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SELECTIVE AND ADAPTIVE HARMONICS ESTIMATION FOR THREE-PHASE SHUNT ACTIVE POWER FILTERS

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The paper deals with on-line estimation of three-phase current harmonics on the basis of adaptive control technique. It is shown that standard observer for positive and negative sequences of each harmonic delivers strong selectivity properties, but has limited speed of convergence and it is suitable when not all harmonics are required to be estimated. A novel structure of estimator with measured currents filtration which guarantees fast asymptotic convergence and simple tuning procedure is proposed. A new approach to shunt active power filter current control based on a combination of current control loop and harmonic estimator is also presented. Proposed approach allows to achieve the asymptotic estimation and asymptotic compensation of all set of harmonics. Simulation and experimental results proof the theoretical findings. References 13, figures 7.

Keywords: shunt active power filter, current harmonics, estimation.

Introduction. Electricity is converted into other types of energy using different semiconductor converters, which are nonlinear loads for electrical grid. Such loads are variable speed AC and DC electrical drives, different lighting systems, power supply devices for industrial, household and office equipment, and many others. Such devices consume from the line source a non-sinusoidal current that delivers a number of negative effects.

The traditional passive filters have well known significant limitations for higher harmonics compensation and therefore starting from 1990-th the active power filters are considered as powerful tool for improvement of power quality to comply with modern standards [1]. During last decades the different modifications of parallel active power filters (also known as Shunt Active Filter – SAF) have been proposed. SAF provides effective compensation of current harmonics caused by nonlinear loads and can be used for reactive power control. An intensive overview of the active power filter topologies, control methods, power electronics issues are given in [11]. From the control point of view, several challenging tasks are considered: output current regulation, dc-link voltage stabilization, current harmonics detection and others.

Standard and advanced control methods applied to solve above-mentioned control tasks employ the instantaneous power theory [2, 3, 10], variety of time-domain approaches, FFT [5], etc. Instantaneous power theory based systems in general provides compensation of all high order harmonics and demonstrate robust performance [2]. From the other hand, selective harmonic compensation [8] gives significant benefits, since the active filter rating and its bandwidth can be strongly reduced. Additionally computational requirements for real time controller can be reduced as well if only selected set of harmonics is estimated and then compensated. The standard block diagram of the active power filter with harmonics estimation is shown in Fig. 1, where standard definitions for variables are used. In [12, 13] authors proposed an on-line method to estimate load current harmonics using Luenberger observer for positive and negative sequences of signals presented in line voltage vector oriented reference frame. High resolution selective harmonic estimation can be achieved applying this methodology. Nevertheless dynamic performance of such estimation algorithms has not been studied and structural limitations to achieve at the same time selectivity and fast estimation is not studied. On the base of estimated harmonics the current reference is constructed for current control loops. Current control is implemented by scalar methods using the relay mode, or by space vector pulse-width modulation.

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To achieve an effective compensation for high frequency harmonics the current loops should be extremely fast in presence of not modeled dynamics, measurement noise and other no idealities. This problem is not addressed in available solutions for harmonics estimation based current control.

In this work as a first step we investigate the dynamic performance and selectivity properties of the harmonic estimator [12, 13]. It is shown that standard estimator has structural limitations to achieve selective estimation and high dynamic performance. The main contribution of this paper is a new structure of the observer with filtered measured signals and a new adaptive current control algorithm that allows simultaneous asymptotic harmonic estimation and current tracking. The preliminary version of this paper has been presented in [9].

Harmonic estimation: Luenberger observer. According to Fortescue's theorem, a balanced three-phase system can be presented by the positive and negative sequences [4]. Let consider the symmetrical three-phase system of currents given by positive (p) and negative (n) sequences [12]

$$\begin{aligned} i_A^p &= I_p\cos(n\omega_1 t), & i_A^n &= I_n\cos(n\omega_1 t), \\ i_B^p &= I_p\cos(n\omega_1 t - 2\pi/3), & i_B^n &= I_n\cos(n\omega_1 t + 2\pi/3), \\ i_C^p &= I_p\cos(n\omega_1 t + 2\pi/3), & i_C^n &= I_n\cos(n\omega_1 t - 2\pi/3), \end{aligned} \tag{1}$$

where I_p, I_n is the positive and negative sequences amplitudes, ω_1 is the main voltage frequency, n is the harmonic number.

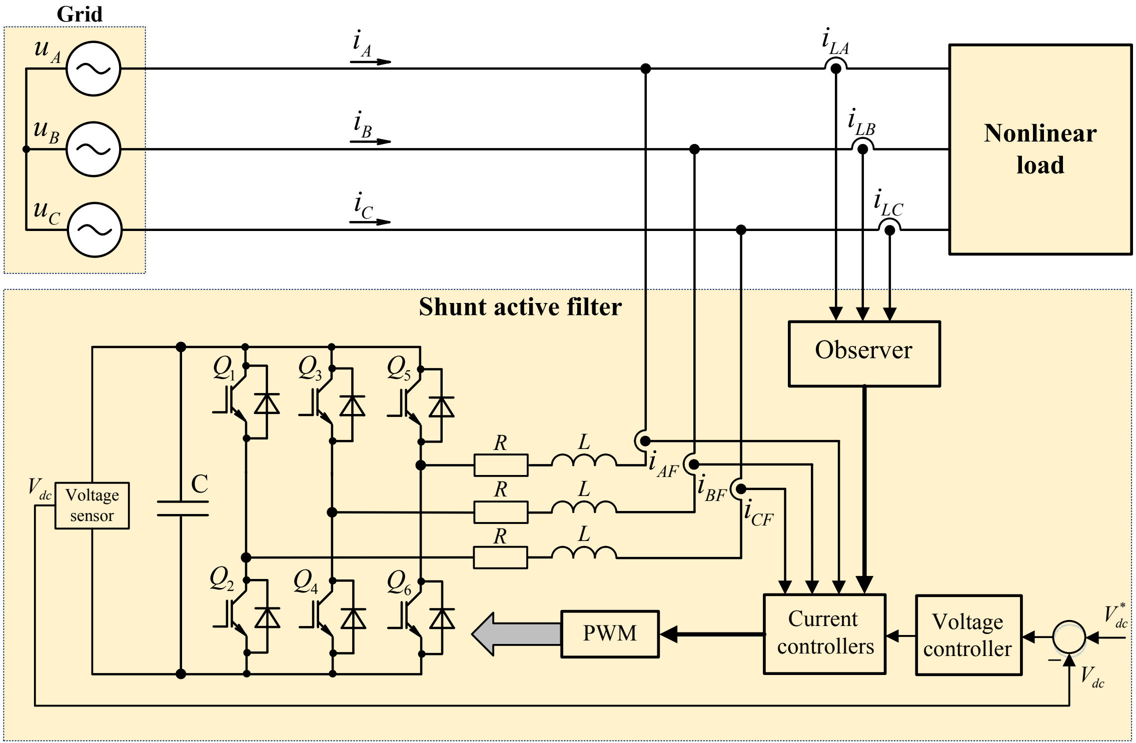

Fig. 1

Transforming signals (1) into two phase system (a-b) and then into line voltage oriented reference frame (d-q) we obtain

$$i_{Ld}^p = I_p\cos(h\omega_1 t),\quad i_{Ld}^n = I_n\cos(h\omega_1 t),\quad i_{Lq}^p = I_p\sin(h\omega_1 t),\quad i_{Lq}^n = I_n\sin(h\omega_1 t), \tag{2}$$

where index L stands for load current, $h = n-1$ is the harmonic order in d-q reference frame for positive sequence, $h = n+1$ – harmonic order in d-q reference frame for negative sequence.

It is well known that if signals (2) have only one frequency $h\omega_m$ and do not have dc components then they can be presented as solutions of the following dynamic system

$$\dot{\mathbf{x}}(t) = \mathbf{A}_h\mathbf{x}(t), \tag{3}$$

where $\mathbf{x} = (x_{dp}, x_{qp}, x_{dn}, x_{qn})^T$ is the vector of positive and negative sequences projections on d and q axes,

$$\mathbf{A}_h = \begin{bmatrix} \mathbf{A}_{ph} & 0 \\ 0 & \mathbf{A}_{nh} \end{bmatrix},\quad \mathbf{A}_{ph} = \begin{bmatrix} 0 & -h\omega_1 \\ h\omega_1 & 0 \end{bmatrix},\quad \mathbf{A}_{nh} = \begin{bmatrix} 0 & h\omega_1 \\ -h\omega_1 & 0 \end{bmatrix}.$$

From (3) the load currents may be computed as

$$i_{Ld} = x_{dp} + x_{dn}, \quad i_{Lq} = x_{qp} + x_{qn}. \tag{4}$$

The general form of the Luenberger observer [6] for system (3) is given by [12, 13]

$$\dot{\hat{\mathbf{x}}}(t) = \mathbf{A}_h \hat{\mathbf{x}}(t) - \mathbf{K}\left[\mathbf{i}_L - \mathbf{C}_h \hat{\mathbf{x}}(t)\right], \tag{5}$$

where $\hat{\mathbf{x}} = \left[\hat{x}_{dp}\ \hat{x}_{qp}\ \hat{x}_{dn}\ \hat{x}_{qn}\right]^T$ is the is a state space vector of the estimator, $\mathbf{i}_L = (i_{Ld}, i_{Lq})^T$ is the current to be estimated, $\hat{\mathbf{i}}_L = \mathbf{C}_h \hat{\mathbf{x}}$ is the estimated current, $\mathbf{C}_h = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix}$; $\mathbf{K} = \begin{bmatrix} -k_1 & -k_2 \\ k_2 & -k_1 \\ -k_1 & k_2 \\ -k_2 & -k_1 \end{bmatrix}$.

From (3) and (5) estimation error dynamics is

$$\dot{\tilde{\mathbf{x}}} = \mathbf{M}_h \tilde{\mathbf{x}}, \tag{6}$$

where $\tilde{\mathbf{x}} = \mathbf{x} - \hat{\mathbf{x}}$, $\mathbf{M}_h = \mathbf{A}_h + \mathbf{K}\mathbf{C}_h$ is the should be designed as a Hurwitz matrix.

In order to provide the selectivity properties of the estimator, it is suggested [5] to construct the correction matrix $\mathbf{K}$ according to

$$k_1 = \delta\omega_n, \quad k_2 = \left[\omega_n^2 - (h\omega_1)^2\right] / 2\omega_1, \tag{7}$$

where δ is damping factor and $\omega_n = (1 - 2\delta^2)^{-1} h\omega_1$ is natural frequency of the oscillations. According to (7) dynamics of the estimation process depends only from damping factor δ and harmonic number h. Such tuning of the observer (5) for harmonic $h\omega_1$ guaranties that $\| \ [j\omega\mathbf{I} - \mathbf{M}_h]^{-1}(-\mathbf{K}) \ \| << 1, \ \forall\omega = n\omega_1, \ n \neq h$, i.e. all harmonics with frequencies different from $h\omega_1$ will be decreased. Hence, the observer (5) has to estimate only one harmonic, providing selectivity property.

In general, any number of harmonics can be estimated on the base of elementary observer (5). Matrix $\mathbf{A}_h$ and $\mathbf{C}_h$ need to be replaced by $\mathbf{A} = \text{blockdiag}\left[\mathbf{A}_{h1}, ..., \mathbf{A}_{hN}\right]$ and $\mathbf{C} = \left[\mathbf{C}_{h1}, ..., \mathbf{C}_{hN}\right]$ with $\hat{\mathbf{x}} = \left(\hat{\mathbf{x}}_1^T, ..., \hat{\mathbf{x}}_N^T\right)^T$ and $\mathbf{K} = \left[\mathbf{K}_{h1}, ..., \mathbf{K}_{hN}\right]^T$, where N are numbers of harmonics, considered for estimation. For example, if $N \in \{e, m, ... z\}$ then all harmonics $\omega = n\omega_1, n \neq \{e, m, .. z\}$ are strongly rejected.

In order to investigate the dynamic behavior of the harmonic estimator we consider the load current given by

$$i_{Ld} = x_{d0} + \sum_{i=1}^{N} (x_{dpi} + x_{dni}), \quad i_{Lq} = x_{q0} + \sum_{i=1}^{N} (x_{qpi} + x_{qni}), \tag{8}$$

where x_{d0} and x_{q0} are active and reactive component of the load current.

Under condition of simulation test the load current in (a-b) reference frame is given by the sum of first i = 1, 2, … 20 harmonics with the same unity amplitudes and phase shift equal to $\pi/(i+1)$. Estimated load current is computed according to

$$\hat{i}_{Ld} = \hat{x}_{d0} + \sum_{h=1}^{N} (\hat{x}_{dpi} + \hat{x}_{dni}), \quad \hat{i}_{Lq} = \hat{x}_{q0} + \sum_{h=1}^{N} (\hat{x}_{qpi} + \hat{x}_{qni}), \tag{9}$$

where $\dot{\hat{x}}_{d0} = -k_0 \tilde{i}_{Ld}$, $\dot{\hat{x}}_{q0} = -k_0 \tilde{i}_{Lq}$ and $\tilde{i}_{Ld} = i_{Ld} - \hat{i}_{Ld}$, $\tilde{i}_{Lq} = i_{Lq} - \hat{i}_{Lq}$ are current estimation errors.

Fig. 2, *a* and Fig. 2, *b* show poles location, dynamics of the current estimation errors, and frequency responses for 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 responses it follows, that selectivity of harmonic estimation is observed in both cases. Higher values of damping factor δ provide faster convergence of the estimation errors to zero (see poles positions as well). However, further increase of damping leads to faster estimation, but with degradation of estimator selectivity.

Discrete time version of the estimator may be obtained in the form of difference equations using standard procedures for linear systems. Poles of the discrete time estimator have been computed using relations $\mathbf{P}=\left(e^{(-\delta\omega_{nh}-j\omega_{nh}\sqrt{1+\delta^2})T_s},\quad e^{(-\delta\omega_{nh}+j\omega_{nh}\sqrt{1+\delta^2})T_s},\quad e^{(-\delta\omega_{nh}+j\omega_{nh}\sqrt{1+\delta^2})T_s},\quad e^{(-\delta\omega_{nh}-j\omega_{nh}\sqrt{1+\delta^2})T_s}\right)^T$, where T_s is a sampling time. Fig. 2, *c* and Fig. 2, *d* demonstrate characteristics of the discrete time estimator with $T_s = 50\ \mu s$ for the same test conditions as in Fig. 2, *a* and Fig. 2, *b*. No significant difference is observed in performances of continuous and discrete time estimator versions.

From the simulation results in Fig. 2 it can be concluded that dynamic performance of the estimation with the same damping for different harmonics is limited by the estimator structure, which does not allow to increase the speed of estimation. Therefore, such structure is suitable in case if selectivity property is strongly required and used to reduce the complexity of estimation scheme, when not all harmonics are required to be estimated.

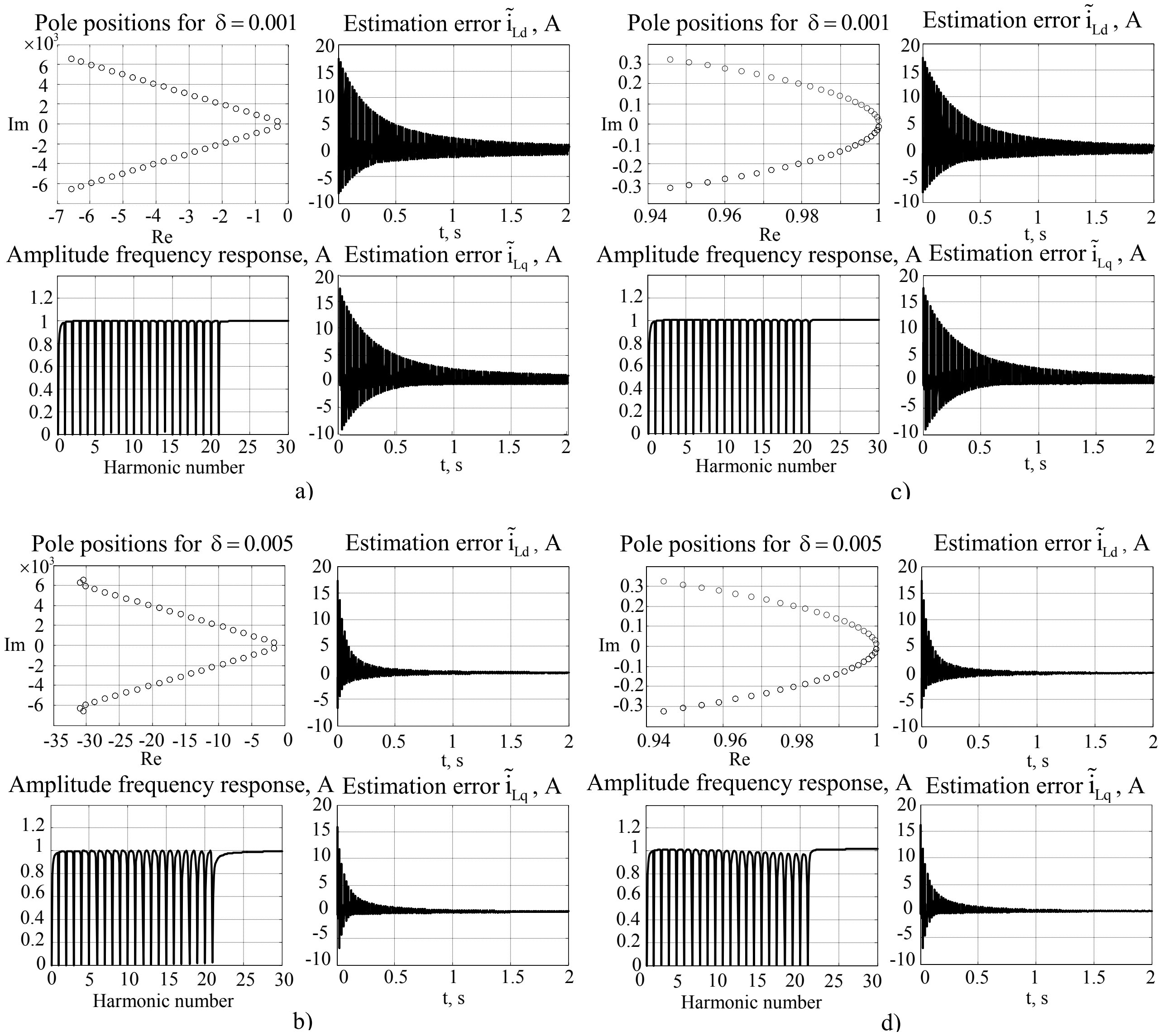

Fig. 2

Estimation with filtered measurement. In real implementation, all signals from the analog sensors are filtered in order to improve the system noise protection. Filtration leads to phase shift, which is different for each harmonic and therefore estimation based on filtered signals does not provide correct information. In order to solve this problem we propose a new adaptive estimation scheme, which uses filtered current signals and has no phase shift. Let us consider the filtered current error signal in (a-b) reference frame

$$\dot{y}_a = -\tau^{-1}y_a + \tau^{-1}i_{La} - \tau^{-1}\hat{i}_{La},$$
$$\dot{y}_b = -\tau^{-1}y_b + \tau^{-1}i_{Lb} - \tau^{-1}\hat{i}_{Lb}, \tag{10}$$

where τ is the filter time constant.

Equation (10) in synchronous reference frame can be written as

$$\dot{y}_d = \omega_1 y_q - \tau^{-1} y_d + \tau^{-1} i_{Ld} - \tau^{-1} \hat{i}_{Ld},$$
$$\dot{y}_q = -\omega_1 y_d - \tau^{-1} y_q + \tau^{-1} i_{Lq} - \tau^{-1} \hat{i}_{Lq}, \tag{11}$$

or in the error form

$$\dot{y}_d = \omega_1 y_q - \tau^{-1} y_d + \tau^{-1} \left(\tilde{x}_{d0} + \tilde{x}_{dp} + \tilde{x}_{dn} \right),$$
$$\dot{y}_q = -\omega_1 y_d - \tau^{-1} y_q + \tau^{-1} \left(\tilde{x}_{q0} + \tilde{x}_{qp} + \tilde{x}_{qn} \right), \tag{12}$$

where

$$\tilde{x}_{d0} = x_{d0} - \hat{x}_{d0}, \qquad \tilde{x}_{q0} = x_{q0} - \hat{x}_{q0}. \tag{13}$$

It can be shown that if estimations are designed as

$$\dot{\hat{x}}_{d0} = k_0 y_d, \quad \dot{\hat{x}}_{dp} = -h\omega_1 \hat{x}_{qp} + k_1 y_d, \quad \dot{\hat{x}}_{dn} = h\omega_1 \hat{x}_{qn} + k_1 y_d,$$
$$\dot{\hat{x}}_{q0} = k_0 y_q, \quad \dot{\hat{x}}_{qp} = h\omega_1 \hat{x}_{dp} + k_1 y_q, \quad \dot{\hat{x}}_{qn} = -h\omega_1 \hat{x}_{dn} + k_1 y_q, \tag{14}$$

then the estimation errors dynamics is globally asymptotically stable for all $\left(k_0, k_1\right) > 0$, i.e:

$$\lim_{t \to \infty} \left(\tilde{x}_{d0}, \tilde{x}_{q0}, \tilde{x}_{dp}, \tilde{x}_{qp}, \tilde{x}_{dn}, \tilde{x}_{qn} \right) = 0. \tag{15}$$

From condition (15) we conclude that asymptotic estimation of the load current is achieved as well.

For given filter time constant τ the dynamics of the estimation is specified by selection of two tuning coefficients $\left(k_0, k_1\right) > 0$. In general case of N harmonics estimation the observer is given by

$$\dot{\hat{\mathbf{x}}} = \mathbf{A}\hat{\mathbf{x}} + \mathbf{K}\mathbf{y},$$
$$\dot{\mathbf{y}} = -\tau^{-1} \mathbf{y} + \tau^{-1} \left(\mathbf{i}_L - \mathbf{C}\hat{\mathbf{x}} \right), \tag{16}$$

where $\hat{\mathbf{x}} = \left(\hat{\mathbf{x}}_0^T, \hat{\mathbf{x}}_1^T, ..., \hat{\mathbf{x}}_N^T \right)^T$, $\mathbf{y} = (y_d, y_q)^T$, $\mathbf{A} = \text{blockdiag}\left[\mathbf{0}, \mathbf{A}_{h1}, ..., \mathbf{A}_{hN}\right]$, $\mathbf{C} = \left[\mathbf{C}_{h0}, \mathbf{C}_{h1}, ..., \mathbf{C}_{hN}\right]$,

$$\mathbf{K} = \left[\begin{array}{cc|cccc|c|cccc} k_0 & 0 & k_1 & 0 & k_1 & 0 & ... & k_N & 0 & k_N & 0 \\ \hline 0 & k_0 & 0 & k_1 & 0 & k_1 & ... & 0 & k_N & 0 & k_N \end{array} \right]^T.$$

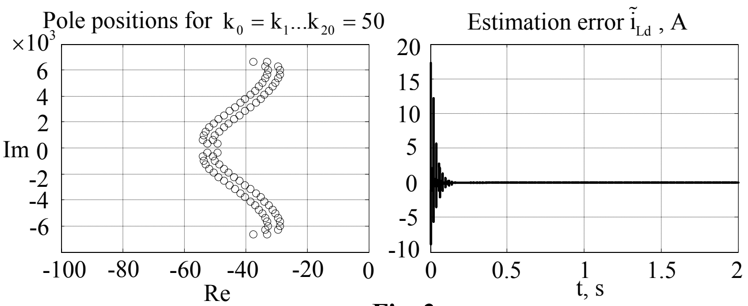

Fig. 3

Observer (16) guarantees convergence of all harmonics, but property of selectivity can be reduced or lost and therefore such observer is suitable if all set of harmonics needs to be estimated. The important feature of the designed estimator is: a) estimation dynamics is stable asymptotically for any positive tuning gains of matrix $\mathbf{K}$; b) freedom in design of matrix $\mathbf{K}$ according to any optimization technique for linear systems. As example, Fig. 3 shows the transients of the designed observer for the test condition of previous section if $k_0 = k_1...k_{20} = 50$ and $\tau = 0.2$ ms. As it is observed from the transients reported in Fig. 3, the selected tuning provides the faster current estimation error convergence compare to results of Fig. 2. Nevertheless selectivity property is lost in this case. Hence proposed structure of the correction matrix may be recommended if all harmonics should be estimated.

Adaptive current control with simultaneous harmonic estimation. On the basis of estimated current harmonics, a reference is formed for the generation of compensating currents of the active filter. The reference for compensation current vector $\mathbf{i}^* = \left(i_d^*, i_q^*\right)^T$ is fed to high-speed PI current controllers, which form the voltage vector $\mathbf{u}^* = \left(u_d^*, u_q^*\right)^T$ of the voltage source inverter [13].

In this section we present a novel approach for SAF control which is based on adaptive current control with the estimation of current harmonics on the base current regulation errors signals.

The proposed algorithm involves the use of filter currents, so its design starts with consideration of the filter model. Three-phase SAF diagram is presented in Fig. 1. SAF consist of the voltage-source inverter with capacitor C for energy accumulating and inductors L for filter currents i_{fA}, i_{fB}, i_{fC} shaping by means of applied inverter voltages u_A^*, u_B^*, u_C^*. In Fig. 1 u_{mA}, u_{mB}, u_{mC} – mains voltages, i_{mA}, i_{mB}, i_{mC} – mains currents, i_{LA}, i_{LB}, i_{LC} – load currents, V_{DC} – dc-link voltage, R – inductor's resistance, $Q_1 - Q_6$ – IGBTs control signals.

Under suitable control of dc-link voltage such that V_{DC} assumed to be constant the averaged power filter model is defined as

$$\begin{aligned} \dot{i}_{fA} &= L^{-1}\left(u_{mA} - u_A^* V_{DC} - R i_{fA}\right), \\ \dot{i}_{fB} &= L^{-1}\left(u_{mB} - u_B^* V_{DC} - R i_{fB}\right), \\ \dot{i}_{fC} &= L^{-1}\left(u_{mC} - u_C^* V_{DC} - R i_{fC}\right). \end{aligned} \tag{17}$$

In synchronous reference frame d-q, aligned to the mains voltage vector, power filter model (17) becomes

$$\dot{\mathbf{i}}_f = \begin{bmatrix} -R/L & \omega_1 \\ -\omega_1 & -R/L \end{bmatrix} \mathbf{i}_f - \frac{V_{DC}}{L}\mathbf{u}^* + \frac{1}{L}\begin{bmatrix} U_m \\ 0 \end{bmatrix}, \tag{18}$$

where $\mathbf{i}_f = \left(i_{fd}, i_{fq}\right)^T$ – filter currents, U_m – mains voltage magnitude.

Consider the load current $\mathbf{i}_L$ (8) that have the main harmonic with frequency ω_1 and one higher harmonic with frequency $h\omega_1$: $i_{Ld} = x_{d0} + x_{dp} + x_{dn}$, $i_{Lq} = x_{q0} + x_{qp} + x_{qn}$. Load currents dynamics may be described using (3) and

$$\dot{x}_{d0} = 0, \quad \dot{x}_{q0} = 0. \tag{19}$$

According to Fig. 1 current balance in d-q reference frame is given by

$$\mathbf{i}_m = \mathbf{i}_L - \mathbf{i}_f. \tag{20}$$

In order to provide harmonic distortions and reactive power compensation, SAF current $\mathbf{i}_f$ must have opposite sign to the sum of harmonic distortions $\left(x_{dp}, x_{qp}, x_{dn}, x_{qn}\right)$ and reactive component x_{q0}.

Thus, the control objectives may be defined as

$$\lim_{t\to\infty} i_{md} = x_{d0}, \tag{21}$$

$$\lim_{t\to\infty} i_{mq} = 0. \tag{22}$$

From model (18) the dynamics of power filter currents can be written as

$$\begin{aligned} \dot{i}_{fd} &= -\left(R/L\right) i_{fd} + \omega_1 i_{fq} + L^{-1} v_d, \\ \dot{i}_{fq} &= -\omega_1 i_{fd} - \left(R/L\right) i_{fq} + L^{-1} v_q, \end{aligned} \tag{23}$$

if converter voltages are defined as $\mathbf{u}^* = \frac{1}{V_{DC}}\left\{\begin{pmatrix} U_m \\ 0 \end{pmatrix} - \mathbf{v}_{dq}\right\}$, where $\mathbf{v}_{dq} = \left(v_d, v_q\right)^T$ is the new control actions.

Let us mark φ^* is the reference value of variable φ, $\hat{\varphi}$ is the estimated value of variable φ, $\tilde{\varphi}$ is the tracking error $\tilde{\varphi} = \varphi - \varphi^*$ or estimation error $\tilde{\varphi} = \varphi - \hat{\varphi}$ of variable φ.

Power filter current references from (21), (22) are given by

$$i_{fd}^* = x_{d0} + \left(x_{dp} + x_{dn}\right) - \hat{x}_{d0} = \tilde{x}_{d0} + \left(x_{dp} + x_{dn}\right), \qquad i_{fq}^* = x_{q0} + \left(x_{qp} + x_{qn}\right). \tag{24}$$

From (23) and (24) filter current tracking errors dynamics becomes

$$\begin{aligned} \dot{\tilde{i}}_{fd} &= -\frac{R}{L}\tilde{i}_{fd} - \frac{R}{L}\left[\tilde{x}_{d0} + \left(x_{dp} + x_{dn}\right)\right] + \omega_1 i_{fq} - \dot{\tilde{x}}_{d0} + h\omega_1 x_{qp} - h\omega_1 x_{qn} + \frac{1}{L} v_d, \\ \dot{\tilde{i}}_{fq} &= -\omega_1 i_{fd} - \frac{R}{L}\tilde{i}_{fq} - \frac{R}{L}\left[x_{q0} + \left(x_{qp} + x_{qn}\right)\right] - h\omega_1 x_{dp} + h\omega_1 x_{dn} + \frac{1}{L} v_q. \end{aligned} \tag{25}$$

Define estimation errors as
$\tilde{x}_{d0} = x_{d0} - \hat{x}_{d0}$, $\tilde{x}_{q0} = x_{q0} - \hat{x}_{q0}$, $\tilde{x}_{dp} = x_{dp} - \hat{x}_{dp}$, $\tilde{x}_{qp} = x_{qp} - \hat{x}_{qp}$, $\tilde{x}_{dn} = x_{dn} - \hat{x}_{dn}$, $\tilde{x}_{qn} = x_{qn} - \hat{x}_{qn}$, and control action

$$\begin{aligned} v_d &= L\left[-\omega_1 i_{fq} + (R/L)\left(\hat{x}_{dp}+\hat{x}_{dn}\right) + \dot{\hat{x}}_{d0} - h\omega_1\hat{x}_{qp} + h\omega_1\hat{x}_{qn} - k_{i1}\tilde{i}_{fd}\right],\\ v_q &= L\left[\omega_1 i_{fd} + (R/L)\left(\hat{x}_{q0}+\hat{x}_{qp}+\hat{x}_{qn}\right) + h\omega_1\hat{x}_{dp} - h\omega_1\hat{x}_{dn} - k_{i1}\tilde{i}_{fq}\right]. \end{aligned} \tag{26}$$

Substituting (26) into (25) current errors dynamics becomes

$$\begin{aligned} \dot{\tilde{i}}_{fd} &= -k_i\tilde{i}_{fd} - (R/L)\tilde{x}_{d0} - (R/L)\left(\tilde{x}_{dp}+\tilde{x}_{dn}\right) - h\omega_1\left(\tilde{x}_{qp}-\tilde{x}_{qn}\right),\\ \dot{\tilde{i}}_{fq} &= -k_i\tilde{i}_{fq} - (R/L)\tilde{x}_{q0} - (R/L)\left(\tilde{x}_{qp}+\tilde{x}_{qn}\right) + h\omega_1\left(-\tilde{x}_{dp}+\tilde{x}_{dn}\right), \end{aligned} \tag{27}$$

where $k_i = (R/L + k_{i1})$.

Consider Lyapunov function

$$V = \frac{1}{2}\left[\left(\tilde{i}_{fd}^2+\tilde{i}_{fq}^2\right) + \gamma_1\left(\tilde{x}_{d0}^2+\tilde{x}_{q0}^2\right) + \frac{1}{\gamma_2}\left(\tilde{x}_{dp}^2+\tilde{x}_{qp}^2+\tilde{x}_{dn}^2+\tilde{x}_{qn}^2\right)\right]. \tag{28}$$

The time derivative of (28) can be derived as follows:

$$\dot{V} = -k_i\left(\tilde{i}_{fd}^2+\tilde{i}_{fq}^2\right) \le 0, \tag{29}$$

if

$$\begin{aligned} &\dot{\tilde{x}}_{d0} = k_1\tilde{i}_{fd}, && \dot{\tilde{x}}_{q0} = k_1\tilde{i}_{fq},\\ &\dot{\tilde{x}}_{dp} = -h\omega_1\tilde{x}_{qp} + (R/L)\gamma_2\tilde{i}_{fd} + \gamma_2 h\omega_1\tilde{i}_{fq}, && \dot{\tilde{x}}_{dn} = h\omega_1\tilde{x}_{qn} + (R/L)\gamma_2\tilde{i}_{fd} - \gamma_2 h\omega_1\tilde{i}_{fq},\\ &\dot{\tilde{x}}_{qp} = h\omega_1\tilde{x}_{dp} + (R/L)\gamma_2\tilde{i}_{fq} - \gamma_2 h\omega_1\tilde{i}_{fd}, && \dot{\tilde{x}}_{qp} = -h\omega_1\tilde{x}_{dn} + (R/L)\gamma_2\tilde{i}_{fq} + \gamma_2 h\omega_1\tilde{i}_{fd}, \end{aligned} \tag{30}$$

where $\gamma_1 k_1 = R/L$, k_{i1}, γ_2 is the tuning parameters.

From (28) and (29) we conclude that signals $\tilde{i}_{fd}, \tilde{i}_{fq}, \tilde{x}_{d0}, \tilde{x}_{q0}, \tilde{x}_{dp}, \tilde{x}_{dn}, \tilde{x}_{qp}\tilde{x}_{qn}$ are bounded, system (27), (30) has standard form considered in persistency of excitation lemma [7], therefore we conclude that $\lim\limits_{x\to\infty}\left(\tilde{i}_{fd}, \tilde{i}_{fq}, \tilde{x}_{d0}, \tilde{x}_{q0}, \tilde{x}_{dp}, \tilde{x}_{dn}, \tilde{x}_{qp}\tilde{x}_{qn}\right) = 0$, hence asymptotic current regulation and asymptotic harmonics estimation are achieved.

From (30) h harmonic estimator equations are obtained as

$$\begin{aligned} &\dot{\hat{x}}_{d0} = -k_1\tilde{i}_{fd}, && \dot{\hat{x}}_{q0} = -k_1\tilde{i}_{fq},\\ &\dot{\hat{x}}_{dph} = -h\omega_1\hat{x}_{qph} - \frac{R}{L}\gamma_2\tilde{i}_{fd} - \gamma_2 h\omega_1\tilde{i}_{fq}, && \dot{\hat{x}}_{dnh} = h\omega_1\hat{x}_{qnh} - \frac{R}{L}\gamma_2\tilde{i}_{fd} + \gamma_2 h\omega_1\tilde{i}_{fq},\\ &\dot{\hat{x}}_{qph} = h\omega_1\hat{x}_{dph} - \frac{R}{L}\gamma_2\tilde{i}_{fq} + \gamma_2 h\omega_1\tilde{i}_{fd}, && \dot{\hat{x}}_{qnh} = -h\omega_1\hat{x}_{dnh} - \frac{R}{L}\gamma_2\tilde{i}_{fq} - h\omega_1\gamma_2\tilde{i}_{fd}. \end{aligned} \tag{31}$$

Considering (31), a general form of N harmonics estimator may be described as

$$\begin{aligned} \dot{\hat{x}}_{d0} &= -k_1\tilde{i}_{fd},\\ \dot{\hat{x}}_{q0} &= -k_1\tilde{i}_{fq},\\ \dot{\hat{\mathbf{X}}} &= \mathbf{A}\hat{\mathbf{X}} + \mathbf{B}\mathbf{U}, \end{aligned} \tag{32}$$

where

$$\hat{\mathbf{X}} = \begin{pmatrix}\hat{\mathbf{X}}_1\\ \vdots\\ \hat{\mathbf{X}}_N\end{pmatrix}; \hat{\mathbf{X}}_1 = \begin{pmatrix}\hat{x}_{dp1}\\ \hat{x}_{qp1}\\ \hat{x}_{dn1}\\ \hat{x}_{dn1}\end{pmatrix}; \hat{\mathbf{X}}_N = \begin{pmatrix}\hat{x}_{dpN}\\ \hat{x}_{qpN}\\ \hat{x}_{dnN}\\ \hat{x}_{dnN}\end{pmatrix}; \mathbf{U} = \begin{pmatrix}\tilde{i}_{fd}\\ \tilde{i}_{fq}\end{pmatrix};\ \mathbf{B} = \begin{pmatrix}\mathbf{B}_1\\ \vdots\\ \mathbf{B}_N\end{pmatrix}; \mathbf{B}_1 = \begin{pmatrix}-\frac{R}{L}\gamma_2 & -\gamma_2\omega_1\\ \gamma_2\omega_1 & -\frac{R}{L}\gamma_2\\ -\frac{R}{L}\gamma_2 & \gamma_2\omega_1\\ -\gamma_2\omega_1 & -\frac{R}{L}\gamma_2\end{pmatrix}; \mathbf{B}_N = \begin{pmatrix}-\frac{R}{L}\gamma_2 & -\gamma_2\omega_N\\ \gamma_2\omega_N & -\frac{R}{L}\gamma_2\\ -\frac{R}{L}\gamma_2 & \gamma_2\omega_N\\ -\gamma_2\omega_N & -\frac{R}{L}\gamma_2\end{pmatrix};$$

$$
\mathbf{A}=\begin{pmatrix} \mathbf{A_1} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \mathbf{A}_N \end{pmatrix};\quad \mathbf{A_1}=\begin{pmatrix} 0 & -\omega_1 & 0 & 0 \\ \omega_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & \omega_1 \\ 0 & 0 & -\omega_1 & 0 \end{pmatrix};\quad \mathbf{A}_N=\begin{pmatrix} 0 & -\omega_N & 0 & 0 \\ \omega_N & 0 & 0 & 0 \\ 0 & 0 & 0 & \omega_N \\ 0 & 0 & -\omega_N & 0 \end{pmatrix}.
$$

Adaptive current control in (26) is given by

$$
\begin{aligned}
v_d &= L\left[-\omega_1 i_{fq}+\frac{R}{L}\sum_{i=1}^{N}\left(\hat{x}_{dpi}+\hat{x}_{dni}\right)+\dot{\hat{x}}_{d0}+\sum_{i=1}^{N}\omega_i\left(\hat{x}_{qni}-\hat{x}_{qpi}\right)-k_{i1}\tilde{i}_{fd}\right],\\
v_q &= L\left[\omega_1 i_{fd}+\frac{R}{L}\left(\hat{x}_{q0}+\sum_{i=1}^{N}\left(\hat{x}_{qpi}+\hat{x}_{qni}\right)\right)+\sum_{i=1}^{N}\omega_i\left(\hat{x}_{dpi}-\hat{x}_{dni}\right)-k_{i1}\tilde{i}_{fq}\right].
\end{aligned}
\tag{33}
$$

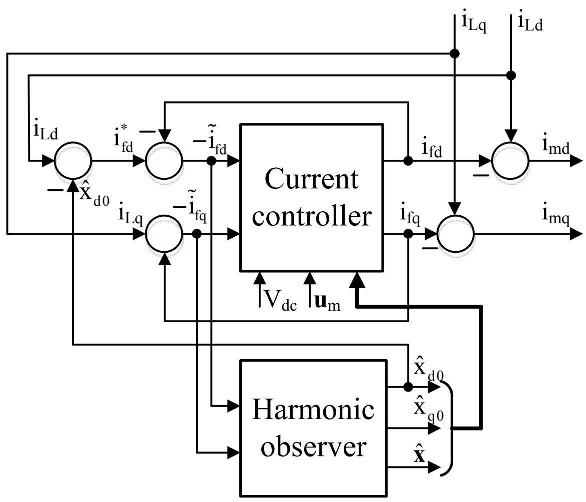

Fig. 4

Block diagram of the adaptive SAF current control system is presented in Fig. 4.

To confirm the obtained theoretical results, a simulation of the proposed SAF current control system was carried out. The load current in (a-b) reference frame is given by the sum of the main harmonic with amplitude 10 A and higher harmonics up to 20th, with the same unity amplitudes and phase shift equal $\pi/(i+1)$. The following SAF parameters were set: R = 0.12 Ohm, L = 3 mH.

As it follows from transients in Fig. 5, proposed control algorithm provides asymptotic current regulation. From comparison of load and mains current FFTs it follows that full cancelation of given harmonic stuff is achieved. Waveforms of mains voltage and current confirms unity power factor.

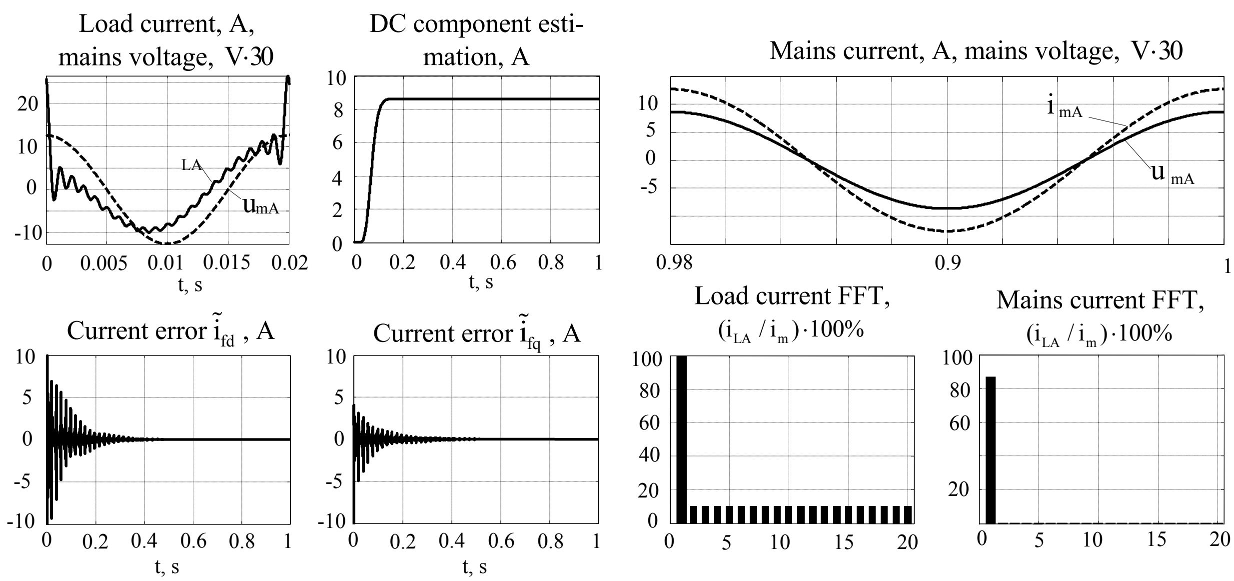

Fig. 5

Experimental results. This Section reports the results of experiments conducted to investigate the dynamics of the estimator (16). The goal of the experiments is to analyze observer behavior in real system with natural measurement noise and quantization effects.

The test rig includes: TMS320F28335 DSP–based controller for observer implementation; nonlinear load, represented by bridge rectifier with capacitance filter and chopper for load current regulation. Sampling time during experiments is set to $T_s = 75$ µs. From preliminary tests with DSP TMS320F28335 it follows, that selected level of sampling time provides stable harmonics estimation with numbers from 1st to 16th.

The waveform and FFT of the uncompensated phase current are shown in Fig. 6, while compensated one is in Fig. 7. From comparison of Fig. 6 and Fig. 7 it follows that waveform of compensated current is close to sinusoidal and harmonics lower 16th are significantly reduced. Low level residual distortions in current waveform are present due to uncompensated, higher than 16th, harmonics.

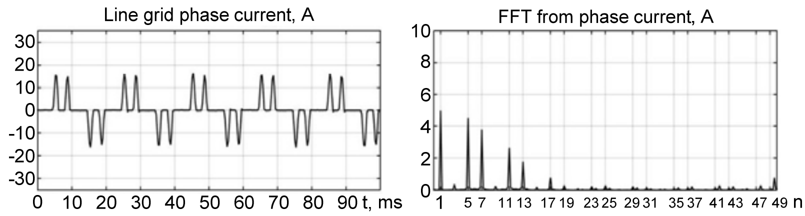

Fig. 6

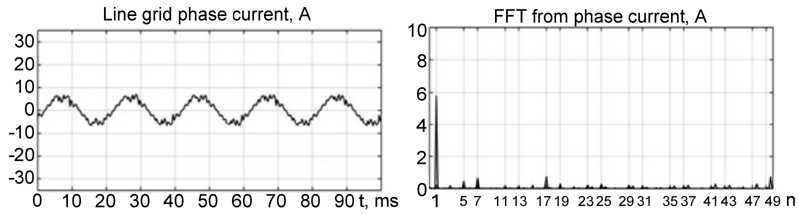

Fig. 7

Conclusions. In the paper it is shown that speed of convergence for standard Luenberger observer with selectivity of estimation is limited by the estimator structure. Such observer is suitable in case if selectivity property is used to reduce the complexity of estimation scheme, when not all harmonics are required to be estimated. A novel structure of the observer with filtered measured currents is presented for estimation of all set of harmonics. Observer guarantees fast asymptotic convergence with no phase delay and has simple tuning procedure. The important feature of the designed estimator is freedom in design of feedback coefficients matrix according to any optimization technique for linear systems, which are stable for any positive tuning gains. The selectivity property of the observer with filtered measured currents with correction matrix, given in (16), is lost in general case, therefore such observer can be used for estimation of all harmonics with further compensation of required ones.

Adaptive current controller presented in Section IV is a combination of harmonic estimator and current control loop. Such approach allows to achieve the asymptotic estimation and asymptotic compensation of all set of harmonics, however selectivity is not possible in this case. Simulation and experimental results confirm theoretical findings and effectiveness of proposed estimation and control schemes.

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СЕЛЕКТИВНЕ ТА АДАПТИВНЕ ОЦІНЮВАННЯ ГАРМОНІК ДЛЯ ТРИФАЗНОГО СИЛОВОГО АКТИВНОГО ФІЛЬТРА

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Стаття присвячена оцінюванню гармонік струму трифазної мережі в реальному часі на основі методів теорії адаптивного керування. В роботі показано, що стандартний спостерігач позитивної та негативної послідовностей кожної гармоніки забезпечує властивості селективності, але має обмежену швидкість оцінювання і придатний для застосування у випадку, коли необхідно оцінити набір вибіркових гармонік. Запропоновано нову структуру спостерігача з фільтрацією виміряних струмів, яка забезпечує швидке асимптотичне оцінювання гармонік та має просту процедуру налаштування. Представлено новий підхід до регулювання струмів активного фільтра на основі поєднання спостерігача гармонік та контурів регулювання струмів. Запропонований підхід дозволяє досягти асимптотичного оцінювання та асимптотичної компенсації всього спектра гармонік струму. Результати математичного моделювання та експериментальних досліджень підтверджують теоретичні висновки. Бібл. 13, рис. 7.
Ключові слова: силовий активний фільтр, гармоніки струму, оцінювання.

УДК 621.314.5

СЕЛЕКТИВНОЕ И АДАПТИВНОЕ ОЦЕНИВАНИЕ ГАРМОНИК ДЛЯ ТРЕХФАЗНОГО СИЛОВОГО АКТИВНОГО ФИЛЬТРА

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Статья посвящена оценке гармоник тока трехфазной сети в реальном времени на основе методов теории адаптивного управления. В работе показано, что стандартный наблюдатель положительной и отрицательной последовательностей каждой гармоники обеспечивает свойства селективности, но имеет ограниченную скорость сходимости и пригоден для применения в случае, когда необходимо оценить набор выборочных гармоник. Предложена новая структура наблюдателя с фильтрацией измеренных токов, которая обеспечивает быстрое асимптотическое оценивание гармоник и имеет простую процедуру настройки. Также представлен новый подход к регулированию токов активного фильтра на основе сочетания наблюдателя гармоник и контуров регулирования токов. Такой подход позволяет достичь асимптотического оценивания и асимптотической компенсации всего спектра гармоник. Результаты математического моделирования и экспериментальных исследований подтверждают теоретические выводы. Библ. 13, рис. 7.
Ключевые слова: силовой активный фильтр, гармоники тока, оценка.

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