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PARAMETRIC ANALYSIS OF SYNCHRONOUS DETECTOR DEVICES OF IMPEDANCE SPECTROSCOPY

G.I. BARYLO, R.L. HOLYAKA, V.V. VIRT, F.F. VEZYR

This paper examines the peculiarities of parametric analysis of synchronous detector devices of impedance spectroscopy on the basis on SPICE - simulation. During the model research of characteristics of measuring transducers of impedance spectroscopy there arises a problem in an insufficient efficiency in limited opportunities. The limited opportunities are modeling research of real circuits of measuring transducers with allowance for parameters of real signals which are form, amplitude and inharmoniousness. With the aim of solving the indicated problem the paper uses the calculation methods based on SPICE Transient Analysis which allow determining the active and reactive components of the measured impedance for actual parameters of signals and components. Such a calculation is performed by synchronous detection of output signals and results integration in the detection time intervals that fit their active and reactive components. Based on of results of the research done criteria for assessing the accuracy of detecting signals are suggested and operating parameters of a quadrature detector are defined.

Keywords: parametric analysis, synchronous detector, impedance spectroscopy, SPICE model, Nyquist plot.

INTRODUCTION

Sensory devices are based on methods impedance spectroscopy are considered one of the most fundamental in a research of a wide range of composite materials and electrochemical objects. Materials, alternative energy, ecology [1] are especially important areas using methods impedance spectroscopy. Modern devices measuring impedance are used in cell biology [2], medical diagnosis, including early detection of cancer [3], immunology [4]. The impedance spectroscopy provides ease of implementation, energy efficiency, high resolution and selectivity of measurements parameter compared with other methods of physical research [5].

The generic units are synchronous detectors [6, 7] and an integrator [8, 9]. Their parameters are determinant from the standpoint of precision measuring transducers impedance. For generate informative signal active and reactive impedance components using quadrature detection [10].

Nowadays decisive stage in the development and research of devices of electronic equipment is a schematic mathematical modeling. This schematic modeling provides checking new methods of signal transformation, functional analysis of the diagrammatic decision and optimization regime of labor. SPICE (Simulation Program with Integrated Circuit Emphasis) is a standard of the schematic modeling especially the junction of solid-state electronics on the basis of the integrated circuits [11].

The fundamental peculiarity of the schematic SPICE modeling of the signal transformers is the necessity of transformation from frequency diagrams to diagrams on the complex plane. Note that in some modern versions of the software package of the schematic modeling, in particular, aforementioned MicroCap [12], the method of impedance analysis with using mathematical functions of real Re and imaginary Im components of the signal is already foreseen. With this function, there is an opportunity to construct the Nyquist plot and calculate the value of the active $\mathrm{Re}\,\hat{Z}$ and the reactive $\mathrm{Im}\,\hat{Z}$ of impedance.

1. THE METHOD OF MEASURING TRANSFORMATION

Measuring transformation on device of impedance spectroscopy is conducted by the way of synchronously quadrature rectification and integration of output voltage of signal transformers according to expressions:

$$V_{SRE} = K_{RE}\int_{t_1}^{t_2}\left(V_Z(t)\cdot A_{RE}(t)\right)dt;$$

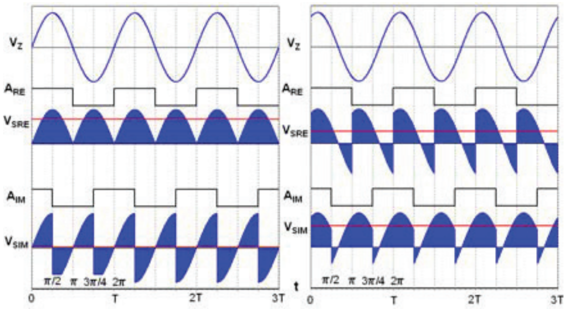
$$V_{SIM} = K_{IM}\int_{t_1}^{t_2}\left(V_Z(t)\cdot A_{IM}(t)\right)dt, \qquad (1)$$

where VSRE and VSIM – voltages, which are the instructive signals of real and imaginary components of impedance; KRE та KIM – are coefficients of proportionality of the function of transformation; VZ(t) – voltage in the investigated the two-terminal (galvanostatic method of transformation); ARE (t), AIM (t) – sign function, which take on a value +1 or -1 in dependence on the phase; t1, t2 – time interval (Fig. 1).

The value of sign function ARE (t), AIM (t) are determined by the time intervals: ARE(t) = 1 at t = [0…π], ARE(t) = -1 at t = [π…2π]; AIM(t) = 1 at t = [0…π/2] and [3π/2…2π], AIM(t) = -1 at t = [π/2…3π/2].

In particular in default of reactive component (Fig. 1,a) phase shift voltage VZ(t) in the investigated two-terminal is zero.This defines the maximum value of the instructive signal of real component (VSRE = max) and zero value of the signal of imaginary impedance component (VSIM = 0).

At the increase of the reactive component and an appropriate change of phase shift (Fig. 1,b) the real component VSRE is decreased, and module of the reactive |VSIM| – is increased.



а) б)

Fig.1. The epures of signal of converter at voltage phase shift 0° (a) and 60° (b)

2. MEASURING TRANSDUCER OF IMPEDANCE BASED ON QUADRATURE DETECTOR

The basic scheme of measuring impedance transformer is based on quadrature detector is on Fig. 2. A principle of function the scheme consists in the synchronous measuring of input measuring V_Z, which is formed by input circles of measuring transformation the galvanostatic or potentiometric type. For realization the detection inverse (on operational amplifier OA_1) and not inverse (on OA_2)) solving repeaters (module coefficient of transformation $|K_V| = 1$)), whose output voltage alternately are switched and averaged by switchboards SW_1, SW_2 and junction in accordance Σ_1, Σ_2. In general, averaging can be put into practice by digital methods, integration or low-frequency filtering. In this scheme of averaging is implemented by integrators INT_1, INT_2. Their output voltages V_{RE} and V_{IM} are served appropriately active and reactive components of the instructive impedance signal. The sign function of active $A_{RE}(t)$ and reactive $A_{IM}(t)$ components are formed respectively by sources SQ_{RE} and SQ_{IM}. Phases of output pulses of these sources are shifted on $\pi/2$.

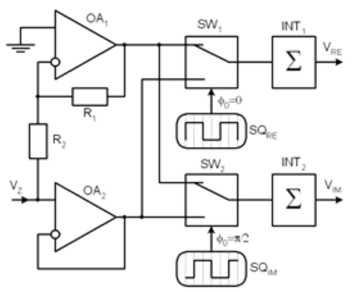


Fig.2. The basic scheme based on quadrature detector

3. THE SCHEME AND METHOD PARAMETRIC ANALYSIS OF QUADRATURE DETECTOR

Parametric analysis is produced on a size the disfigurement of the Nyquist plot. This analysis should be performed by the example of elementary RC two-terminal with a characteristic frequency $f_0 = 1/(2\pi RC)$, which is a limit of the frequency range of impedance measurement. On this characteristic frequency active Z_{RE} and reactive Z_{IM} components of impedance are equalized $Z_{RE}(f0) = ZIM(f0)$). In particular, for frequency = 0,1 Mhz parameters RC of circle can be following: Rx = 1 kΩ, Cx = 1,591 nF. Frequency dependences of active Re and reactive - Im of impedance components and the Nyquist plot this RC circle with the characteristic frequency f_0 = 0,1 MHz are on Fig. 3.

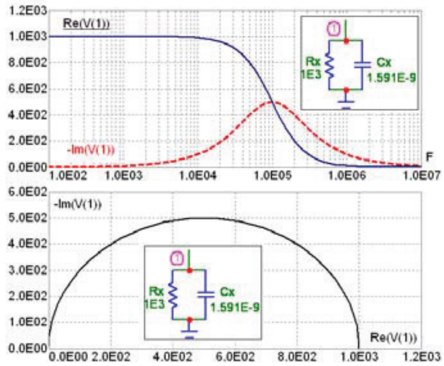


Fig.3. Frequency dependences of impedance components and the Nyquist plot

For minimization the influence another node of signal transformation on results of parametric analysis the quadrature detector two conditions are provided. At first idealized model of given current source is used and at second the output instruction signals are formed exceptionally at mathematical level (without using the nodes at fisical level). The scheme of model investigation the quadrature detector in which these conditions are realized is on Fig. 4.

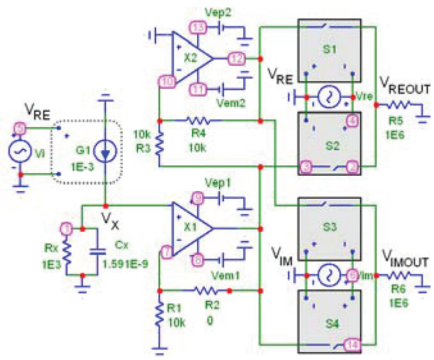


Fig.4. The scheme of model investigation of quadrature detector

The function of numerical integration SD (Running integral with respect to time) library MicroCAP - SD(V(X)), is used for formation output signals where V(X) is a voltage in nodes X.

Current source G1 with a coefficient of transformation K_I = 1E-3 is followed the current voltage V_{RE} (source Vi). The output voltage on the two-terminal R_X, C_X is repeated on the operational amplifier X1 (with a zero resistance of the resistor of feed-back R2 = 0) and inverted on the operational X2. In phase with this current voltage VRE signals the control of keys S1 and S2 are formed by the source. The first of them commutes the voltage of inverting, and the second commutes non-inverting repeaters. As a result of this commutative the output voltage V_{REOUT} is formed on resistor R5 (junction 2). Its further numerical integration SD(V(2)) provides formation the informative signal of active impedance components SD_{RE}. Similarly, from the schematic point of view the informative signal of active impedance components SD_{IM} is formed. The phase of voltage Vim is the only one difference here, which forms signals the control of keys S3 and S4. As is noted, phase voltage V_{IM} of this source is displaced by a quarter period relatively current voltages V_{RE} of the source Vi.

Firstly we will consider exactness of the signal converting into an ideal variant without the account of frequency and phase limitations of operating amplifier. Mainly this idealization provides for using the model with infinitely large value the bandwidth GBW (Gain Band Width) $\to\infty$ Example of the results of investigation the signal of quadrature detector for this idealised case (variant A) is on Fig. 5 and Fig. 6.

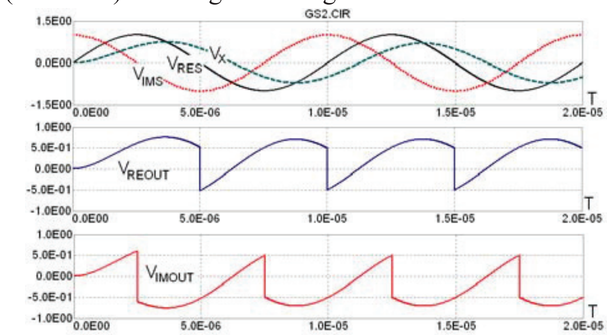


Fig.5. Diagrams the voltages of detector (variant A) at GBW $\to\infty$

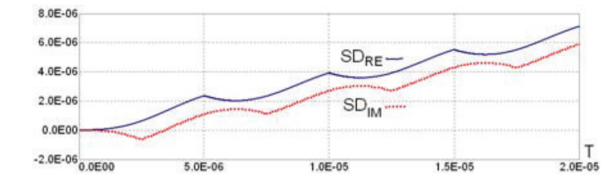


Fig.6. Diagrams the integrals of detector (variant A) at GBW $\to\infty$

Considering, that current signal coincides from characteristic frequency f_0 = 0,1 MHz of investigational two-terminal (R_X = 1E3, C_X = 1.591E-9), instantaneous values the output signal of SD_{RE} and reactive SD_{IM} impedance components must mutually coincide. However, how it is on Fig. 6 diagrams, function integrals the output voltage differ significantly. The indicated divergence of signals is a result especially of the process of integration and its initial conditions. It is clear that output functions of integration of signals are not linear, and thus on throughout the duration of periods of questioner signal the integrals of SD_{RE} and SD_{IM} are not coincide. However, in the moment of completion each of this periods it is desirable, that these integrals will coincided.

How it is on the next diagrams of signal the similarly scheme of quadrature detector (variant B - Fig. 7, Fig. 8), coincide the integrals SDRE and SDIM in a case of equality frequency the output function and characteristic frequency investigational two-terminal achieved by changing the initial conditions of integration – the phase of source VRE are displaced on $\pi/4$, and the source VIM – on $3\pi/4$ (mutual phase shift between these sources remains unchanged, namely, $\pi/2$).

Consequently, a specification of their models is following:

.MODEL VRE SIN (F=100K PH=pi/4);

.MODEL VIM SIN (F=100K PH=3*pi/4).

It is possible to see that indicated phase delays allow to level the instantaneous values of integrals of SDRE and SDIM in moments of completion each of periods of signals– 1E-5, 2E-5 and others like that. Consequently, the values of integrals of SDRE and SDIM in these moments can serve as quantitative parameters that describe the informative values of corresponding components of the measureable impedance.

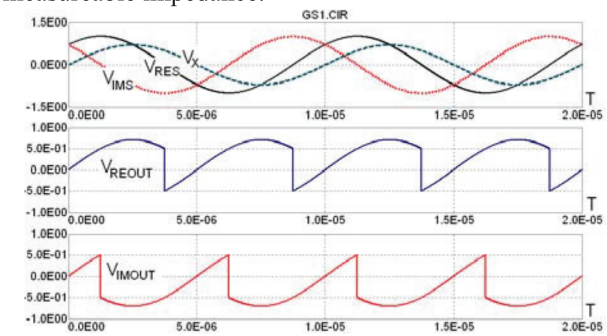


Fig.7. Diagrams the voltages of detector (variant B) at GBW $\to\infty$

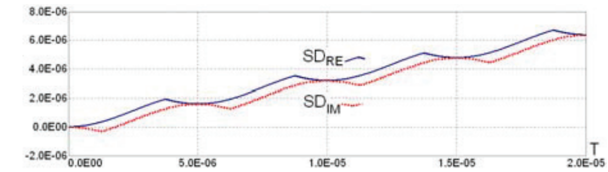


Fig.8. Diagrams the integrals of detector (variant B) at GBW $\to\infty$

From taking into account of the above-mentioned initial conditions the numerous investigation of exactness of signal transformation of quadrature detector were undertaken at the different values of parameters of models of operating amplifier. Thus, with the aim to exposure of characteristic conformities to law the turn-based change of frequency parameters of strengtheners was conducted, during fixing other, less meaningful parameters.

So, diagrams the voltages of detector are on Fig. 9 and Fig. 10 R_X = 1E3, C_X = 1.591E-9 for the set of values for bandwidth GBW = 3E5, 1E6, 3E6, 1E12 during the fixing of other parameters of model:

.MODEL OA OPA (LEVEL=2, C=3P, A=1E9, VOFF=1u, SRP=1E9, SRN=1E9, VEE=-5, VCC=5, VPS=5, VNS=-5, CMRR=1E6).

The results of quantitative comparison of exactness the signal transformation are got during this researches are shown on: Fig. 11 (nominal terms), where ReZ ≡ SD_{RE}, -ImZ ≡ SD_{IM} at R_X = 1E3, C_X = 1.591E-9;

Fig. 12 (maximum terms), where ReZR ≡ SD_{RE}, -ImZR ≡ SD_{IM} at R_X = 1E3, C_X = 0 (for the two-terminal without reactive component), ReZC ≡ SD_{RE}, -ImZC ≡ SD_{IM} at R = ∞, C_X = 1.591E-9 (for the two-terminal without active impedance).

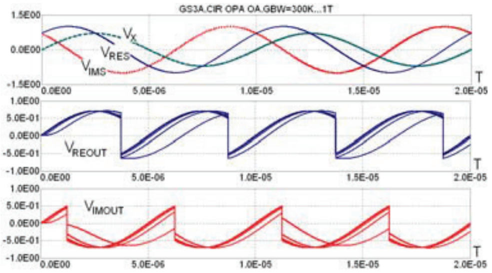


Fig.9. Diagrams the voltages of detector at GBW = 3E5, 1E6, 3E6, 1E12

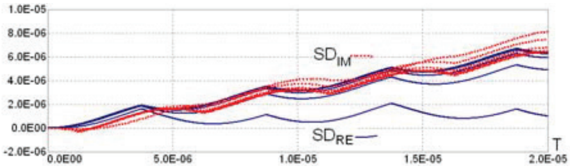


Fig.10. Diagrams the integrals of detector at GBW = 3E5, 1E6, 3E6, 1E12

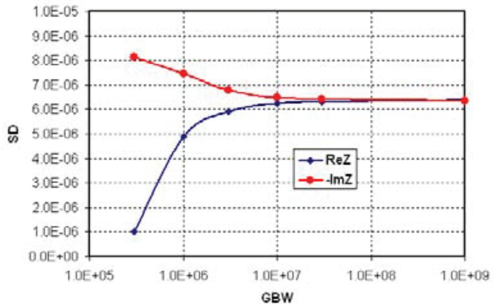


Fig.11. Dependences ReZ and -ImZ from GBW at R_X = 1E3, C_X = 1.591E-9

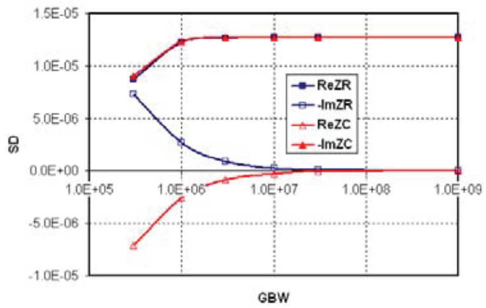


Fig.12. Dependences ReZ and -ImZ from GBW at maximum terms

These results give the opportunity to conduct a quantitative analysis of influence of bandwidth GBW on the errors of signal transformation. The equality of values ReZ = -ImZ at nominal terms and ReZR = -ImZC = Max, ReZC = -ImZR = 0 at maximum terms is the criterion of high exactness of detection of signals, as it was already marked. For example it is possible to mark a fact, that at GBW = 1E6 (in particular, to the aforementioned operational amplifier AD8541/2/4) the divergence of values ReZ ≡ SD_{RE}, -ImZ ≡ SD_{IM} are very considerable: ≈5E-6 and ≈7,5E-6, accordingly. Divergence from zero values of quantity are also considerable ReZC and -ImZR: ≈-0,25E-6 and ≈0,25E-6, accordingly. Thus it is shown that for measuring of the impedance of two-terminal with characteristic frequency f_0 = 0,1 MHz (R_X = 1E3, C_X = 1.591E-9) the operational amplifier of the quadrature detector must be characterized by the bandwidth GBW = 1E7 and higher.

CONCLUSION

The proposed approaches and examples of parametric analysis of synchronous detector device impedance spectroscopy are using SPICE models. Therefore, schematic modeling is based on real Re and imaginary Im components of the AC Analysis is characterized by significant limitations to conduct parametric studies of signal transducers. The impedance Nyquist plot gets on the base of the Bode plot using the method of analysis namely AC Analysis. However, this method in its concept is the small-signal to with the calculation of amplitude-frequency and phase frequency characteristics for ideal harmonic signals in which amplitude has a maximum small value conducted in its process. Therefore, schematic modeling is based on real Re and imaginary Im components of the AC Analysis does not allow conducting the parametric investigation of signal transformers with real signal.

In this work with the aim of the decision of the indicated problem the calculation methods are based on SPICE Transient Analysis, which allows determining the active ZRE and the reactive ZIM components of measuring impedance for actual parameters of signal and electronic elements. Such calculation performed by synchronous detection of output signals and results integration in the detection time intervals that fit their active and reactive components. The active component of the output is detected and integrated with phase the input signal and the reactive component - with phase displacement on π/2.

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Virt Volodymyr, PhD. Lviv Polytechnic National University. Signal transducers of impedance type for photovoltaic devices, construction and research of control systems energy-saving solar cells

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Параметрический анализ синхронных детекторов устройств импедансной спектроскопии / Г.І. Барило, Р.Л. Голяка, В.В. Вірт, Ф.Ф. Везир // Прикладная радиоэлектроника: науч. – техн. журнал. – 2017. – Том 16, №.1, 2 – С. 41 – 45.

В работе исследуются особенности параметрического анализа синхронных детекторных устройств импедансной спектроскопии на основе SPICE - моделирования. В ходе модельного исследования характеристик измерительных преобразователей импедансной спектроскопии возникает проблема недостаточной эффективности в возможностях по проведению модельных исследований реальных схем измерительных преобразователей с учетом параметров реальных сигналов – формы, амплитуды, негармоничности. С целью решения указанной проблемы в данной работе используются методы расчета на основе SPICE Transient анализа, позволяющие определить активную и реактивную составляющие измеряемого импеданса для фактических параметров сигналов и элементной базы. Такой расчет проводят путем синхронного детектирования выходных сигналов и интегрирования результата детектирования во временных интервалах, соответствующих их активным и реактивным составляющим. На основе результатов проведенного исследования предложены критерии оценки точности детектирования сигналов, и определены рабочие параметры квадратурного детектора.

Ключевые слова: параметрический анализ, синхронный детектор, импедансная спектроскопия, SPICE модель, диаграмма Найквиста.

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Параметричний аналіз синхронних детекторів пристроїв імпедансної спектроскопії / Г.І. Барило, Р.Л. Голяка, В.В. Вірт, Ф.Ф. Везир // Прикладна радіоелектроніка: наук. – техн. журнал. – 2017. – Том 16, №.1, 2 – С. 41 – 45.

В роботі досліджуються особливості параметричного аналізу синхронних детекторних пристроїв імпедансної спектроскопії на основі SPICE - моделювання. В ході модельного дослідження характеристик вимірювальних перетворювачів імпедансної спектроскопії виникає проблема недостатньої ефективності в обмежених можливостях щодо проведення модельних досліджень реальних схем вимірювальних перетворювачів з урахуванням параметрів реальних сигналів – форми, амплітуди, негармонічності. З метою вирішення вказаної проблеми в даній роботі використовуються методи розрахунку на основі SPICE Transient аналізу, що дозволяють визначити активну та реактивну складові вимірюваного імпедансу для фактичних параметрів сигналів та елементної бази. Такий розрахунок проводять шляхом синхронного детектування вихідних сигналів та інтегрування результату детектування в часових інтервалах, що відповідають їх активним та реактивним складовим. На основі результатів проведеного дослідження запропоновано критерії оцінки точності детектування сигналів, та визначено робочі параметри квадратурного детектора.

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

Іл.: 12. Бібліогр.: 12 найм.