboring harmonics.

V. CONCLUSIONS

The harmonics observer configuration method which allows to provide a high-speed estimation of the three-phase mains harmonic stuff with selectivity of estimation is proposed. The correspondence between damping factors for each harmonics observer and observer performance is determined as well as influence of the observer poles placement on the estimation dynamics and selectivity of estimation. It is shown that design procedure is greatly simplified when observer tuning gains are computed on the base of the desired poles placement. The problem of "weakly" damped poles of the observer is avoided in this case. The obtained observer tuning coefficients greatly simplify its technical implementation by reducing requirements for the computing performance of the controller. Experimental study confirms the obtained results.

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