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METHOD OF ANALYSIS ERRORS OF MEASURING CONVERSION OF IMPEDANCE SPECTROSCOPY WITH ACTIVATION NONHARMONIC SIGNALS

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Summary. *In this paper, we examine the peculiarities of SPICE simulation measuring transducers impedance spectroscopy. Based on results of modeling research proposed the method of analysis errors measured values of active and reactive impedance component, which based on a comparison of small-signal AC analysis and Transient analysis. During AC analysis received impedance Nyquist plot in the idealized case and in the Transient analysis calculated value active $Re\hat{Z}$ and reactive $Im\hat{Z}$ impedance components for actual parameters of measuring transducers, including forms of activating signals. Implementation of this approach is done by synchronous detection output signals and the integration results in the detection time intervals that fit their active and reactive components.*

Key words*: impedance spectroscopy, SPICE model, parametric analysis, Nyquist plot.*

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Formulation of the problem. This work is dedicated to the problem research the parameters of signal transducers impedance spectroscopy, in which the purpose of structural simplification and expansion of the range of frequencies used nonharmonic mainly pulse signals in the form of a meander. Replacing single-response frequency of harmonic signals sinusoidal form on pulse signals allows refusing the need to use tunable master oscillator frequency sine function that is typically implemented based on high-precision digital-to-analog converters and smoothing filters.

Necessary to notice that taking into account of parametric restrictions tunable over a wide frequency spectrum generators, signals the last, is not single-response frequency. Thus, the problem is the impact analysis of form distortion signals on the result of measuring conversion impedance. The problem is of particular relevance at high frequencies, where the real parameters of components of signal converters, operational amplifiers mostly limit slew rate setting signal, its amplitude-frequency and phase response. As a result of this, there are measurement errors impedance characteristics which are caused by harmonic distortion signals.

Introduction and problem setting. One of the topical areas of development microelectronic sensor is based on the method of impedance spectroscopy (another name – spectroscopy electrical impedance) [1, 2]. Informative signals measuring devices based on impedance spectroscopy [3, 4] – active and reactive component of the research two-terminal impedance – are a variety of approaches, including quadrature detection signal [5].

Significant impact on the sensor electronics as a whole and diagnostic devices based on impedance spectroscopy method in particular is a new area of information and of computer networks – Internet of Things or Physical World Internet [6]. New requirements for devices Internet of Things – structural simplicity, the ability to operate with independent low-voltage power supply, minimum size and energy consumption, enhanced functionality [7, 8] are the crucial criteria further development of signal transducers impedance spectroscopy [9].

The task of parametric analysis of measuring impedance transducers with activation signals nonharmonic solved by mathematical modeling circuit. The standard of circuit simulation and especially solid-state electronics units based integrated circuits are SPICE

(Simulation Program with Integrated Circuit Emphasis). Based on this standard, created and update a wide range of application packages circuit simulation, including PSPICE (Personal SPICE), Proteus, LTSPICE (Linear Technology SPICE), MicroCap. [10, 11].

Scheme research and method of forming signals. The obtained results in this paper are based on our proposed method SPICE modeling of research which conducted comparing small-signal AC analysis and Transient analysis. During AC analysis received impedance Nyquist plot in the idealized case and in the Transient analysis calculated value active $Re\hat{Z}$ and reactive $Im\hat{Z}$ impedance components for actual parameters of measuring transducers, including forms of activating signals. Implementation of Transient analysis involves the use of synchronous detection output signals and the integration result in the detection time intervals that fit their active and reactive components. The active component of the output signal is detected and integrated phase with the input signal setting and the reactive component – offset $\pi/2$.

Signal conversion carried out based on quadrature detector. Scheme of the transducer (Fig. 1) contains master oscillator pulse signal V1, voltage-current at a controlled source G1 type IofV, non-inverting X1 and inverting X2 repeating amplifier, switches S1, S2, S3, S4 and sources Vre, Vim pulse voltage control these switches. Voltage V(1) on research two-terminal (circle R1, C1) is detected a release of active V(4) and reactive V(6) components, respectively, load resistors Rload1, Rload2.

In this example the master oscillator V1 specify parameters: VZERO = -1; VONE =1; P1 = 0; P2 = 10u; P3 = 500u; P4 = 510u; P5 = 1000u. It corresponds the amplitude of the voltage pulses ±1 V with frequency 1 kHz at length front and recession dt = 10 microseconds. The amplitude of the current pulses I(G1) through two-terminal with considering conversion efficiency of source G1 ($K_I = 10^{-3}$) is 1 mA.

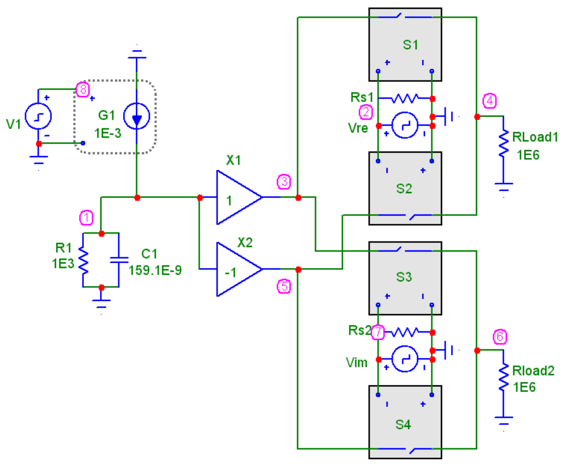

Figure 1. SPICE equivalent circuit of pulse measuring transducer impedance on the quadrature detector

An example of such a signal measuring transducer with activation pulse signals shown in Fig. 2 and Fig. 3, where: I (G1) – current of source G1; V(1) – voltage on research two-terminal; V(Vre), V(Vim) – setting the voltage sources Vre, Vim of quadrature detector; V(4), V(6) – instantaneous magnitude output voltage detector; SD(V(4)), SD(V(6)) – informative signals active $Re\hat{Z}$ and reactive $Im\hat{Z}$ impedance components obtained by integration voltage V(4), V(6) using the tool type SD (Running integral with respect to time).

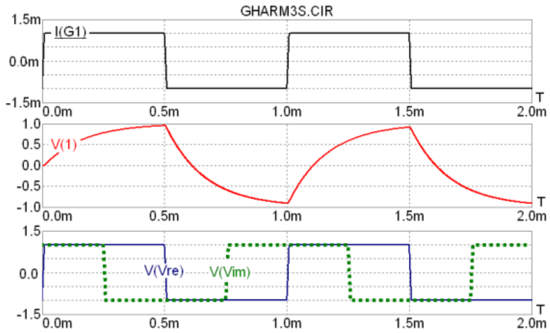

Figure 2. Diagrams of input and control signals

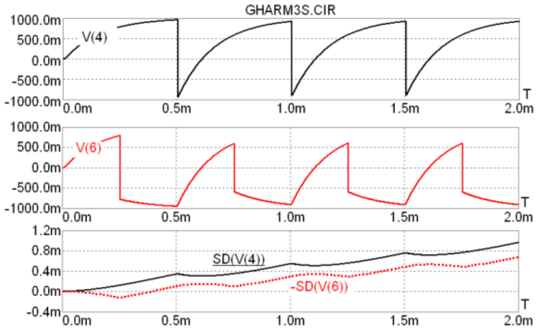

Figure 3. Diagrams of output signals

Analysis of signals. The above example demonstrates the existence of significant fluctuations and nonmonotonous signals SD(V(4)), SD(V(6)) along period. Therefore, in order to ensure the accuracy of the results of research in the parametric analysis schemes should be given considerable attention to the synchronization of measuring conversion, which in turn is determined by the time-division resolution ΔT (Maximum Time Step). Moreover, it is clear that in order to improve the accuracy of the measurement signal it is desirable to increase the duration of integration T_Σ.

Also it is obvious that reduction ΔT and increase T_Σ integration provides increased accuracy, however, use very low values ΔT and high values T_Σ causes increase calculation time signals. Values of these quantities were optimized in the following examples duration of integration $T_\Sigma = 100$ ms (Transient Time range: 100 ms), that at 1 kHz corresponds to 100 pulses completion time period of 1 ms. At change ΔT was determined comparison informative signals SD (V (4)), SD (V (6)):

ΔT = 1E-6, SD(V(4)) = 41.7425, SD(V(6)) = 38.1962;
ΔT = 1E-5, SD(V(4)) = 41.7567, SD(V(6)) = 38.1962;
ΔT = 1E-4, SD(V(4)) = 41.5023, SD(V(6)) = 38.7915.

These data show that the difference between the values obtained SD(V(4)), SD(V(6)) at ΔT = 1E-6 and these values at ΔT = 1E-5 is insignificant. Instead, the ΔT = 1E-4 have their values differ from previous ones that it shows a lack of time-division resolution. According to these results further research was asked ΔT = 1E-6.

In the first phase conducted research model was determined influence on informative signals SD (V (4)), SD (V (6)) duration dt square wavefronts:

dt = 1E-6, SD(V(4)) = 41.7616, SD(V(6)) = 38.2006;
dt = 1E-4, SD(V(4)) = 40.8002, SD(V(6)) = 37.7707;
dt = 2E-4, SD(V(4)) = 38.6369, SD(V(6)) = 36.2522.

The increase in fronts causes a certain decrease of SD(V(4)), SD(V(6)), and therefore the ratio between the duration of pulses and fronts period is the distortion of the measurement results. To conduct the parametric analysis of measuring transducers developed methods of modeling research which is allowed to determine measurement error.

Methods of analysis errors. Methods is using Fourier transform rectangular pulses. Imagine pulse signal in the form of rectangular function $P_H(t)$, which is displayed in a harmonic series:

$$P_H(t) = \frac{4}{\pi}\sum_{k=1}^{\infty}\frac{\sin(k\omega t)}{k}, \qquad (1)$$

where k = 1, 3, 5 … – odd harmonics.

At deviation from the rectangular shape such function is modified in the first approximation described harmonic series:

$$P_H(t) = \frac{4}{\omega\tau\pi}\sum_{k=1}^{\infty}\frac{\sin(k\omega t)}{k^2}\sin(k\omega t), \quad (2)$$

We perform the quantitative comparative analysis depending on the measured quadrature detector. For this specify an array of values SD(V(4)), SD(V(6)) for a set of characteristic frequencies. The term „set of characteristic frequencies" we mean the minimum number of frequencies which are most characterize the accuracy of measuring changes in all areas of the characteristic impedance Nyquist plot. The characteristic Nyquist point of dispense diagram for basic serial RC characterized circle center frequency $f_0 = 1/(2\pi RC)$ where observed extreme point and typical areas of Nyquist plot presented a number of frequencies: $f_0/10$, $f_0/4$, $f_0/2$, f_0, $2f_0$, $4f_0$, $10f_0$.

Using the expression active impedance component parallel RC circle:

$$\operatorname{Re}\hat{Z} = \frac{R}{1+(2\pi fRC)^2}, \quad (3)$$

introduce the term of modulation of the normalized coefficient:

$$p(f) = \frac{\operatorname{Re}\hat{Z}}{R} = \frac{1}{1+(2\pi fRC)^2}, \quad (4)$$

At the point of extremum idealized diagram Nyquist parallel RC circle active component of impedance is $\operatorname{Re}\hat{Z} = R/2$. Then, took that:

$$\frac{1}{1+(2\pi fRC)^2} = \frac{1}{2}, \quad (5)$$

and found the ratio:

$$C = \frac{1}{2\pi f_0 R}, \quad (6)$$

With such a ratio normalized modulation factor is given by:

$$p(f) = \frac{1}{1+\left(f/f_0\right)^2}, \quad (7)$$

Numerical values $p(f/f_0)$ for a number of characteristic frequencies are given in Table. 1. The minimum number of frequencies covering all areas characteristic diagram Nyquist (approximately 0.99 to 0.01 maximum values) and therefore using the signal measuring transducer can quite qualitatively assess the accuracy of its operation.

Table 1

Calculated values of normalized modulation coefficient of active component

f	$f_0/10$	$f_0/4$	$f_0/2$	f_0	$2f_0$	$4f_0$	$10f_0$
p(f)	0,990	0,941	0,800	0,500	0,200	0,058	0,009

Solving the problem of accuracy analysis operation measuring transducer impedance for the above set of characteristic frequencies form the three arrays and compare informative signal active and reactive impedance. The first array M1 obtains using AC analysis. The second array M2 get the method of Transient analysis. The third array M3 obtains similar method Transient analysis using the pulsed source.

The numerical values of these arrays of signals are summarized in Table. 2, where the following symbols: Re_c and Im_c – values of active and reactive components of impedance modulus obtained during AC analysis; SDre_s and SDim_s – values of active and reactive components of impedance modulus obtained during Transient analysis; SDre_p and SDim_p – Transient analysis of similar value when activating pulse signal.

Table 2

Arrays M1, M2, M3 of output signals impedance converter

f	Re_c	Im_c	SDre_s	SDim_s	SDre_p	SDim_p
1.00E2	9.901E2	9.898E1	6.305E-2	6.246E-3	9.379E-2	6.205E-3
2.50E2	9.412E2	2.352E2	5.998E-2	1.485E-2	8.425E-2	1.569E-2
5.00E2	8.001E2	3.999E2	5.109E-2	2.522E-2	6.846E-2	2.893E-2
1.00E3	5.002E2	5.000E2	3.205E-2	3.164E-2	4.176E-2	3.820E-2
2.00E3	2.001E2	4.001E2	1.267E-2	2.551E-2	1.658E-2	3.118E-2
4.00E3	5.886E1	2.354E2	3.629E-3	1.497E-2	4.870E-3	1.845E-2
1.00E4	9.908E0	9.904E1	7.237E-4	6.294E-3	8.214E-4	7.775E-3

For ease of the comparative analysis in Table 3 presents these data sets in a normalized form.

Re_s = SDre_s · K_{S0};

Im_s = SDm_s · K_{S0};

Re_p = SDre_p · K_{P0};

Im_p = SDim_p · K_{P0},

where K_{S0} – an empirical normalization factor.

The empirical normalization factor K_{S0} get by the ratio of the value Re_c to SDre_s at frequency f = f_0 = 1.00E3 (K_{S0} = 1.57E4). This factor determines the conversion function of the integrator. Instead, the normalization factor K_{P0} calculate using the theoretical value $K_0 = 4/\pi \approx 1{,}273$, which according to formula (1) defines the ratio of effective values rectangular and sinusoidal signals of equal amplitude and already established empirical coefficient K_{S0}: $K_{P0} = K_{S0} / K_0$ (K_{P0} = 1.23E4).

Table 3

Arrays M1, M2, M3 of normalized signal impedance converter

f	Re_c	Im_c	Re_s	Im_s	Re_p	Im_p
1.00E2	9.901E2	9.852E2	9.899E2	9.806E1	1.157E3	7.651E1
2.50E2	9.412E2	9.372E2	9.417E2	2.331E2	1.039E3	1.935E2
5.00E2	8.001E2	7.983E2	8.021E2	3.959E2	8.441E2	3.568E2
1.00E3	5.002E2	5.009E2	5.033E2	4.968E2	5.150E2	4.710E2
2.00E3	2.001E2	1.980E2	1.989E2	4.005E2	2.045E2	3.845E2
4.00E3	5.886E1	5.670E1	5.698E1	2.350E2	6.005E1	2.275E2
1.00E4	9.908E0	1.131E1	1.136E1	9.882E1	1.013E1	9.588E1

For the given set of frequencies characteristic values Re_s and Im_s obtained by Transient analysis with high accuracy (within a few percent) coincide with the reference results Re_c and Im_c, respectively, obtained in the method of AC analysis. This shows the high precision conversion signal at activation harmonic vibrations. The significant differences are observed at lower frequencies, including frequency f = 1E2. This difference is about 20%. Graphic illustration of these results shown in Fig. 4. The problem of inaccuracy of the conversion signal at the transition from harmonic to the pulse signals shown in Nyquist plot (Fig. 5), where the notation c, s and p correspond, arrays M1, M2 and M3 of data.

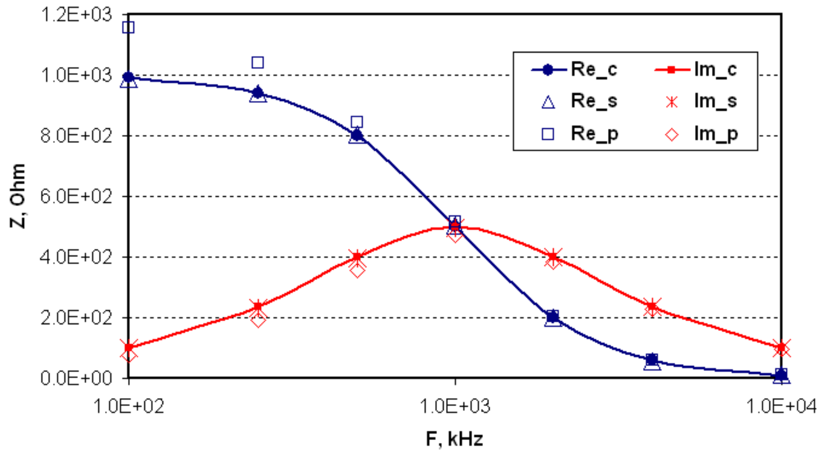

Figure 4. Dependence of active Re and the module of reactive Im components for the set of characteristic frequency arrays M1, M2, M3

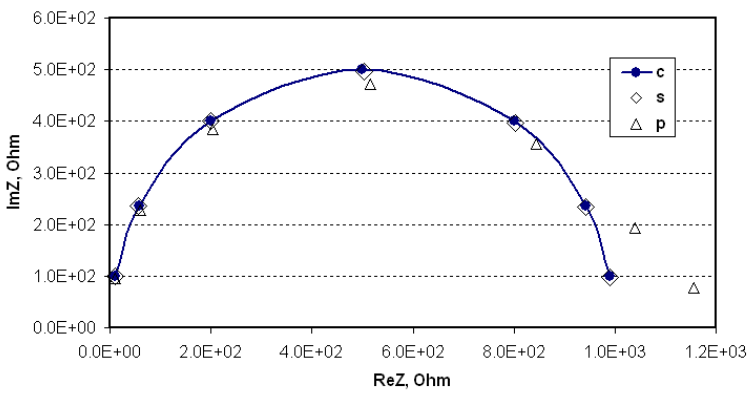

Figure 5. Impedance Nyquist plot based on arrays M1, M2, M3

Specifically on the Nyquist plot is possible to show selection criteria above proposed set of characteristic frequencies – from one side the number of values of these frequencies is small (in this case – 7), but on the other side, the function diagram Nyquist frequencies in these fully describes all defining its area. At higher frequencies is a perfect coincidence of results of measuring conversion. Then with decreasing frequency (offset on the diagram to the right) coincidence disturbed and after the center frequency f_0 measurement error is deteriorated.

The cause of the errors is the impact on the results of measuring conversion higher harmonic in the pulsed signal. Graphical representation of such effects demonstrated in Fig. 6. On the horizontal axis are the frequencies of higher harmonics f_H in normalized relative frequency pulse signal form. On the vertical axis is represented coefficient K_H which is responsible for the impact of harmonics on the parameters of the pulsed signal. For a number of normalized frequency pulse signal 1.0, 1.4, 2.0, 3.0, 5.0, 7.0 (harmonic H1) is accepted coefficient $K_H = 1$. Then the number of his third harmonic (H3) with coefficient of influence $K_H = 1/3$ is respectively: 3.0, 4.2, 6.0, 9.0, 15.0, and 21.0.

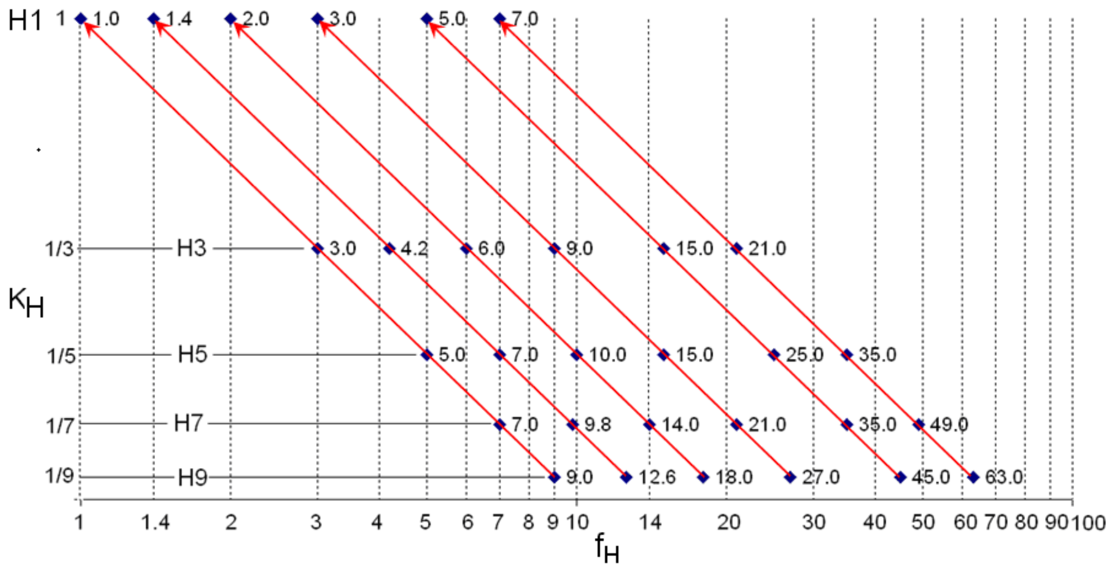

Figure 6. Graphical representation of the impact of higher harmonics pulse signal

Conclusions. Submitted the method of parametric analysis of signal transducers impedance spectroscopy in which the purpose of structural simplification and expansion of the range of frequencies used the nonharmonic signal in particular pulse signals. Such parametric analysis is of particular relevance at high frequencies, where the real parameters of components of signal converters, operational amplifiers mostly limit slew rate setting signal, its amplitude-frequency and phase response. As a result of this, there are measurement errors impedance characteristics which are caused by harmonic distortion signals. Replacing single-response frequency of harmonic signals sinusoidal form on pulse signals allows refusing the need to use tunable master oscillator frequency sine function that is typically implemented based on high-precision digital-to-analog converters and smoothing filters.

The obtained results in this paper are based on our proposed method SPICE modeling of research which conducted comparing small-signal AC analysis and Transient analysis. During AC analysis received impedance Nyquist plot in the idealized case and in the Transient analysis calculated value active $\mathrm{Re}\hat{Z}$ and reactive $\mathrm{Im}\hat{Z}$ impedance components for actual parameters of measuring transducers, including forms of activating signals. Implementation of Transient analysis involves the use of synchronous detection output signals and the integration result in the detection time intervals that fit their active and reactive components. The active component of the output signal is detected and integrated phase with the input signal setting and the reactive component – offset $\pi/2$. Signal conversion carried out based on quadrature detector.

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УДК 621.382

МЕТОДИКА АНАЛІЗУ ПОХИБОК ВИМІРЮВАЛЬНОГО ПЕРЕТВОРЕННЯ ІМПЕДАНСНОЇ СПЕКТРОСКОПІЇ З АКТИВАЦІЄЮ НЕГАРМОНІЧНИМИ СИГНАЛАМИ

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Резюме. *Розглянуто особливості SPICE моделювання вимірювальних перетворювачів імпедансної спектроскопії. На основі результатів модельних досліджень запропоновано методику аналізу похибок вимірюваних значень активної та реактивної складових імпедансу, яка ґрунтується на порівнянні малосигнального AC аналізу за змінним струмом та перехідного Transient аналізу. В ході AC аналізу отримано імпедансні діаграми Найквіста в ідеалізованому випадку, а в ході Transient аналізу розраховано значення активної* $Re\hat{Z}$ *та реактивної* $Im\hat{Z}$ *складових імпедансу для фактичних параметрів вимірювальних перетворювачів, у тому числі – форми активуючих сигналів. Реалізація такого підходу здійснюється шляхом синхронного детектування вихідних сигналів та інтегрування результату детектування в часових інтервалах, що відповідають їх активним та реактивним складовим.*

Ключові слова: *імпедансна спектроскопія, SPICE модель, параметричний аналіз, діаграма Найквіста.*

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