Virtual Instrument for Non-Conventional Total Harmonic Distortion Factors Evaluation

N.N. Lopatkin, Yu.A. Chernov
Department of Physics and Informatics
Faculty of Mathematics and Physics
The Shukshin Altai State Humanities Pedagogical University (ASHPU)
Biysk, Russia
nikolay_lopatkin@mail.ru

***Abstract*—The importance and the physical meaning of the integral and differential factors of the voltage (and current) harmonics are highlighted. The core part of the LabVIEW virtual instrument for the evaluation of the voltage harmonics integral factors is presented. The simulating LabVIEW verification by means of the meander signal has been accomplished.**

***Keywords*—voltage and current harmonics, THD, weighted THD, n-order voltage harmonics integral factors, n-order voltage harmonics differential factors, LabVIEW, virtual instrument**

I. INTRODUCTION

The quality of the feeding voltage and, first of all, its harmonic contents, directly influences the functions of the connected electric and electronic equipment. False operations of alarm and control systems, occurrence of undesirable harmonics in amplified signals, motors torque pulsations, and fast aging of elements and insulants are only few negative effects of the power supply or network voltage nonsinusoidality [1-3].

The power electronics giving the means for the conversion and for the regulation of the electric energy parameters, itself has generated and has aggravated the specified problems due to the increased complexity of the signals waveforms. But then it started to solve them successfully. For example, now the power electronics offers and applies among the compensators of the various inactive components of the apparent power such ones which eliminate distortion of the waveform of the current consumed from a network [4].

The output voltage quality of the autonomous voltage source inverter (VSI) has now improved not at the expense of bulky output filters, but by the application of the modern pulse methods of the regulation and by the increase of the modulation clock frequency (where the increase of the switching losses of the controlled semiconductor power switches acts as the constraint). Two kinds of modulation of the output voltage are combined in various types of the multilevel VSI (MLVSI). These are the pulse-width modulation (PWM) and the amplitude modulation (AM) [4]. It gives the high quality of the output voltage, and as a result of the current consumed by the load (for example, asynchronous motor), at the lowered requirements to the voltage rating of the power switches. The accurate estimation of the voltage quality contributes to the achievement of the necessary balance between the level of the harmonic component (within the acceptable range), the level of the dynamic losses in switches (and the corresponding value of the efficiency factor) and the specific (per output power) cost price of the inverter.

So the more fine voltage waveform analysis is needed compared to the analysis provided by the standard means. The appropriate non-conventional factors of harmonics have now been existing for over 30 years; these are the integral and the differential factors of harmonics [5].

II. PROBLEM DEFINITION

The most known and conventional electrical engineering factors, quantitatively characterising the presence of high order harmonics in voltage and current signals, are the voltage and current factors of harmonics (classical THD factors, which are called the voltage and current nonsinusoidality ratio in radio electronics).

The factor of voltage harmonics K_{hu}, i.e. voltage THD, (here the voltage is considered as the excitation signal in some circuit) can be defined in the integrated form by the following formulae in terms of the values obtained by the application of the operator $\frac{1}{T}\cdot\int_0^T(\ldots)^2\,dt$ to the instantaneous voltage values in the time domain:

$$K_{hu}=\frac{U_{(hh)}}{U_{(1)}}, \quad (1)$$

$$K_{hu}=\frac{\sqrt{U^2-U_{(1)}^2}}{U_{(1)}}==\sqrt{\left(\frac{U}{U_{(1)}}\right)^2-1}, \quad (2)$$

here U, $U_{(1)}$, and $U_{(hh)}$ are the RMS values of the whole voltage signal u, its fundamental component $u_{(1)}$ and high harmonics component $u_{(hh)}$, respectively, meaning $u=u_{(1)}+u_{(hh)}$.

Thanks to the Parseval's identity, we have also the spectral form definition of the voltage harmonics factor in frequency

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domain, in terms of the known RMS values $U_{(n)}$ of the separate harmonics with every order n:

$$K_{hu} = \frac{\sqrt{U^2_{(hh)}}}{U_{(1)}} = \frac{\sqrt{\sum_{n=2}^{\infty} U^2_{(n)}}}{U_{(1)}}. \qquad (3)$$

In accordance with the current standard of the Russian Federation on the electric energy quality [6], this voltage harmonics factor should be calculated with use of (3) under consideration of the finite number N of high harmonics, and N = 40 is established. As will be shown, such the limitation on the number of the taken into account harmonics is unacceptable in many cases.

The LabVIEW software-hardware environment (Laboratory Virtual Instrument Engineering Workbench) is used as the standard tool for carrying out the measurements, the analysis of their data, and the control of devices and investigated objects in industry, scientific researches and education. This product has been developed in the USA by the National Instruments company, and now it is successfully applied in many countries of the world, including Russia. Language of applied graphic programming G escapes the need of writing of the program codes. The block diagram of a programmed problem itself generates the code of the virtual tool (virtual instrument VI) [7].

The LabVIEW environment provides the enough wide range of means for the harmonic contents monitoring [8-10], but the THD assessment remains the main indicator of the power waveform distortions. The LabVIEW regular virtual instrument «Distortion Measurements Express VI» makes it possible to easy estimate the signal THD, specifying the order number N of the highest counted harmonic component.

However, as the modelling shows and the analysis of nonlinear circuits with nonsinusoidal voltage and currents waveforms shows, and as it can be seen in the data of some publications, for example, in [11], the low value of voltage THD itself does not guarantee enough low value of a current THD. The main reason of this appears from the fact that the load, as a rule, is not purely active, and itself has a filtering effect on the current. There is therefore the need for the consideration of the above mentioned integral and differential factors of harmonics. The functional diagram core part of the LabVIEW virtual instrument for the evaluation of the most important integral factors of the voltage harmonics is considered in this publication.

III. Integral and Differential Factors of Voltage Harmonics

The offered by the professor G.S. Zinoviev (NSTU, Novosibirsk), various order integral factors of harmonics (IFH) and differential factors of harmonics (DFH) include the load filtering effect on the investigated signals [4, 5, 12-15].

The various order IFH makes weighted (by the harmonic number) summation of harmonics, as a matter of fact, modelling the effect of the action of the amplitude-frequency characteristic of the idealized electric circuit of the corresponding order. Such the ideal filter passes the fundamental harmonic without the magnitude reducing and reduces the magnitudes of the high harmonics by the number of times equal to the harmonic order number raised to the filter order power.

These IFH and DFH are closely related to the method of the differential equations algebraization (DEA) which exists in numerous single-purpose variants. The DEA allows to find asymptotically with the preset accuracy the closed analytical form expressions for the mathematical relations between the voltage and current RMS values, using the coefficients of the differential equations without their solving [4, 5].

Let us assume the following notation for the q-fold multiple integral of the voltage instantaneous function u:

$$\overline{u}^{(q)} = \underbrace{\int \ldots \left(\int u dt \right) \ldots dt}_{q \text{ times}},$$

similarly, we assume notations $\overline{u}^{(q)}_{(1)}$ and $\overline{u}^{(q)}_{(hh)}$ for its components $u_{(1)}$ and $u_{(hh)}$ (so $\overline{u}^{(q)} = \overline{u}^{(q)}_{(1)} + \overline{u}^{(q)}_{(hh)}$) and, at last, $\overline{U}^{(q)}$, $\overline{U}^{(q)}_{(1)}$ and $\overline{U}^{(q)}_{(hh)}$ for the RMS values of the appropriate quantities.

We can now define the voltage IFH of the arbitrary order q via the equations similar to (1)…(3):

$$\overline{K}^{(q)}_{hu} = \frac{\overline{U}^{(q)}_{(hh)}}{\overline{U}^{(q)}_{(1)}}, \qquad (4)$$

$$\overline{K}^{(q)}_{hu} = \frac{\sqrt{\left(\overline{U}^{(q)}\right)^2 - \left(\overline{U}^{(q)}_{(1)}\right)^2}}{U_{(1)}/\omega^q} = \sqrt{\left(\frac{\overline{U}^{(q)} \cdot \omega^q}{U_{(1)}}\right)^2 - 1}, \qquad (5)$$

$$\overline{K}^{(q)}_{hu} = \frac{\sqrt{\left(\overline{U}^{(q)}_{(hh)}\right)^2}}{U_{(1)}/\omega^q} = \sqrt{\sum_{n=2}^{\infty} \left(\frac{U_{(n)}}{n^q \cdot U_{(1)}}\right)^2}, \qquad (6)$$

here ω is the angular frequency of the fundamental component.

Likewise, the corresponding notation should be assumed for the values related to the voltage DFH, in particular for the instantaneous values,

$$\hat{u}^{(q)} = \frac{d^q}{dt^q} u, \quad \hat{u}^{(q)}_{(1)} = \frac{d^q}{dt^q} u_{(1)}, \text{ and } \hat{u}^{(q)}_{(hh)} = \frac{d^q}{dt^q} u_{(hh)},$$

(so $\hat{u}^{(q)} = \hat{u}^{(q)}_{(1)} + \hat{u}^{(q)}_{(hh)}$) and for their respective RMS values, $\hat{U}^{(q)}$, $\hat{U}^{(q)}_{(1)}$ and $\hat{U}^{(q)}_{(hh)}$.

Thus, we can now define the voltage DFH of the arbitrary order q via the equations similar to the voltage IFH definitions (4)…(6):

$$\hat{K}_{hu}^{(q)} = \frac{\hat{U}_{(hh)}^{(q)}}{\hat{U}_{(1)}^{(q)}}, \quad (7)$$

$$\hat{K}_{hu}^{(q)} = \frac{\sqrt{\left(\hat{U}^{(q)}\right)^2 - \left(\hat{U}_{(1)}^{(q)}\right)^2}}{U_{(1)} \cdot \omega^q} = \sqrt{\left(\frac{\hat{U}^{(q)}}{U_{(1)} \cdot \omega^q}\right)^2 - 1}, \quad (8)$$

$$\hat{K}_{hu}^{(q)} = \frac{\sqrt{\left(\hat{U}_{(hh)}^{(q)}\right)^2}}{U_{(1)} \cdot \omega^q} = \sqrt{\sum_{n=2}^{\infty}\left(\frac{U_{(n)} \cdot n^q}{U_{(1)}}\right)^2}, \quad (9)$$

Obviously, the various order DFH factors can be treated in frequency domain as the same order IFH factors with negative value of the order q. The voltage IFH should be considered while the investigated circuit has the inductive type of the reactance, and the voltage DFH should be used while the investigated circuit has the capacitive type of the reactance. The classical voltage THD, i.e. the factor of voltage harmonics K_{hu} corresponds to the q=0, and it can provide the adequate valuation of the response harmonic contents only for the circuit with the pure active load.

The harmonic distortion factors similar to the first order IFH are also used for the current waveform estimation in some Western countries, particularly, in the USA (probably, since about 2000). The authors of [16] along with the basic weighted THD (WTHD), that is completely corresponds to the $\overline{K}_{hu}^{(1)}$, have also developed the system of the weighted THD factors for the induction motor load with the frequency-dependent parameters.

Let us here consider the LabVIEW-modelling level of the voltage signal IFH evaluation for the base measurement algorithm improvement.

IV. Virtual Instrument for Evaluation of Voltage Harmonics Integral Factors

As can be seen from (4)…(6), the implementation of the virtual instrument for the voltage signal IFH evaluation is possible by the three different ways. The spectral approach corresponds to (6) and has the disadvantage of the unavoidable series truncation error that can be quite high and unacceptable, for example, under the PWM signal estimation. So it is used here only for the THD estimation.

The based on (5) equation applies integrating the whole signal u and finding the fundamental component magnitude $U_{(1)m}$ (without finding the full form expression of the fundamental component $u_{(1)}$):

$$\overline{K}_{hu}^{(q)} = \sqrt{\left(\frac{\overline{U}^{(q)} \cdot \omega^q}{U_{(1)m}}\right)^2 \cdot 2 - 1}\cdot$$

The substantiated form of the defining expression (4) remains the most appropriate one, even though it needs the full form expression of the fundamental component $u_{(1)}$ to get the instantaneous high harmonics component $u_{(hh)}$:

$$\overline{K}_{hu}^{(q)} = \frac{\overline{U}_{(hh)}^{(q)} \cdot \omega^q}{U_{(1)}}.$$

The block diagram of the testing simulation containing the core part of the LabVIEW virtual instrument for the voltage harmonics integral factors evaluation is presented in Fig. 1.

The virtual instrument “Simulate Signal Express VI” is used here to imitate the input rectangular voltage wave. The direct current voltage components (the mean values) of the input and the output signals of each integral block are eliminated.

V. Results of LabVIEW Simulation

The estimates of the THD for the LabVIEW-simulated input square-wave voltage (50 Hz, 50 V) are summarized in Table I for the all above mentioned variants of the implementation of the virtual instrument core part (at q equal to zero). The spectral form results are received from the standard block “Distortion Measurement”.

As can be seen, all the three approaches lead to the same results (provided the harmonics number N is enough high).

TABLE I. THD Estimates for Meandr

Used Formula	THD Estimate	
	Input sampling rate	
	5000 Hz	*50000 Hz*
$\sqrt{\sum_{n=2}^{N}\left(U_{(n)}\right)^2} \Big/ U_{(1)}$, N = 40	0.4776970151875	0,4703881385751
$\sqrt{\sum_{n=2}^{N}\left(U_{(n)}\right)^2} \Big/ U_{(1)}$, $N \geq N_1$	0.4830059340529 $N_1 = 49$	0.4834216497318 $N_1 = 499$
$\sqrt{\left(\frac{U}{U_{(1)m}}\right)^2 \cdot 2 - 1}$	0.4830059340529	0.4834216497318
$\frac{U_{(hh)}}{U_{(1)}}$	0.4830059340529	0.4834216497318
Exact value for ideal signal $\sqrt{\frac{\pi^2}{8} - 1}$	15 digits after decimal point 0.483425847608679	

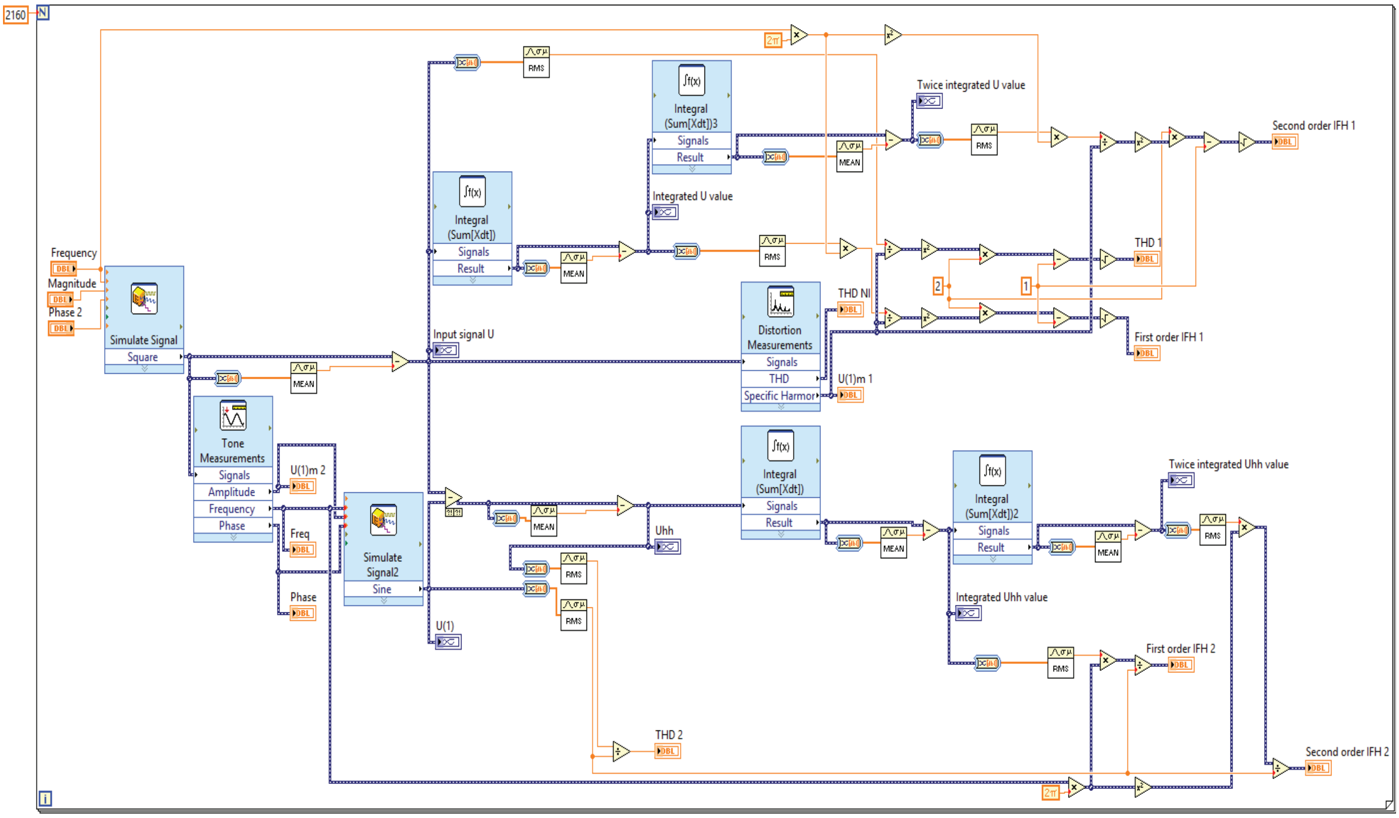


Fig. 1. The block diagram with the core part of the LabVIEW virtual instrument for the voltage harmonics integral factors IFH evaluation

The $N = 40$ is insufficient even for the voltage with the simplest pulse waveform.

The estimates of this IFH are placed in Table II and Table III for the first order $\overline{K}_{hu}^{(1)}$ and the second order $\overline{K}_{hu}^{(2)}$ integral factors of harmonics, respectively. The simulated waveforms of the signals considered under the $\overline{K}_{hu}^{(1)}$ and $\overline{K}_{hu}^{(2)}$ estimation via the equation (5) and via the equation (4) are presented in Fig. 2 and in Fig. 3, respectively.

Despite the absence of the operations for the fundamental component $u_{(1)}$ generating in the algorithm using the equation (5), this equation is much more complex than (4) and lead to the more high error value.

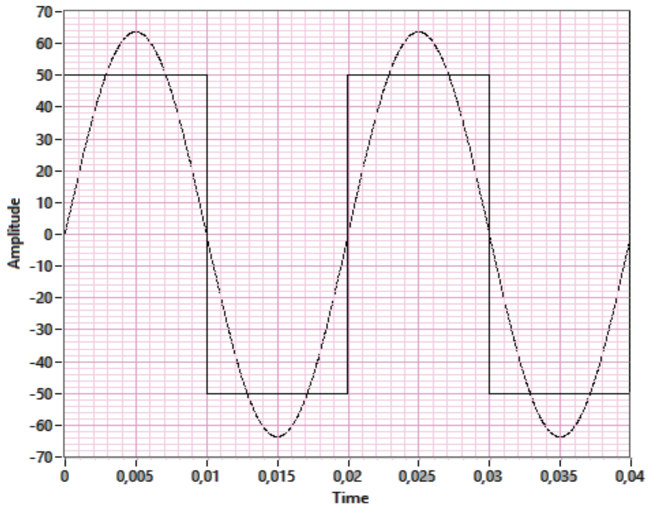
The twice integrated input voltage waveform in Fig. 2,c has the just-noticeable distortion of the sinusoidality, and the low sampling frequency is resulting in the significant difference between the two estimates of the second order IFH (about 20.4 %).

TABLE II. FIRST ORDER IFH ESTIMATES FOR MEANDR

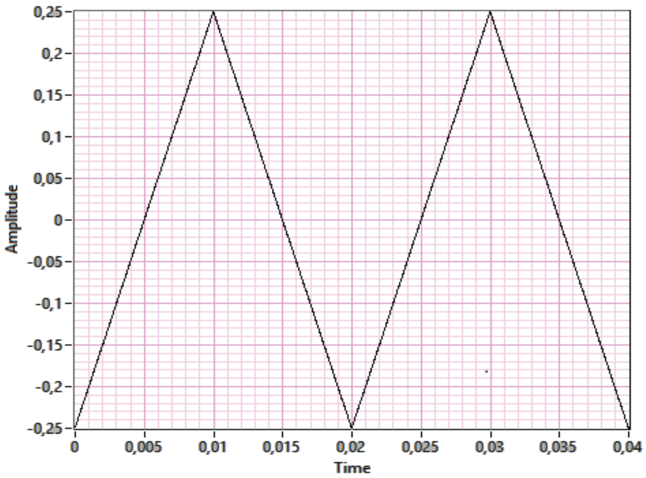
Used Formula	**First Order IFH ($\overline{K}_{hu}^{(1)}$) Estimate**	
	Input sampling rate	
	5000 Hz	***50000 Hz***
$\sqrt{\left(\frac{\overline{U}^{(1)}\cdot\omega}{U_{(1)m}}\right)^2\cdot 2-1}$	0.123109	0.121173
$\frac{\overline{U}_{(hh)}^{(1)}\cdot\omega}{U_{(1)}}$	0.121765	0.121159
Exact value for ideal signal $\sqrt{\frac{\pi^4}{96}-1}$	15 digits after decimal point 0.121152926519304	

TABLE III. SECOND ORDER IFH ESTIMATES FOR MEANDR

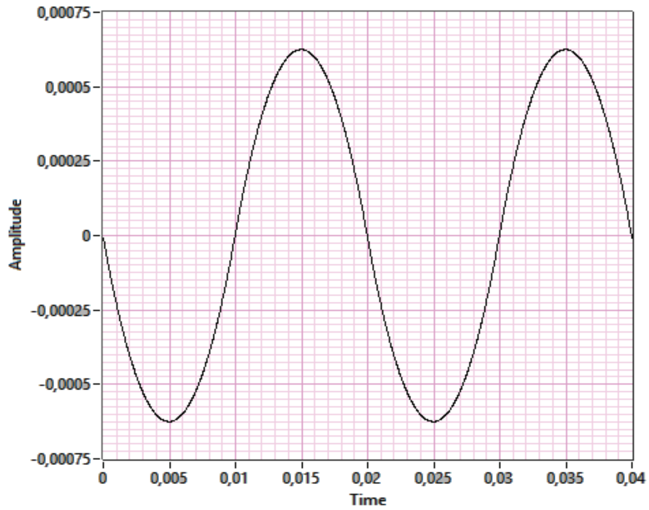
Used Formula	**Second Order IFH ($\overline{K}_{hu}^{(2)}$) Estimate**	
	Input sampling rate	
	5000 Hz	***50000 Hz***
$\sqrt{\left(\frac{\overline{U}^{(2)}\cdot\omega^2}{U_{(1)m}}\right)^2\cdot 2-1}$	0.0460371	0.0381287
$\frac{\overline{U}_{(hh)}^{(2)}\cdot\omega^2}{U_{(1)}}$	0.0382257	0.0380423
Exact value for ideal signal $\sqrt{\frac{\pi^6}{960}-1}$	15 digits after decimal point 0.038040460577417	



a) The input square-wave voltage u and its fundamental component $u_{(1)}$.

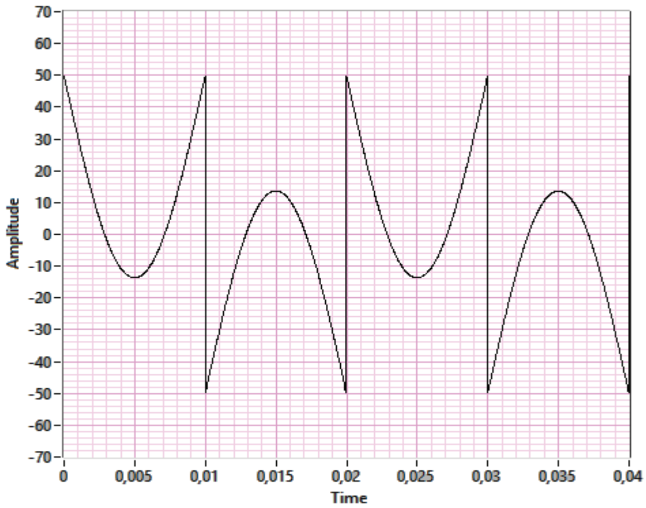


b) The integrated input square-wave voltage u.

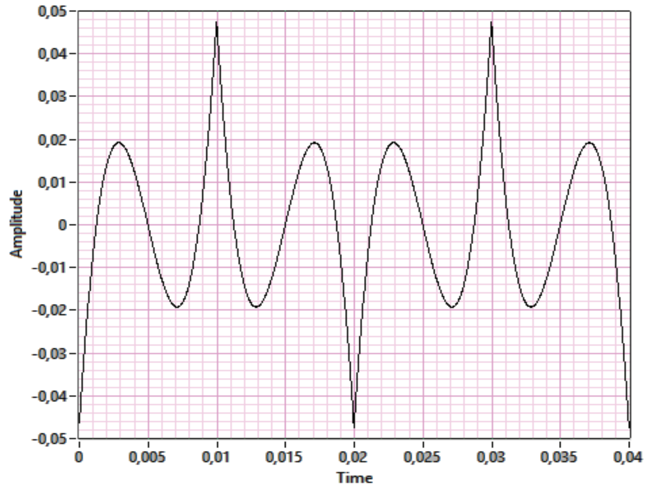


c) The twice integrated input square-wave voltage u.

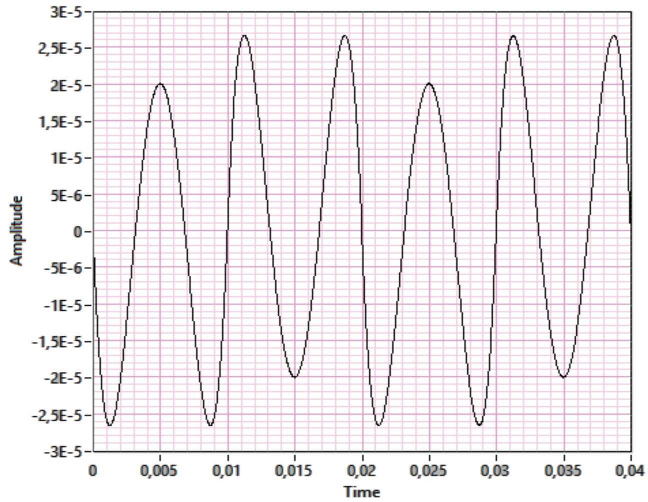
Fig. 2. The simulated waveforms of the signals related to the estimation of the first order $\overline{K}^{(1)}_{hu}$ and the second order $\overline{K}^{(2)}_{hu}$ integral factors of voltage harmonics via the whole input voltage instantaneous function u processing.



a) The higher harmonics component $u_{(hh)}$ of the input square-wave voltage.



b) The integrated higher harmonics component $\overline{u}^{(1)}_{(hh)}$ of the input voltage.



c) The twice integrated higher harmonics component $\overline{u}^{(2)}_{(hh)}$ of the input voltage.

Fig. 3. The simulated waveforms of the signals related to the estimation of the first order $\overline{K}^{(1)}_{hu}$ and the second order $\overline{K}^{(2)}_{hu}$ integral factors of voltage harmonics via the higher harmonics component $u_{(hh)}$ processing.

The higher the sampling frequency, the closer to each other and closer to the ideal signal IFH value the results of estimation by the two considered approaches.

The using of equation (5) with the whole instantaneous function u processing could be recommended only for the mobile measuring systems with some cheap DSP having enough high sampling frequency. In case the measuring system is based on the stationary or mobile PC with installed NI LabVIEW, the immediate high harmonics component $u_{(hh)}$ processing is the most preferred due to its high sensitivity.

VI. CONCLUSIONS

The importance and the physical meaning of the integral and differential factors of the voltage harmonics have been discussed. The similar integral and differential current harmonics factors are needed for the circuits fed by some current source, for instance, the current source inverters.

From the methodical point of view we may say that the integral and differential factors of the voltage harmonics, being the parameters of the voltage source which are carrying the information on its higher harmonic voltage, make it possible to estimate the higher harmonic current and the THD of the load current without loading connection (i.e. a priori, before the load is connected) via the processing the known load parameters. This situation is similar to the application of the Ohm's law for the current value (amperage) prediction by the preset voltage value under the known load impedance.

As has shown in professor Zinoviev's publications, the induction motor phase current THD is practically proportional not to the factor of voltage harmonics K_{hu} (voltage THD), but to the first order integral factor of the voltage harmonics $\overline{K}_{hu}^{(1)}$ (voltage WTHD).

The developers of the standards on the electric energy quality should take into account the fact of the insufficiency of the measuring of the only 40 first harmonics for the adequate assessment of the voltage waveforms with the rich harmonic contents, such as the PWM-modulated VSI output voltage.

The core part of the LabVIEW virtual instrument for the evaluation of the voltage harmonics integral factors is presented. The simulating LabVIEW verification by means of the meander signal has been accomplished.

The simulation results are quite encouraging concerning the prospects of the further improvement and application of the developed virtual instrument to the MLVSI output voltage estimation. The performance capabilities concerning the data acquisition with use of the just received NI ELVIS II are under consideration.

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