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CORRECTION OF THE INFLUENCE OF HIGHER HARMONICS DURING SYNCHRONOUS DETECTION OF QUASI-SINUSOIDAL SIGNALS

P.I. Borschov[1*], O.L. Lameko[2], V.G. Melnyk[1***]**
[1] Institute of Electrodynamics National Academy of Sciences of Ukraine,
56, Beresteiskyi Ave., Kyiv, 03057, Ukraine,
e-mail: **pavbor2010@gmail.com**.
[2] Research and Development Center "Energoimpulse" Institute of Electrodynamics National Academy of Sciences of Ukraine,
56, Beresteiskyi Ave., Kyiv, 03057, Ukraine.

This article examines errors caused by the influence of higher harmonics during synchronous detection of step-approximated quasi-sinusoidal signals in electrical impedance meters and other devices. Numerical modeling of the synchronous detection process is performed in case of coinciding shapes of the input and reference detector's signals. It is shown that when the number of approximation steps in the input and reference signals is equal, the dependence of the error on the phase of the input signal is periodic, with the period of error variation coinciding with the width of the signal step. An analytical expression is derived showing that the maximum error value decreases proportionally to the square of the number of signal approximation steps. Changing the shape of the reference signals of the detectors by varying the number of approximation steps is proposed to reduce the error. In this case, the error decreases proportionally to the square of the least common multiple of the numbers of steps in the input and reference signals. A combination of stage numbers that have no common factors are found to be an optional choice. It is demonstrated that the error under study can be reduced by several dozen times without narrowing the frequency range of the converted signals. An experimental determination of errors caused by the influence of higher harmonics was carried out, results of which confirmed the effectiveness of the proposed method for correcting these errors. References 13, figures 5, tables 3.
Keywords: impedance, quasi-sinusoidal signal, higher harmonics, synchronous detection, error correction.

Introduction. Test voltage generators in the form of a stepped quasi-sinusoid are becoming increasingly widespread in many areas of measurement technology [1–3]. Their advantages include high stability and discreteness of signal parameter adjustment, ease of implementation thanks to the use of digital and digital-to-analog integrated components, and minimal need for microprocessor computing resources. The use of such generators in electrical impedance meters or other devices where the signal modulus and phase are informative quantities allows for significant advantages to be achieved at minimal additional cost: ease of changing the operating frequency, precise generation of auxiliary reference signals with digital setting of the required initial phase, and strict synchronization with the main signal [4, 5].

One of the promising applications of quasi-sinusoidal step voltage generators is the construction of bridge-type impedance meters, in which they are used to generate alternating currents through compared measurement objects and standards. The generalized structure of such devices is shown in Fig. 1. The signal from the SG generator is connected to the input of the measuring circuit, which generates an output signal whose informative parameters are the amplitude S_x and phase φ_x. The output signal is synchronously detected using in-phase and quadrature detectors, with the reference signal of the in-phase detector being in

ORCID: * https://orcid.org/0000-0003-1363-9252; ** https://orcid.org/0000-0003-4427-2318;
*** https://orcid.org/0000-0002-4470-4339

phase with the generator signal, and the quadrature detector being phase-shifted by 90º. Measuring and processing the output signals of the S_S and S_Q detectors allows for a very accurate determination of the parameters of the impedance being studied.

The development of modern technologies increases the need for high-precision impedance parameter meters. In particular, this is very important for metrological support of measurements at industrial frequencies [6]. The AC transformer bridges used for this purpose are too complex, expensive and insufficiently accurate. Our earlier works [7] showed the prospects of using bridge circuits with a step quasi-sinusoidal test voltage generator at such frequencies. Quadrature AC bridges with two such generators, one of which produces a test voltage that is quadrature to that supplied to the measurement object, allow the use of a reference standards in the form of active resistance for any impedance under study. This solves the problem of insufficient accuracy of reactive standards at low frequencies. However, as studies show, achieving the precision accuracy of such meters is limited by specific measurement errors caused by the influence of higher harmonics of the step voltage. Similar difficulties occur in other devices with AC data signals. This problem has not been sufficiently studied to date.

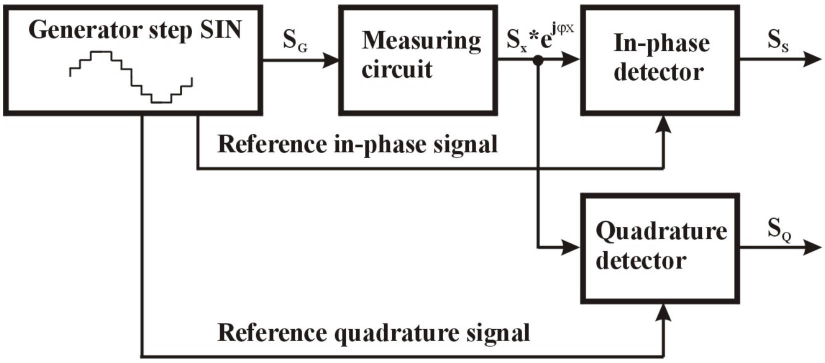

Fig. 1

The aim of the work is to study the errors of synchronous detection of step quasi-sinusoidal signals, as well as to substantiate the method of their correction.

Error values depend significantly on the type of synchronous detectors used. The most widely used synchronous detectors are of two types: commutators based and multiplying converters based [8], including those using digital-to-analog converters (DACs). Synchronous detectors based on commutators employ square-wave reference signals, which implement alternate, coherent (in-phase or quadrature) multiplication of the signal by +1 and –1 during each period. Using DACs as multiplying elements allows the use of reference signals with a shape close to sinusoidal. For synchronous detection of stepped quasi-sinusoidal signals, synchronous detectors with DACs are most easily implemented; their reference signals have the same number of steps as the input signal. Detectors with a reference signal approaching an ideal sinusoid (represented in the form of large arrays of digital sinusoid samples) have higher accuracy. However, the generation of such reference signals is limited by the speed of the DAC.

Numerical simulation of the synchronous detection process. The estimation of the synchronous detection errors was carried out using numerical simulation in the MATHCAD software package. As an example, the calculation of the synchronous detection errors of the stepped sinusoidal signal consisting of 32 steps per period was carried out. The reference signals of the in-phase and quadrature detectors had the same number of steps. The model of each signal is an array of 44800 points per period of the fundamental frequency of the signal. The initial phase of the reference signal of the in-phase detector was zero. The initial phase of the reference signal of the quadrature detector was $\pi/2$. The input signal of the detectors is an array of values of the step heights of a quasi-sinusoid with initial phases from 0 to $\pi/2$ with a step of $\pi/128$. The output signals of the detectors are calculated as the sums of the products of the input and each of the reference signals, averaged over the period of the signals. The errors of the detectors are calculated as the ratios of the deviations of the output signals from the output signals of ideal detectors (in which the reference signals are pure sine and cosine). Note that this model takes into account the complete array of higher harmonics of signals.

Relative errors of the in-phase detector:

$$\delta_S = \frac{S_0 \cdot \cos\varphi_x - S_S}{S_0}. \quad (1)$$

Relative errors of the quadrature detector:

$$\delta_Q = \frac{S_0 \cdot \sin\varphi_x - S_Q}{S_0}, \tag{2}$$

where S_S, S_Q are the values of the output signals of the in-phase and quadrature detectors at the phase of the input signal φ_x; S_0 is the value of the output signal of the in-phase detector at zero phase of the input signal:

$$S_0 = \frac{1}{32}\sum_{i=0}^{31}\sin^2\left(\frac{\pi}{32}(1+2i)\right) = 0{,}5\,. \tag{3}$$

Fig. 2 shows the results of mathematical modeling – the dependences of the errors of synchronous detectors in the range of phases of the input signal from 0 to π/2. The yellow line is the error of the in-phase detector, the black line is the error of the quadrature detector.

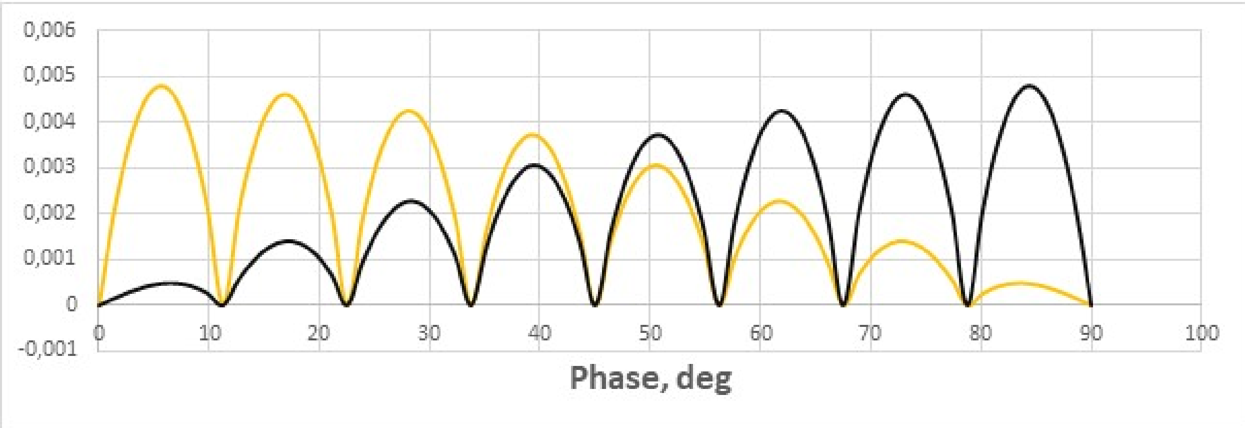

Fig. 2

The errors under study arise because when multiplying the higher harmonics that are simultaneously present in the input and reference signals, zero-frequency components appear. They are summed up with the useful signal caused by the fundamental harmonic and it distorts the detection results.

From the data provided, it is clear that the errors dependences on the phase of the input signal are periodic – they have 8 periods in the phase range from 0 to π/2. Meaning one period is equal to one step of the reference signals. In this case of the phases corresponding to the beginning of each step, the error values are minimal. For the phases corresponding to the middle of the steps, they are maximal for a given step. When the phase changes from 0 to π/2, the maximum values of the in-phase detector errors for each stage decrease, while those of the quadrature detector increase. The maximum values of each error are about 0.0048. Note that the same errors are also obtained when using detectors with rectangular reference signals, since the higher harmonics numbers in the input and reference signals are the same in both cases.

When measuring impedance parameters, the errors under study directly affect the measurement results. For example, the conversion coefficient of a measuring transducer for the active component of impedance is normalized at zero phase of the common-mode detector's input signal. Error in the measurement of the active component occurs if the measurement object contains a reactive component. If the object being measured contains a reactive component, and the phase of the current through the object corresponds to half of the first stage of the signal, then an error in the measurement of the active component occurs, equal to the value calculated according to (1). A similar error arises when measuring the predominant reactive component of the object's impedance in the presence of a small active component, if the phase of the current through the object is close to π/2.

Error analysis. If the values of the stepped quasi-sinusoidal function are equal to the values of the continuous sinusoid in the middle of the steps, then the signal containing k steps per period can be represented as follows [9, 10]:

$$s_{32}(t) = b_1[\sin\omega t + \sum_{i=1}^{\infty}\frac{1}{ki \pm 1}\sin[(ki \pm 1)\omega t]\;, \tag{5}$$

where t is time; ω is the circular fundamental frequency of the signal; b_1 is the coefficient determining the amplitude of the fundamental frequency component:

$$b_1 \approx 1 - \frac{\pi^2}{6 \cdot k^2}. \tag{6}$$

Thus, the signal has a fundamental (first) harmonic, as well as odd harmonics with numbers ($ki \pm 1$), $i = 1 \ldots \infty$. The amplitude of a harmonic decreases in proportion to its number.

If the phase shift of the input signal relative to the reference signal of the common-mode detector is φ_x, then the output signal of the ideal common-mode detector should be:

$$SINF\,0_{\varphi_x} = 0{,}5 \cdot \cos\varphi_x. \tag{7}$$

Signal at the detector input:

$$s_{\varphi_x}(t) = b_1[\sin(\omega t + \varphi_x) + \sum_{i=1}^{\infty} \frac{1}{ki \pm 1} \sin[(ki \pm 1) \cdot (\omega t + \varphi_x)]. \tag{8}$$

Detection consists of multiplying this signal by the reference signal described by (5). Each product of sines is replaced by half the difference of the cosines of the difference and the sum of the arguments. The cosines of the sums of the arguments are variable components. Their average values over the period of the fundamental frequency are zero. If they are excluded, the result of synchronous detection takes the form:

$$SINF_{\varphi_x} = \frac{b_1^2}{2} \{\cos\frac{\pi}{k} + \sum_{i=1}^{\infty} \frac{1}{(ki \pm 1)^2} \cos[(ki \pm 1)\varphi_x]. \tag{9}$$

Components caused by higher harmonics:

– cosines of the sums of the arguments

$$\cos[(ki+1)\varphi_x] = \cos ki\varphi_x \cdot \cos\frac{\pi}{k} - \sin ki\varphi_x \cdot \sin\varphi_x; \tag{10}$$

– cosines of the differences of the arguments

$$\cos\left[(ki-1)\varphi_x\right] = \cos ki\varphi_x \cdot \cos\varphi_x + \sin ki\varphi_x \cdot \sin\varphi_x. \tag{11}$$

From the graph of the error of the common-mode detector (Fig. 1) it is evident that the error has a maximum value at the phase of the input signal corresponding to half the duration of the first stage of the reference signal, i.e., $\varphi_x = \varphi_1 = \pi/k$. At this point, the second components in (10) and (11) become zero, since $\sin(i \cdot \pi) = 0$ for any integer "i". Let us determine the signal component caused by higher harmonics at the signal phase φ_x:

$$\Delta S_{HG\varphi_1} = \frac{b_1^2}{2} \cos\frac{\pi}{k} \left[\sum_{i=1}^{\infty} \frac{\cos i\pi}{(ki-1)^2} + \sum_{i=1}^{\infty} \frac{\cos i\pi}{(ki+1)^2} \right]. \tag{12}$$

For each value of i:

$$\Delta S_{HG\varphi_{1i}} = \frac{b_1^2}{2} \cos i\pi \cos\frac{\pi}{k} \left[\frac{1}{(ki-1)^2} + \frac{1}{(ki+1)^2} \right]. \tag{13}$$

After transformations, expression (13) takes the form:

$$\Delta S_{HG\varphi_{1i}} = b_1^2 \cos i\pi \cos\frac{\pi}{k} \frac{1}{(ki)^2} \frac{1 + \frac{1}{(ki)^2}}{1 - \frac{2}{(ki)^2} + \frac{1}{(ki)^4}}. \tag{14}$$

We expand the last factor in a series in powers of the small value $1/(ki)^2$ and discard the higher-order terms:

$$\Delta S_{HGi_{\varphi 1}} \approx b_1^2 \cos i\pi \cos\frac{\pi}{k} \frac{1}{(ki)^2} \left(1 + 3\frac{1}{(ki)^2} \right). \tag{15}$$

The deviation of the multiplier $\left(1+3\cdot(ki)^{-2}\right)$ from 1 decrease with increasing *k, i*. If this multiplier is replaced by 1, the maximum relative error in calculating each will not exceed 0.03 for *k*>10 (i.e., for most practical cases). Since we are analyzing the conversion error, this deviation is the "error in determining the error" and does not significantly affect the measurement result.

If we take into account that cos($i\pi$) is equal to "-1" for odd "*i*", and "1" for even, we obtain an alternating-sign series:

$$\Delta S_{HG_{\varphi 1}} = b_1^2 \cdot \cos\frac{\pi}{k} \cdot \frac{1}{k^2} \sum_{i=1}^{\infty} \frac{(-1)^i}{i^2} \quad . \tag{16}$$

The sum of the alternating-sign series of inverse squares of integers is equal to "$-\pi^2/12$" [11]:

$$\Delta S_{HG_{\varphi 1}} = -b_1^2 \cdot \cos\frac{\pi}{k} \cdot \frac{\pi^2}{12\cdot k^2} \quad . \tag{17}$$

This sum takes into account the entire array of higher harmonics of the signals.

The output signal of the detector from (9) taking into account (17):

$$SINF_{\varphi 1} = \frac{b_1^2}{2} \cos\frac{\pi}{k} \left(1 - \frac{\pi^2}{6\cdot k^2}\right). \tag{18}$$

For a phase value corresponding to half the first stage, the output signal of an ideal common-mode detector is:

$$SINF0_{\varphi_1} = 0{,}5 \cdot \cos\frac{\pi}{k}. \tag{19}$$

The ratio of the received signal (18) to the ideal:

$$\frac{SINF_{\varphi 1}}{SINF0_{\varphi 1}} \approx b_1^2 \left(1 - \frac{\pi^2}{6\cdot k^2}\right) = \left(1 - \frac{\pi^2}{6\cdot k^2}\right)^3 . \tag{20}$$

Hence, the maximum relative error of the output signal of the common-mode detector (with the phase of the input signal corresponding to half of the first stage) is approximately equal to:

$$\delta_{SINF\varphi 1} \approx -\frac{\pi^2}{2k^2}. \tag{21}$$

From Fig. 2 it is clear that the obtained value also characterizes the maximum value of the error of the quadrature detector. Table 1 shows the values of the maximum errors of synchronous detectors, in which the shape of the reference signals coincides with the shape of the input signal, depending on the number of signal steps.

Table 1

Number of steps per period	Max. error
16	$1{,}9\cdot 10^{-2}$
25	$8\cdot 10^{-3}$
32	$4{,}8\cdot 10^{-3}$
50	$2\cdot 10^{-3}$
64	$1{,}2\cdot 10^{-3}$
100	$4{,}8\cdot 10^{-4}$
200	$1{,}2\cdot 10^{-4}$
400	$3\cdot 10^{-5}$
1000	$5\cdot 10^{-6}$

When performing precision measurements of impedance parameters, very high requirements are imposed on the measurement error. In particular, the solution to the problem of creating a precision AC quadrature bridge for metrological support of measurements at industrial frequencies requires ensuring an error in measuring electrical capacitance of no more than $5\cdot 10^{-6}$. As can be seen from the data in Table 1, such a value can only be achieved with a number of signal approximation steps of at least 1000. It is obvious that increasing their number leads to a reduction in the frequency range at which impedance parameters are measured due to the limited speed of the DAC, as well as the need for additional time to enter the control digital code into the DAC.

Recently, many researchers have been working on creating synthesizers of sinusoidal signals based on Josephson matrices [12], but this solution requires significant costs and is not suitable for commercial use.

Solution. The performed analysis relates to the variant of constructing synchronous detectors, in which both the input signal and the reference signals have the same number *k* of steps per period. In this case, the numbers of harmonics that coincide in both signals are equal (ki±1), i=1…∞. Here the error value decreases proportionally to the square of the number of steps.

The authors propose the way to reduce studied errors that does not require increasing the number of signal steps. To solve the problem, it is sufficient to change the number of reference signal steps. If the number of input and reference signal steps is different, the highest harmonic, the number of which coincides in the signals, is determined by the least common multiple of the numbers of input and reference signal steps. According to (21), k will be equal to this least common multiple, which can be significantly greater than the number of steps (in the best case, equal to their product). Table 2 shows the calculated values of the maximum errors of synchronous detectors for the variant of constructing a detector with reference signals, the number of steps in which differs from the number of steps in the input signal.

Table 2

Number of steps in the input signal	Number of steps in reference signals	Least common multiple of the numbers of steps	Maximum error	Error Reduction Factor
32	28	224	$1\cdot10^{-4}$	49
32	25	800	$8\cdot10^{-6}$	625
64	50	1600	$2\cdot10^{-6}$	625
64	100	1600	$2\cdot10^{-6}$	625
100	128	3200	$5\cdot10^{-7}$	1024

The data in Table 2 demonstrate a significant reduction in the error level under study when changing the number of stages in the reference signals compared to the previously discussed detector design. Specifically, with 32 stages in the input signal, changing the number of stages in the reference signals by 25 is sufficient to reduce the error to 10^{-5}. To meet the requirements of even more precise measurements, a 64/50 stage ratio can be selected, and for further accuracy enhancement, a 100/128 stage ratio is suitable.

Note that generating reference signals with a multiple of 4 stages is the easiest method, since it is easy to obtain the quadrature detector reference signal by shifting the generation start by ¼ of the in-phase reference signal count table. However, it is not difficult to generate a quadrature reference signal with any number of stages, including those not multiples of 4 and even odd numbers. This requires generating a separate "cosine" table, distinct from the original "sine" table.

Experimental verification of the research results. The research results were verified on an experimental sample of the precision quadrature AC bridge created in the Institute of Electrodynamics of the National Academy of Sciences of Ukraine. The generator and detectors in the device are implemented on the basis of 16-bit multiplying DACs of the LTC1592 type (Linear Technology), connected according to the bipolar scheme. The analog input signal of the generator was obtained from the source of stable constant voltage on the ADR3650 microcircuit (Analog Devices). To carry out the described experiments, the output signal of the generator was connected directly to the analog inputs of the detectors. Sequences of digital codes from sine-cosine tables for the corresponding number of steps of the quasi-sinusoidal signal were used as reference signals of the detectors. Synchronization of the generator and detectors is ensured by forming the moments of writing codes to the DAC from one timer, which is part of the control microprocessor. The clock frequency of the timer was 12800 cycles per signal period. The phase shift of the generator signal relative to the reference signals of the detectors was adjusted by delaying the start of signal generation by an integer number of cycles, due to which the resolution of the phase adjustment was π/6400, i.e., 0.028155 degrees. Digital readings of the output voltages of the detectors were obtained using analog-to-digital converters on ADS1244 microcircuits (Burr-Brown, Texas Instruments). The results of the study take into account the influence of higher harmonics of signals that were not suppressed by analog elements of the DAC. Since the frequency bandwidth of these elements is about 10 MHz, and the frequency of the signals was 50 Hz, the influence of harmonics with numbers up to 200,000 was taken into account. The harmonics suppressed by analog elements did not have a significant effect, as their amplitudes were negligible.

Fig. 3–5 show the results of experimental determination of the error dependencies of synchronous detectors for various combinations of the number of steps. The yellow lines show the graphs of the error dependencies of the in-phase detector, the gray lines show the quadrature one. Combination of Fig. 3: 32 steps in the input signal, 25 in the reference ones.

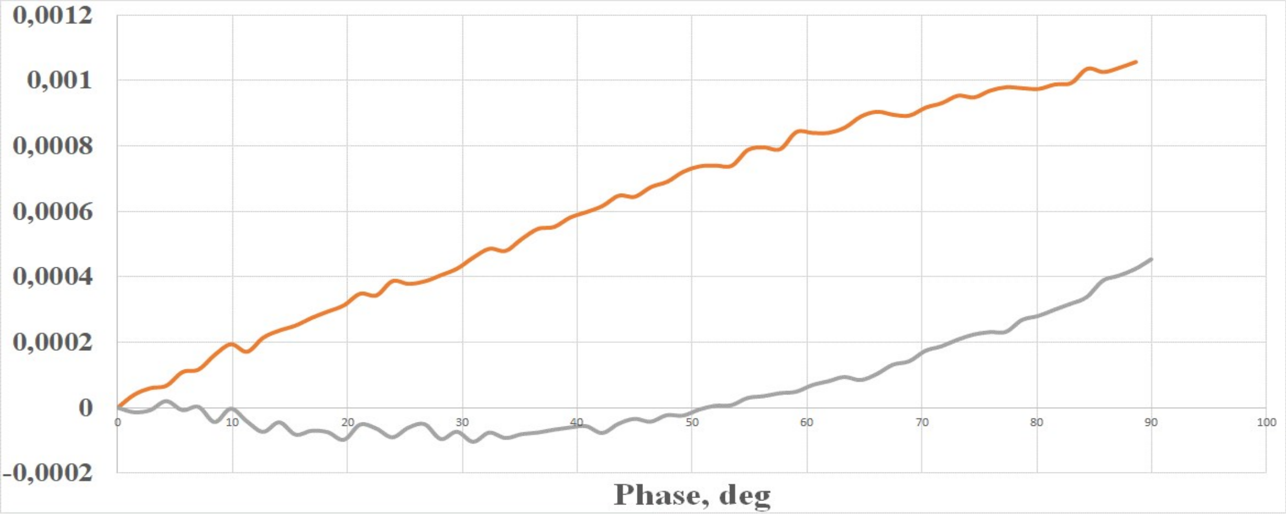

Fig. 3

Combination of Fig. 4: the same number of steps in the input and reference signals – 100 each.

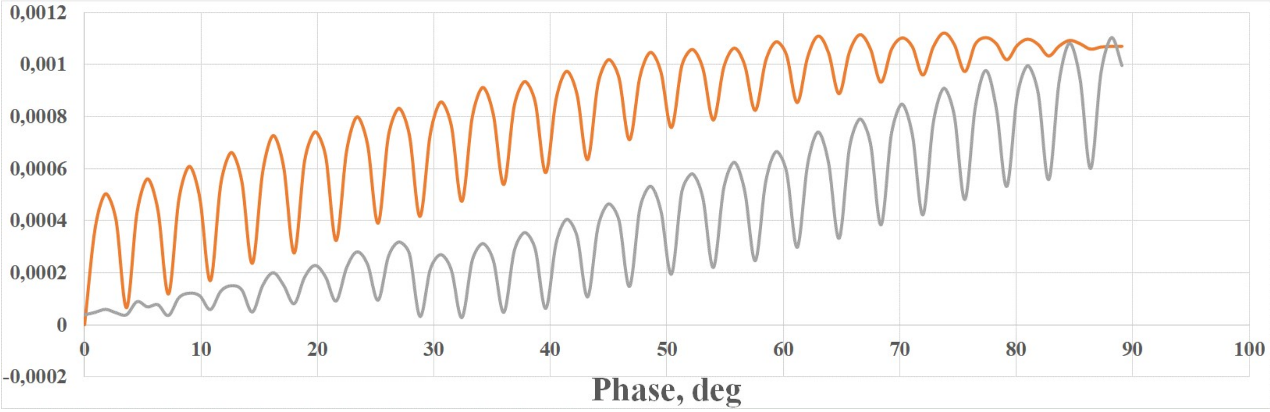

Fig. 4

Combination of Fig. 5: 100 steps in the input signal, 128 in the reference ones.

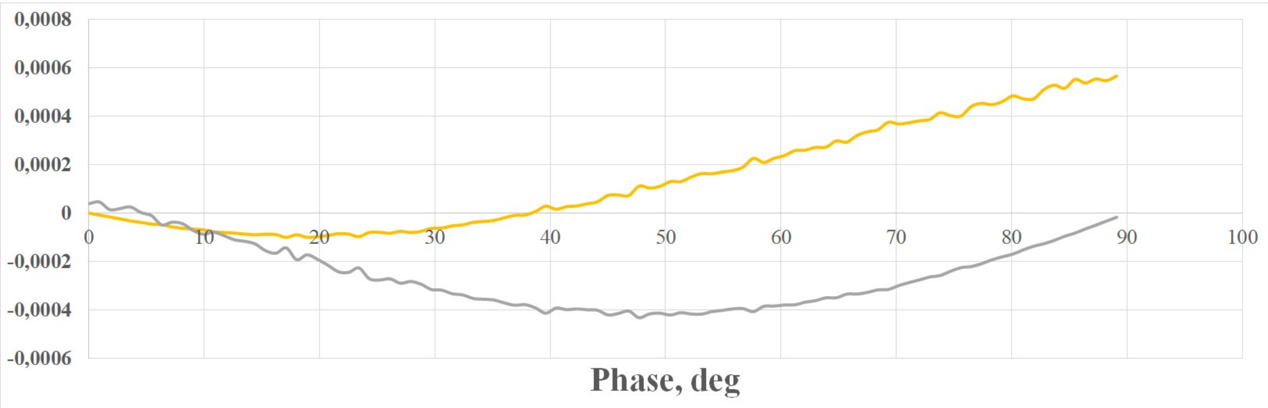

Fig. 5

Comparison of the graphs in Fig. 3–5 with the graphs in Fig. 2 shows that the total error (in addition to the component caused by higher harmonics) has another, aperiodic component that is not associated with the number of steps in the signals. There is a theory, that this component is caused by time delays in the response of the analog units of the equipment, which leads to the fact that the phase difference of the reference signals of the detectors differs from π/2 [13]. Analysis of this component is beyond the scope of this study. The level of error caused by higher harmonics can be estimated by the amplitude of the periodic component, which predominates in Fig. 4, and is weakly expressed in Fig. 3 and 5. An approximate estimate in Fig. 3 and 5 is that it`s less than $2\cdot10^{-5}$. Table 3 shows the results of the experimental determination of the maximum errors of synchronous detectors, caused by the influence of higher harmonics, for two variants of synchronous detectors: with reference signals, the number of steps of which is equal to the number of steps in the input signal, and with reference signals with a different number of steps.

Table 3

Number of steps in the input signal	Number of steps in the reference signals	Least common multiple of the number of steps in signals	Maximum error due to the influence of higher harmonics
25	25	25	$8 \cdot 10^{-3}$
32	32	32	$4{,}8 \cdot 10^{-3}$
32	25	800	$<2 \cdot 10^{-5}$
100	100	100	$4{,}8 \cdot 10^{-4}$
100	128	3200	$<2 \cdot 10^{-5}$

The data in rows 1, 2 and 4 of Table 3 coincide quite accurately with the data in Tables 1 and 2. It is difficult to obtain exact values of the studied error for rows 3 and 5 of Table 3, since the error due to the influence of higher harmonics turns out to be negligibly small in comparison to the error caused by other factors.

Conclusions.

1. The presence of higher harmonics in the step quasi-sinusoidal signals leads to the appearance of specific errors in the synchronous detection of such signals. The results of numerical modeling and analytical research show that the dependence of the error on the phase shift of the input signal relative to the reference signals of the detectors is periodic.

2. When the number of approximation steps in the input and reference signals is equal, the period of the error change coincides with the width of the signal step.

3. The maximum value of the error caused by the influence of higher harmonics decreases proportionally to the square of the number of steps in the signals.

4. A way to reduce the studied errors is proposed, which consists in using reference signals with a number of steps different from their number in the input signal. In this case, the error decreases proportionally to the square of the least common multiple of the numbers of steps in the input and reference signals. The optimal choice is a combination of numbers of steps that do not have common factors.

5. Experimental studies have confirmed the possibility of a significant (20-200 times) reduction in error without narrowing the frequency range of input signals.

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УДК 621.317

КОРЕКЦІЯ ВПЛИВУ ВИЩИХ ГАРМОНІК ПІД ЧАС СИНХРОННОГО ДЕТЕКТУВАННЯ КВАЗІСИНУСОЇДАЛЬНИХ СИГНАЛІВ

П.І. Борщов[1*], канд. техн. наук, **О.Л. Ламеко**[2**], канд. техн. наук, **В.Г. Мельник**[1***], докт. техн. наук
[1] **Інститут електродинаміки НАН України,**
пр. Берестейський, 56, Київ, 03057, Україна,
e-mail: **pavbor2010@gmail.com.**
[2] **Науково-виробничий центр "Енергоімпульс" Інституту електродинаміки НАН України,**
пр. Берестейський, 56, Київ, 03057, Україна.

Роботу присвячено дослідженню похибок, обумовлених впливом вищих гармонік під час синхронного детектування ступінчасто-апроксимованих квазісинусоїдальних сигналів в вимірювачах параметрів електричного імпедансу та в інших пристроях. Проведено числове моделювання процесу синхронного детектування для випадку співпадіння форми вхідного та опорних сигналів детекторів. Показано, що за рівності чисел ступенів апроксимації вхідного та опорних сигналів залежність похибки від фази вхідного сигналу має періодичний характер, при цьому період зміни похибки співпадає з шириною ступені сигналів. Отримано аналітичний вираз, з якого випливає, що максимальне значення похибки зменшується пропорційно квадрату числа ступеней апроксимації сигналів. Задля зменшення похибки запропоновано змінити форму опорних сигналів детекторів шляхом зміни числа ступенів апроксимації. Завдяки цьому похибка знижується пропорційно квадрату найменшого загального кратного чисел ступенів вхідного й опорних сигналів. Оптимальним вибором є комбінація чисел ступенів, що не мають загальних співмножників. Показано можливість зниження похибок в кілька десятків разів без звуження частотного діапазону сигналів. Проведено експериментальне визначення похибок, обумовлених впливом вищих гармонік, результати якого підтвердили ефективність запропонованого метода корекції. Бібл. 13, рис. 5, табл. 3.

Ключові слова: імпеданс, квазісинусоїдальний сигнал, вищі гармоніки, синхронне детектування, корекція похибок.

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