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MODELING OF COMPLEX STRUCTURES FOR THE SHIP'S POWER COMPLEX USING XILINX SYSTEM

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One of the most essential tasks for a number of systems of the automatic controls in the autonomous electric power systems of the water transport is accurate calculation of variable harmonic components in the non-sinusoidal signal. In the autonomous electric power systems operating with full semiconductor capacity, the forms of line currents and voltages are greatly distorted, and generator devices generate voltage with inconsistent frequency, phase and amplitude. It makes calculation of harmonic composition of the distorted signals be a non-trivial task. The present paper provides a mathematical set for solution of the outlined problem including the realization in the discrete form. The simplicity and efficiency of the system proposed make possible to perform its practical realization with the help of cheap FPGA. The test of the developed system has been performed in the medium Matlab.

Keywords: power systems, intellectual systems, harmonic components, ship

1. Introduction

The modern ship's electric power systems (SEPS) are characterized by the presence in its composition of a great number of the conversion load, including frequency transformer, un-interruptive power supply, inverters, rectifiers and other consuming devices varying in their non-linear volt-ampere features.

Similar load has a negative impact on the supplying network of the alternating current, generating into it highest harmonic components of currents and voltages.

At the same time, a great deal of the ship's automation systems apply the line currents and voltages to form the reference signal. Thus, for example, an automatic voltage regulator (AVR) of the ship's synchronous generators (SG) performs regulation by an average value of voltages and currents in the circuit. However, with the distorted form of the variable signals (that is caused by the presence of a wide range of highest harmonics) their average value increases and an automatic voltage regulator (AVR), correcting the error, decreases the exciting current of the synchronous generator that results in loss of voltage in the ship's electric power systems (SEPS). Consequently, decrease in relative value and increase in highest harmonics take place, and, thus, the electromagnetic moment of the non-synchronous motors decreases, the level of interferences influencing the systems of the ship's automatic controls becomes higher, and the losses in the power supply lines enlarge. Practically, such an error is corrected by the adjustment of the voltage corrector (VC). However, as the harmonic composition periodically varies depending on the mode of operation and the composition of the load of the electric power station, the setting of the voltage corrector should be changed constantly. This problem should be solved by measuring the level of the basic harmonics of the current and voltages of the ship's circuit.

On the other side, it is known that filter-compensating devices (FCD) are the most efficient means to increase the quality of electric energy in the ship's power supply systems at the moment. Their efficiency in higher harmonic suppression and compensation of their volt-ampere reactive may be provided only by the high accuracy of the calculation of parameters in the target harmonics of the line currents and voltages.

2. Settlement of the problem

Thus, the required functional set of the systems taken as an example determining their efficiency, in particular, and their operational performance in general, is a set for identification of external parameters of the control system. The major function of the block is extraction of harmonic components required for their analysis, calculation of their parameters from the distorted signal and application of the results of that analysis in the control of the means of the increasing values for quality of the electric energy in the ship's electric power systems. With this, such parameters as levels of target harmonics of currents and voltages, values of summary harmonic distortions, values of distortion capacity, volt-ampere reactive, etc. are regulated.

If sources of energy for a ship's electric power station may be represented as a generator of the sinusoidal signal

$$x(t) = a_1(t)\sin\left(\omega_1(t)t + \varphi_1(t)\right) \tag{1}$$

where $a_1(t)$ – amplitude, $\omega_1(t)$ – rate of phase change and $\varphi_1(t)$ – phase – non-stationary parameters of the generator; the scheme under research may be represented by the structural sketch in Figure 1.

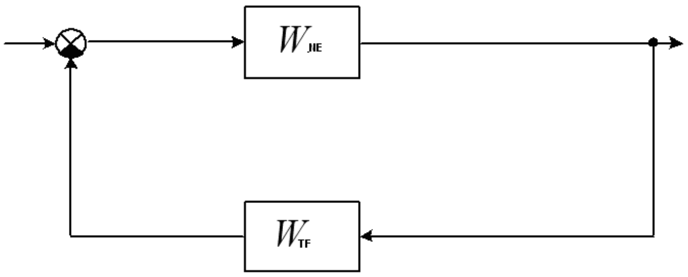

Figure 1. Simplified schematic diagram of the system under research:
W_{TF} – non-linear element, W_{NE} – transfer function of the generator set in the ship's electric power system, generating periodically non-stationary signal x(t)

As it would seem, this standard for the theory of the automatic control of the form structural scheme cannot be analyzed by the tools of the classical frequency criteria as the sense itself for the frequency characteristics of a non-stationary element is lost. With this, the non-linear element WHЭ itself is, generally, non-stationary as the main semi-conductor load of the ship's electric power system is a set of a closed system (for example, autonomous inverters and converters) described by commutation functions and consequently containing periodically varying coefficients.

In the view of the problem being solved, it is required to determine the harmonic composition of the non-stationary signal in order to use it as a set of reference signals in the system of the quality management for the electric energy in the ship's electric power system. The present paper proposes to use a certain function approximating the target harmonics of the distorted signal. The structural sketch of such a system is given in Figure 2.

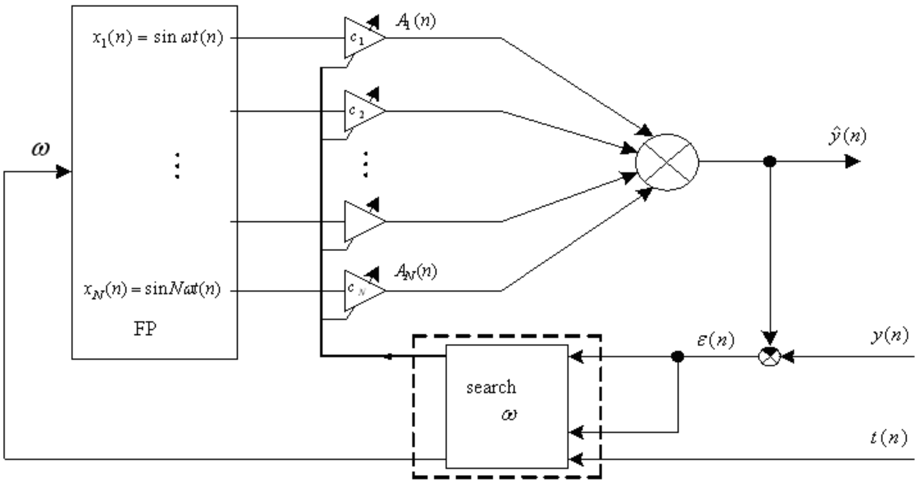

Figure 2. The structural sketch of the approximator, performing monitoring of the frequency ω and the components of the harmonics of the signal y

Identification of the target non-stationary harmonics of the distorted signal is made by adjustment of the parameters of the relevant function-prototype (FP). In its general form, the input signal y(t) of the identification system, being a signal proportional to the circuit current or voltage in the ship's electric power system, may be described by Fourier's series:

$$y(t) = \sum_{k=1}^{N} a_k(t)\sin\left(k\omega_k(t)t + \varphi_k(t)\right) = x(t) + \xi(t),$$

where $a_k(t)$ is amplitude, $\omega_k(t)$ is a rate of phase change and $\varphi_k(t)$ is a phase angle of k-harmonics, N is a number of harmonics (in general $N = \infty$), $\xi(t) = \sum_{k=2}^{N} a_k(t)\sin\left(k\omega_k(t)t + \varphi_k(t)\right)$ is a set of non-approximated (i.e. non-recoverable by the device being designed) harmonics.

Let's introduce the vector for the parameters $\phi(t) = [a(t), \omega(t), \varphi(t)]^T$, which belong to the space of parameters $\Phi(t) = \left\{[a, \omega, \varphi]^T\right\}$.

The approximation error is exhibited by the expression

$$\varepsilon = y - \hat{x}, \tag{2}$$

where $\hat{x}(t) = \hat{a}_1(t)\sin\left(\hat{\omega}_1(t)t + \hat{\varphi}_1(t)\right)$ is a recovered harmonic component. Moreover, it is evident that the more components ξ(t) of the function will be recovered by the relevant generators of the approximating functions the less the error (2) will be.

And also let the energetic function of the error be exhibited by the mean square error

$$E = \frac{1}{2}\varepsilon^2. \tag{3}$$

The function (3) is the function of three variables, that is E(A, ω, φ) or E(ф). The task of the approximation is to seek such an algorithm of variation of elements of vector ф, with which minimization of the function (3) takes place, i.e. the search of such a value $\overline{\phi}$ of the vector ф, to which the extreme value of the function E (minimum), where the following condition would be realized:

$$E(\phi) \geq E(\hat{\phi}), \quad \forall E \in \Phi, \tag{4}$$

where Φ is a permitted area or an area of the possible values for the vector ф, determined by the limitations

$a \in [a_{\min}, a_{\max}]$, $\omega \in [\omega_{\min}, \omega_{\max}]$ and $\varphi \in [\varphi_{\min}, \varphi_{\max}]$.

At this stage we have approached the task of seeking the extreme (4) (minimum) of the energetic function (3). The function is differentiable by all the elements; however the expression (2) assumes non-linear conversion of the elements for the input vector ф. The latter circumstance challenges the possibility to apply gradient algorithms mostly recommended by themselves in the extreme systems.

Let's consider mathematical aspects of the possibility to apply gradient methods in the task outlined for the case of recovery of one target harmonics. Let's write down the gradients for the recovered parameters in the vector ф:

$$\begin{aligned} \frac{d\hat{a}(t)}{dt} &= -\mu_A \frac{\partial[E(t,\phi(t))]}{\partial\hat{a}(t)} \\ \frac{d\hat{\omega}(t)}{dt} &= -\mu_\omega \frac{\partial[E(t,\phi(t))]}{\partial\hat{\omega}(t)} \\ \frac{d\hat{\varphi}(t)}{dt} &= -\mu_\varphi \frac{\partial[E(t,\phi(t))]}{\partial\hat{\varphi}(t)} \end{aligned} \tag{5}$$

The energetic function may be represented as follows

$$E(t,\phi(t)) = \frac{1}{2}\varepsilon(t,\phi(t))^2 = \frac{1}{2}\left[y(t) - \hat{a}(t)\sin\left(\hat{\omega}(t)t + \hat{\varphi}(t)\right)\right]^2.$$

Substituting it into (5) and differentiating the right-hand part, we will have

$$\begin{aligned}
&\frac{d\hat{a}(t)}{dt} = -\mu_A \varepsilon(t)\sin\left(\hat{\omega}(t)t + \hat{\varphi}(t)\right) \\
&\frac{d\hat{\omega}(t)}{dt} = -\mu_\omega \varepsilon(t)\hat{a}(t)t\cos\left(\hat{\omega}(t)t + \hat{\varphi}(t)\right) \\
&\frac{d\hat{\varphi}(t)}{dt} = -\mu_\varphi \varepsilon(t)\hat{a}(t)\sin\left(\hat{\omega}(t)t + \hat{\varphi}(t)\right)
\end{aligned} \tag{6}$$

As it is clear, the time parameter outside the cosine mark appears in the second equation of the system (6). Thus, for this energetic function the expression of the gradient for the angle velocity contains a combined, i.e. secular (age) and, simultaneously, a non-linear term. When applying Newton-Raphson's method (or similar ones), using a hessian, several of such terms will appear. So, whatever small the function of the error ε(t) would be, in the course of time the secular term will be increasing without limits.

This fact explains the failures in realization of the numerical techniques on the basis of similar algorithms created by using common approaches of adaptive systems and gradient methods in particular, practical realization of which in the described cases of application faces with the divergence of the process when monitoring the changes in signal phase and frequency.

Consequently, it is necessary to develop such an algorithm for identification of the harmonic composition of signals proportional to currents and voltages in the circuit which makes possible to provide the convergence of the process with the existing non-linear features and the non-stationary character of the system under review and, at the same time, to support the implementation of the up-to-date digital systems especially under the necessity to identify a set of harmonic components of the signal that requires parallel and pseudo-parallel operation of a number of copies or nuclei of the algorithm sought.

3. The solution of the task outlined

The core of the proposed principle of the approximation of every harmonics of the measured signal is in the formation of the periodical function basing on the function-prototype Rk(ωk(t),φk(t),t), where k is a number of the approximated harmonics (or simply Rk(k,t)); so changing its parameters we will strive to approach the minimum of the error between the input signal and periodical function. Proceeding from the physical sense of the processes under the review, as it was stated above, it is reasonable for FP to use the function Rk(t)=sin(ωk(t)t+φk(t)). Thus, every harmonics will be approximated by the weight function (Dirac response) $\hat{x}_k(t) = \hat{a}_k(t)R(k,t)$.

Thus, the frequency ω(t) and phase function φ(t) of the target function are variable, so let's go to the notion of the complete phase ψ(t)=ω(t)t+φ(t), taking into account all the variations of the function phase. The system (6) will be expressed as

$$\frac{d\hat{a}(t)}{dt} = -\mu_A \varepsilon(t)\sin\hat{\psi}(t) \tag{7.1}$$

$$\frac{d\hat{\omega}(t)}{dt} = -\mu_\omega \varepsilon(t)\hat{a}(t)t\cos\hat{\psi}(t) \tag{7.2}$$

$$\frac{d\hat{\psi}(t)}{dt} = \hat{\omega}(t) + \mu_\psi \frac{d\hat{\omega}(t)}{dt} \tag{7.3}$$

The energetic function would be expressed in the form of the following expression: $E(t) = \frac{1}{2}\left[y(t) - \hat{a}(t)\sin\hat{\psi}(t)\right]^2$, i.e. for the error of the approximation we will have $\varepsilon(t) = y(t) - \hat{a}(t)\sin\hat{\psi}(t) = y(t) - \hat{x}(t)$.

It should be noted that the change in the phase of the input signal may be compensated by the similar change in the initial phase of the approximating function (that will exactly correspond to the behaviour of the signal being approximated), short-time change in the frequency of the same function or by the combination of these processes.

Let's pass on the integral of the function (7.2) and the final interval [ti – T/2, ti + T/2] of T duration, where one more interval of FP is determined. As one can see, FP used by us is 2π-periodical (i.e. T=2π/ω) and odd-symmetrical in respect to the middle of the interval where it was determined and integrated. Let's assume that the amplitude of the approximated harmonics for the time of the FP period does not change (or changes slowly). So, for the basic harmonics we will have

$$\hat{\omega}_1(t) = -\mu_{\omega 1} \int_{t_i - \frac{T}{2}}^{t_i + \frac{T}{2}} \varepsilon(t)\hat{a}_1 t \cos\hat{\psi}(t)dt \tag{8}$$

Considering (1)-(2) and taking into account that according to the experimental research [1-4] odd harmonics are predominant in the ship's circuit в, express (8) in the following form

$$\hat{\omega}_1(t) = -\mu_{\omega 1} \int_{t_i - \frac{T}{2}}^{t_i + \frac{T}{2}} [a_1(t)\sin\psi_1(t) + a3(t)\sin\psi_3(t) + \\ a_5(t)\sin\psi_5(t) + ...]\hat{a}_1(t)t\cos\hat{\psi}_1(t)dt \tag{9}$$

If the frequency of the period for the Function-Prototype coincides with the period of the approximated harmonic, i.e. $\hat{\omega}_1(t) = \omega_1$ so (9) will transformed into:

$$-\mu_{\omega 1} \int_{t_i - \frac{T}{2}}^{t_i + \frac{T}{2}} t\left[\frac{a_1\hat{a}_1}{2}\sin[2\omega_1(t)t + \varphi_1(t) + \hat{\varphi}_1(t)] + \frac{\hat{a}_1 a_3}{2}\left[\sin[4\omega_1(t)t + \hat{\varphi}_1(t) + \varphi_3(t)] + \right.\right.$$
$$\left.\left. + \sin[2\omega_1(t)t + \hat{\varphi}_1(t) - \varphi_3(t)] + ...\right] - \frac{\hat{a}_1 a_1}{2}\sin[2\omega_1(t)t + \varphi_1(t) + \hat{\varphi}_1(t)]\right] = \tag{10}$$
$$= -\mu_{\omega 1} \int_{t_i - \frac{T}{2}}^{t_i + \frac{T}{2}} t\frac{\hat{a}_1 a_3}{2}[\sin[4\omega_1(t)t + \hat{\varphi}_1(t) + \varphi_3(t)] + \sin[2\omega_1(t)t + \hat{\varphi}_1(t) - \varphi_3(t)] + ...]$$

In the connection with that only odd harmonics will take place in the input signal, so under the mark of the integral vice versa only even harmonics with frequencies $2\omega_1$, $4\omega_1$, $6\omega_1$ etc. will remain, and the integral of their sum in the interval T will be equal to 0 due to the even non-symmetry of the sine components.

With appearing the error δ between the real and recovered frequencies of the main harmonics under-integral expression in (9) will also contain the given even harmonics.

In fact, the calculated integral conversion in a general form will represent the resultant of the function of the approximator error ε(t) by means of the window (or using the terms of scanning systems, weight) function $\hat{x}_k(t)$. Thus, the result of integrating the expression (9) is the value of correlation FP and ε(t). If δ tends to zero, (9) will also tend to zero irrespective of he phase shift between FP and every harmonics of the input signal or their amplitudes. The latter feature of the expression enables to simplify it to the form

$$\hat{\omega}_1(t) = -\beta_{\omega 1} \int_{t_i - \frac{T}{2}}^{t_i + \frac{T}{2}} \varepsilon(t)r(t)dt,$$

where r(t) – even- or odd-symmetric in respect to the interval of integration of FP (derivative of R(t)). The form of this function determines the dynamic qualities of the tracking system for the frequency of the basic harmonic. It should be noted that T is a variable value. It is this circumstance that enables to synchronize the FP with the period of the target harmonic and reject the standard measure of time (frequency), having the long-term stability with due necessity.

Taking the above-mentioned into account, the function will be expressed as follows:

$$\hat{\omega}_1(t) = -\beta_{\omega 1} \int_{t_i - \frac{\pi}{\hat{\omega}_1}}^{t_i + \frac{\pi}{\hat{\omega}_1}} \varepsilon(t) r(t) dt \, .$$

For the numerical system this function may be expressed in the following discrete form:

$$\omega_{i+1} = \omega_i + \tau\beta_{\omega 1}\varepsilon_i r_i \, ,$$

where τ is the time for the integration step.

Within every cycle corresponding to the period of FP, the FP has a number of certain arms and spots. As for the latter, one may say about the initial point of the period, about the final one as well as about zeroes and extreme values of the FP. It is reasonable as an increment of the target parameter to use distance (time) between certain points. Thus, as the expression (9) will represent the sum of the harmonic components with the lowest frequency (the first resonance frequency) equal to 2ω1, and consequently the correlation function will tend to zero already in the period corresponding to the half of the period of the main harmonic, so the sufficient interval of the integration may be considered the half of the period of the main harmonics or intervals divided by it. In other words, the increment of the frequency (period) change in the FP will be equal to the integral (9) at the half-period of the frequency of the main harmonic. In the discrete form:

$$\omega_{i+1} = \omega_i + \frac{2\beta_{\omega 1}\tau}{T}\varepsilon_i r_i \, .$$

Otherwise, expressing the period by means of frequency FP we will have

$$\omega_{i+1} = \omega_i + \frac{\beta_{\omega 1}\tau\omega_i}{\pi}\varepsilon_i r_i \, .$$

Substituting αω= τ βω1/π, we will have

$$\omega_{i+1} = \omega_i + \alpha_\omega \omega_i \varepsilon_i r_i \, . \tag{11}$$

Coefficient αω also determines the dynamic features of the frequency tracking system and depends on the form of the FP. Product αωωi in the expression (11) enables to preserve these specific features with changing the frequency of the input signal, i.e. in fact it describes the reconfigurable filter as it determines constant value of the time of the integrator adapting to the non-stationary frequency of the restorable harmonic.

In the same way we express in the discrete form the expression (7.3), describing the complete phase of the FP

$$\psi_{i+1} = \psi_i + \tau\omega_i + \tau\alpha_\psi \alpha_\omega \omega_i \varepsilon_i r_i \, . \tag{12}$$

The complete description of the approximator calculated on the basis of the expressions (11) and (12), in the discrete form will be represented by the system

$$\begin{aligned} \omega_{i+1} &= \omega_i + \alpha_\omega \omega_i \varepsilon_i \cos(\psi_i) \\ \psi_{i+1} &= \psi_i + \tau\omega_i + \tau\alpha_\psi \alpha_\omega \omega_i \varepsilon_i \cos(\psi_i) \\ a_{i+1} &= a_i + \tau\alpha_a \varepsilon_i \sin(\psi_i) \\ \varepsilon_i &= y_i - R_i \\ R_i &= a_i \sin(\psi_i) \end{aligned} \tag{13}$$

In case of realization of the numerical methods of the solution for the given system by means of the digital calculating devices arrangement of the FP in the discrete form starts influencing the dynamic functions of the system. In other words, a number of steps in discretization of the FP gains significance in this case. On the other hand, one may not proceed from the continuous function striving for the desired features and, on the contrary, taking dynamic characteristics it is possible to produce a discrete function-prototype (DFP) satisfying them.

The key role in the solution of the implementation of the solution (13) is given to the coefficients α, the selection of which is the compromise between the velocity of the approximator adjustment in accordance with the changes of an input signal and the accuracy of approximation. Virtually, large values of coefficients make possible to lessen the time of transition processes, however at the same time non-linear distortions start prevailing in the approximating signal. Therefore, in order to improve the values it is possible to apply additional filters for FP parameters or adaptive readjustment of coefficients. The hybrid variant of the tracking system in which internal DFP with high velocity of approximation is used for tracking and output signal of the approximator is taken from the additional external DFP, arguments of which are renewed only in the characteristic points mentioned above. Renewal takes place only by current (or filtered) parameters of the internal DFP.

4. Results of the modeling

Modelling according to the proposed algorithm has demonstrated the convergence of the solution without any limitations in the interval of modelling. The results of modelling are given in Fig. 3 and Fig.4.

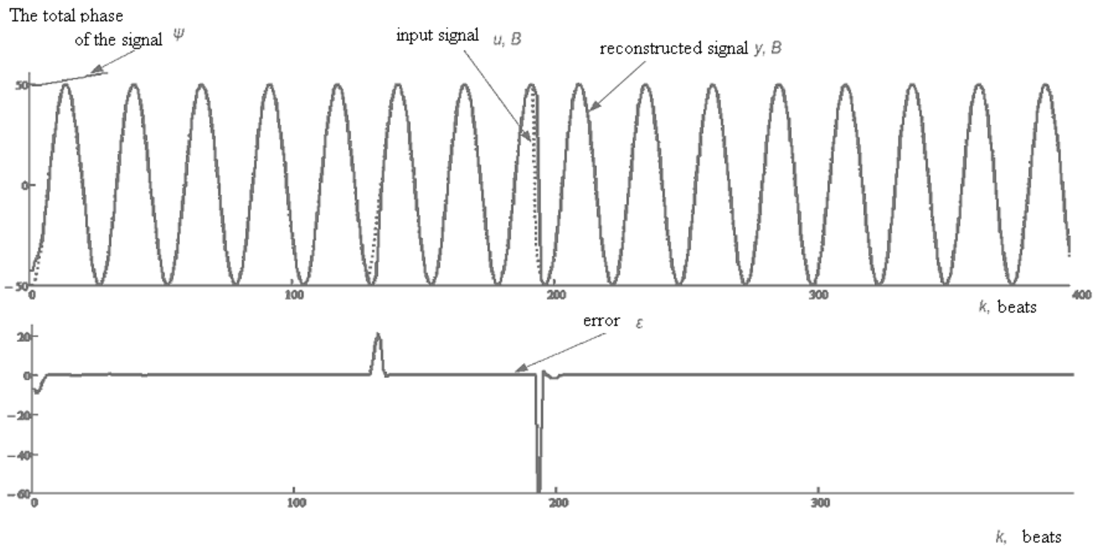

Figure 3. Tracking of the main harmonic y(k) of the distorted signal v(k) with variable frequency ω(k) and error of tracking ε(k) according to the proposed algorithm

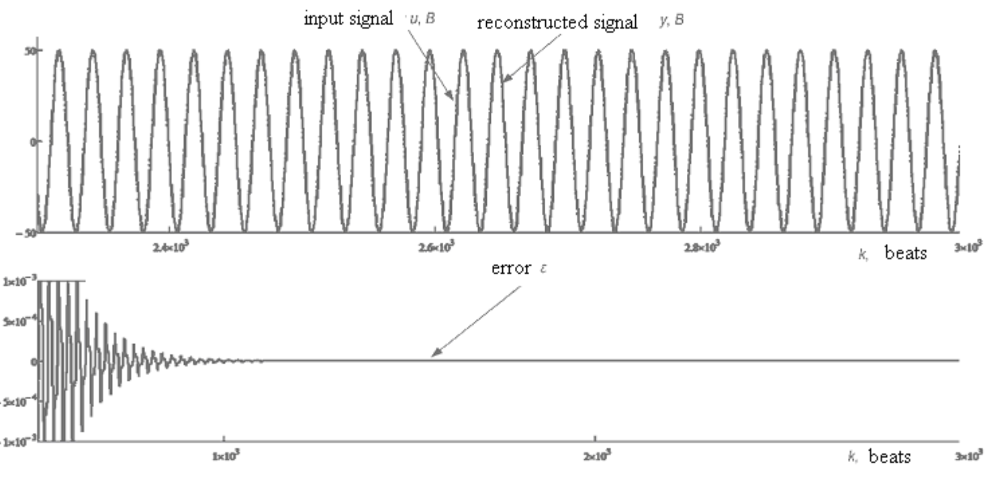

Figure 4. The process of tracking of the main harmonic y(k) of the distorted signal v(k) in the large time interval

Fig.5 shows the results of modelling the process of tracking over the main harmonic of the signal v(t), if the 5th and the 7th harmonics are available with the levels 10% and 5% respectively.

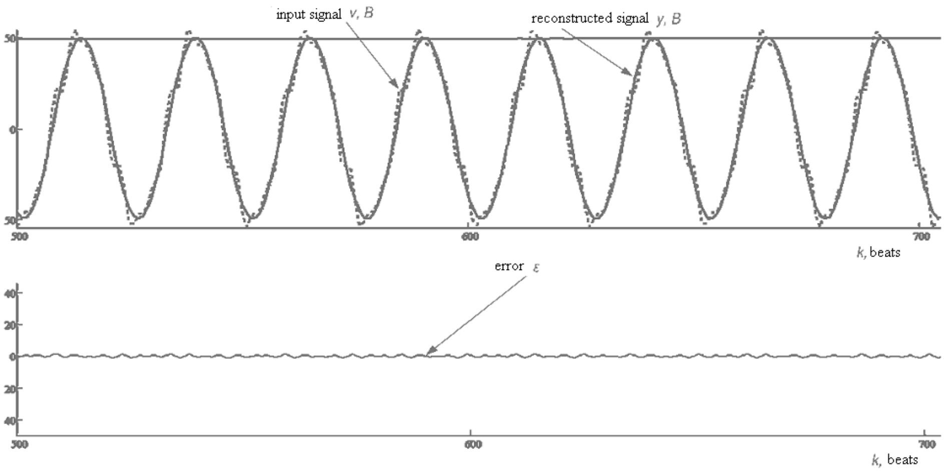

Figure 5. Approximation of the main harmonic y(k) of the distorted signal v(k) if the 5th and the 7th harmonics are available

Fig. 6 provides the result of modelling of the transition process of the approximator. The frequency of the input signal changes with the leap from 50 down to 46.5 Hz without any additional filtration of the restored signals.

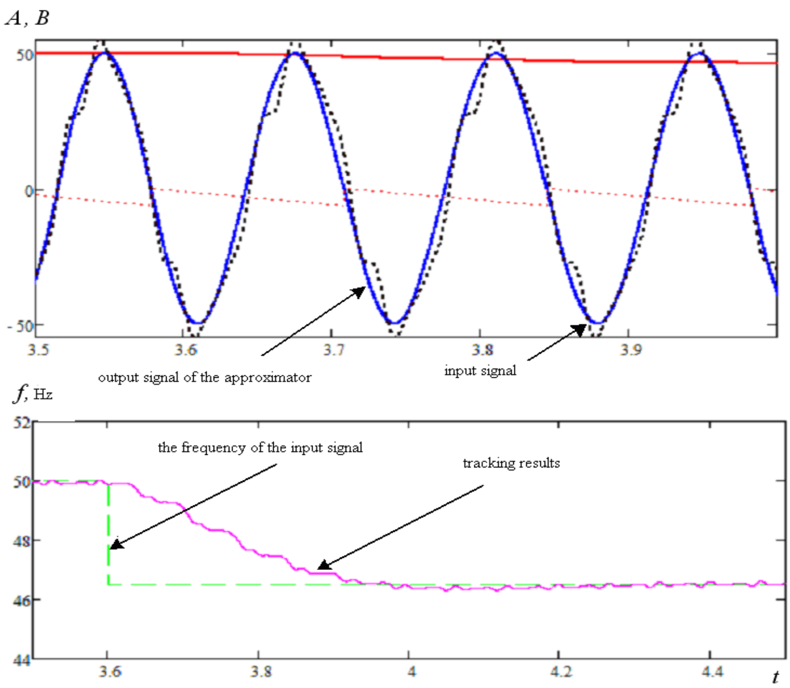

Figure 6. Response of the approximator to the leap-ahead change in frequency of the input signal

5. Comparison with the existing solutions

The proposed method of tracking over the parameters of the main (and, in general, of any) harmonic of the distorted signal, makes possible to provide unique, stable and convergent solution of the non-linear dynamic system. The obtained algorithm provides the unique asymptotic trajectory, being periodical and lying in the vicinity of the approximated function – target harmonic of the signal.

This method may be successfully applied in design of the multivariable systems for identification of external parameters in the water transport and in other autonomous electric power systems.

A number of existing solutions with which the proposed system may be compared is rather limited. For example, such distributed methods as fast or discrete Fourier transform are beyond the comparison in connection with the fact that with the frequency shift the component of the input signal is expressed itself as the so-called effect of leakage as a result of which the frequency deviation for 5 Hz causes the appearance of errors in the evaluation of amplitude more than 10%.

The comparative analysis of the operation of the designed system and the extended Kalman filter produces the following results of modelling. Application of the extended Kalman filter with the availability of the 5th and 7th harmonics besides the main harmonic with amplitudes 10% and 5% respectively, does not allow having an error less than 4%. At the same time, the system proposed by the author, under the same conditions has an error not exceeding 0.2% by the frequency. And if we use a filter of low frequencies by the signal of the restored frequency, the error reduces to the level less than 0.04%.

6. Practical implementation

The simplicity of the proposed algorithm allows implementing multivariable approximator with minimum requirements to the computational hardware of the device. The simplest and the most effective algorithm with computational function or a FP tabular model may be implemented in the FPGA. FPGA architecture, its flexibility and possibility to implement parallel computational processes makes them the most promising platform for the practical implementation of the reviewed tracking system.

Modelling of the scheme operation (Fig.7), realizing the system (13) by means of FPGA, and generation of the firmware code have been made by means of software Xilinx System Generator in Matlab 14. Spartan 6 in Xilinx has been chosen as FPGA. Fig.8 provides the report about the number of FPGA resources required while creating the tracking system for the parameters of one harmonic of the input signal, produced by means of block Xilinx Resource Estimator. This realization of the described algorithm is used for acquisition of the main harmonic of the circuit voltage in order to provide correct operation of automatic voltage regulators of the ship's synchronous generators (AVR for the SG) under the conditions of high distortion of voltages and currents in the ship's circuit.

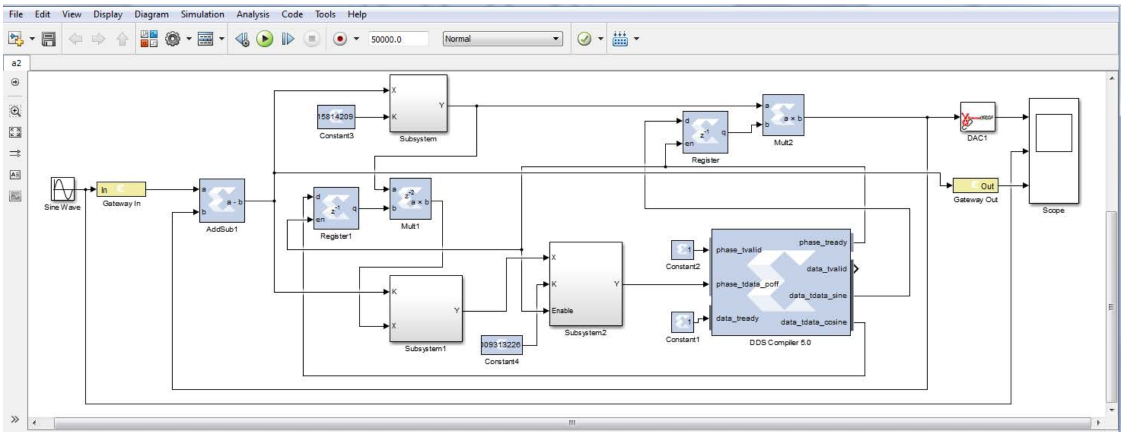

Figure 7. Configuration of FPGA for implementation of the system (13)

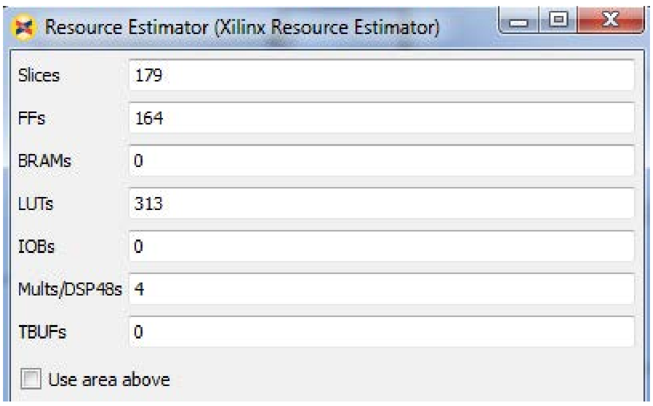

Figure 8. Report of Xilinx Resource Estimator about applied FPGA resources

As it is seen from a small number of the required computational resources, not exceeding even 2% of the available ones in the applied FPGA, a multivariable system of parallel restoration of a number of harmonic components of the distorted signal may be developed on the basis of one micro scheme.

7. Conclusions

The task of acquisition of non-stationary harmonics of currents and voltages in the autonomous circuits of water transport craft has been solved. There have been found simple and effective mathematical tools which make it possible to solve the outlined task by means of FPGA. It allows restoring simultaneously dozens of target components.

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