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Parametric Analysis of Input Circuits of Galvanostatic Type Impedance Measuring Transducers

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Abstract: The main approaches of parametric analysis of impedance measuring transducers on the base of SPICE modeling are considered in paper. In the modeling process, the galvanostatic measurement method is used, which is on the base of the determination of the ratio and phase delay between the voltage and the harmonic current with the specified amplitude and frequency. As a result of simulation, the possibility of significant increase of the measurement transformation accuracy is found by means of modifying the input circuits of the impedance measuring transducers.

Keywords: Galvanostatic type, Impedance spectroscopy, Measuring transducer, Nyquist diagram, Parametric analysis, SPICE model.

1. Introduction

The impedance spectroscopy method is played a significant role in fundamental and applied materials research. This method is used for the study of any materials in liquid and solid aggregates [1]. The impedance spectroscopy method is particularly effective method to solve the investigation problems of charge transfer processes in heterogeneous systems, including boundaries of phase separation, electron boundaries, micro and nanostructures. Therefore, the impedance spectroscopy method is considered one of the fundamental in the studying process of composite materials and electrochemical objects [2]. Compared to other physical research methods, the impedance spectroscopy method is providing the simplicity of implementation, the energy efficiency, the high resolution and the selectivity of measured parameters [3]. The typical examples of problems solved by the impedance spectroscopy method are: applied material science [4], ecology [5], and research in the field of cell biology [6], medical diagnosis [7], and immunology [8]. The galvanostatic and potentiostatic methods are the base of the measuring transducers of impedance spectroscopy. In the galvanostatic method the informative value of the impedance measuring is the time dependence of the instantaneous voltage value on the investigated two-pole at the predetermined current modulation [9]. Instead, the informative value of the potentiostatic method is the time dependence of the instantaneous value of the current at a given voltage modulation. In both methods, as the results of the measurement transformation the two impedance components of the investigated object are found: its active $\mathrm{Re}\hat{Z}$ and reactive $\mathrm{Im}\hat{Z}$ resistance [10]. Further, taken into account these impedance components, the impedance hodograph on an integrated plane, also called the

Nyquist diagram are plotted. The Nyquist diagram shape is permits to determine the structure and parameters of the investigated two-pole [11].

An urgent task at the process of sensor devices designing on the base of impedance spectroscopy method is the analysis of the element base characteristics influence on the functioning accuracy of the impedance measuring transducers. This paper is devoted to the parametric analysis problem of input circuits of galvanostatic type impedance measuring transducers. The base of the above research is the SPICE schematic simulation [12, 13].

2. The Structural Diagram of Galvanostatic type Impedance Measuring Transducers

In galvanostatic method the measuring impedance transducers are form the signals by means of determination the ratio and phase delay between the voltage on the investigated two-pole and harmonic current with a given amplitude and frequency. The main units of measurement transducers are (Fig. 1): the harmonic current source (CS) frequency controlled; Voltage Transducer and Amplifier (VTA); Synchronous Detector (SD); Integrator (INT); Low Frequency Amplifier (LFA); Analog-to-Digit Converter (ADC); Microcontroller (MC), performing the device control with further converted digital signals - Control & Digit Signal (CT & DS).

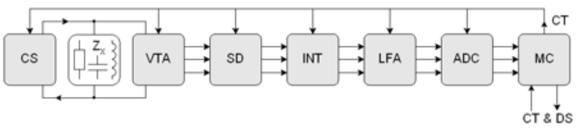


Fig. 1. Structural diagram of galvanostatic type impedance transducers.

The main criteria of elemental base choosing for impedance transducers is compliance with the requirements of microelectronic devices in terms of minimizing the dimensions, ensuring high energy efficiency and low cost. These criteria are crucial for the development of microelectronic devices for impedance spectroscopy, in particular, taking into account the requirements of the Internet of Things (IoT) or Internet Physical World Internet [14, 15].

In this paper, the main approaches of parametric analysis of input circles of galvanostatic type impedance measuring transducers on the base of operational amplifiers are considered.

3. The Input Circles Circuits of Galvanostatic Type

An elementary circuits of the input circle of galvanostatic type measuring transducers is shown in Fig. 2, a. Functionally, the circuits provides the stabilization of the activation current through the investigated two-pole Z_X, and corresponding to the CS knot (Fig. 1), implements a voltage transformation V(SG) of the harmonic signal with a controlled frequency (source SG) into current $I(Z_X)$. The transformation coefficient is set by the resistance of the resistor R_I. - $I(Z_X) = V(SG)/R_I$.

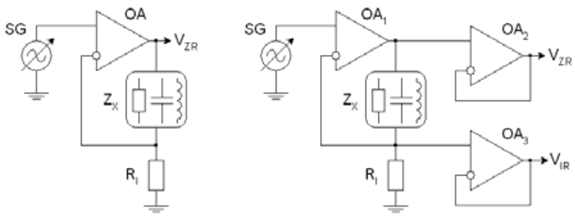


Fig. 2. The input circles circuits of galvanostatic type.

Such an elementary circuit is typical for sources of stabilized current without the additional explanations. However, during the development of impedance measuring transducers, there is a certain specific problem and, consequently, a corresponding task that is not typical for common current stabilizers circuits. This task is the impossibility to directly use the V_{ZR} output voltage as an impedance informative signal of the two-pole Z_X. This voltage is the sum of the two components is the voltage $V(V_{ZR})$ on the two-pole V_{ZR} and the voltage $V(R_I)$ on the resistor R_I. And although, in the first approximation, the voltage $V(V_I)$ corresponds to the voltage of the SG source and is considered an additive component constant; nevertheless, this approximation leads to significant impedance measurement errors.

Obviously, such errors minimization is involve a voltage subtraction $V(V_{ZR})$-$V(R_I)$ in case of the circuit engineering point of view. It is implemented by a subtraction (differential) amplifier. To this amplifier the basic requirements are the minimum bypassing of input circle and the minimum frequency distortion of the impedance characteristic. Taking into account the previously mentioned considerations the concerning such distortions by gaining cascades and priority to use the voltage repeaters, in the transducers circuit the two repeaters on operational amplifiers OA_2, OA_3 were introduced.

As will be shown below, the use of exactly two identical repeaters, and not just the essentially important repeater on OA_3, which prevents the effect of shunting of high-resistance knot on the resistor R_I, largely allows to voltage subtraction procedure $V(V_{ZR})$-$V(R_I)$) with minimized frequency distortions.

4. Circuit and Model Research Results

The model research circuit (SPICE substitution circuit) of the input circles of galvanostatic type measuring transducers is shown in Fig. 3, and the model research results of amplitude-frequency and phase-frequency characteristics (the db designation corresponds to decibels, and ph is the phase delay degrees) are in Fig. 4 and Fig. 5. The frequency characteristic of two-pole impedance is the investigated objects. The two-pole is represented by a parallel RC-circuit (R_X, C_X). The characteristics analysis of the measuring transducer was performed for two values of GBW (Gain Band Width) bandwidths of the operating amplifiers (GBW = 1E6 and 1E7).

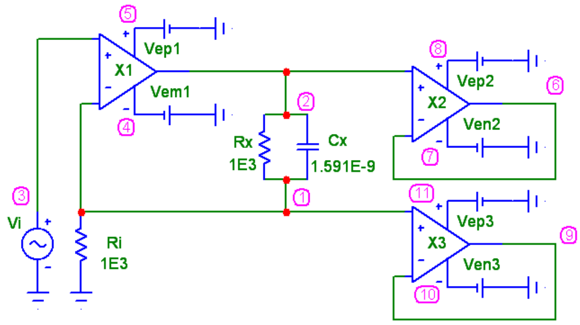


Fig. 3. Scheme model research of galvanostatic type input circles.

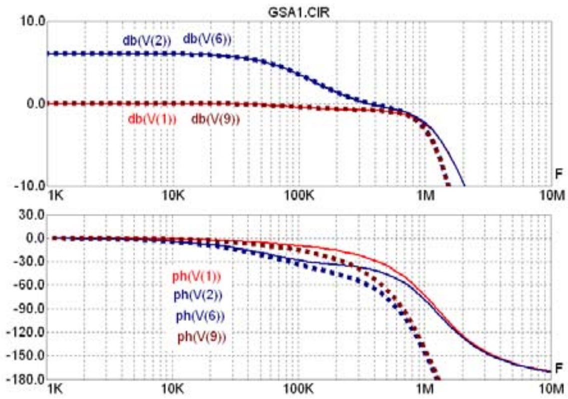


Fig. 4. Frequency response and phase response of voltages at GBW = 1E6.

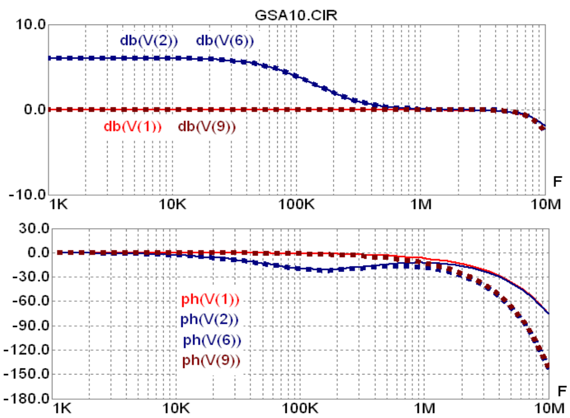
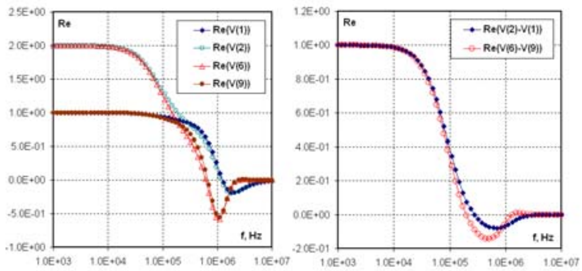


Fig. 5. Frequency response and phase response of voltages at GBW = 1E7.

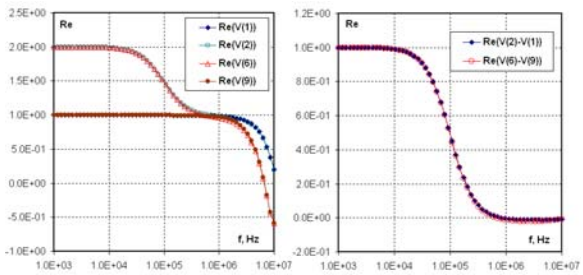
Implementation of impedance spectroscopy methods involves the transition from frequency diagrams to diagrams on a complex plane (Nyquist diagrams). Therefore, the analysis of the measurement conversion accuracy by means of the above-mentioned frequency response and phase response is problematic. In a numbers of modern versions of SPICE simulation software packages, in particular the MicroCAP package there is provided a method for impedance analysis using the mathematical functions of real Re and imaginary Im signal components. By means of this functions it is possible to investigate the frequency dependences of the corresponding values of the active Re$\hat{Z}$ and the reactive Im$\hat{Z}$ impedance, and, thus, to plot the Nyquist diagram.

Results examples of such research are shown in Fig. 6 - Fig. 11. The active Re (V (1), Re (V (2), Re (V (6), Re (V (9) and the reactive Im (V (1), Im (V (2), Im (V (6), Im (V (9) the voltage components are the informative signals of the corresponding impedances with the conversion coefficient K_I, the value of which is determined by the impedance of the resistor Ri. For these research results Ri = 1E3 and thus conversion coefficient of K_I = 1E-3. Since, in this example, R_X = Ri, at low frequencies voltages V (2) and V (6) are twice higher than V (1) and V (9) voltages. Therefore, at low frequencies Re (V (1)) = Re (V (9)) = 1E0, Re (V (2)) = Re (V (6)) = 2E0.



a) b)

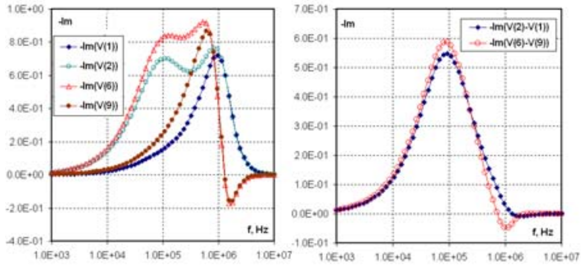
Fig. 6. Active Re voltage components (a) and their differences (b) at GBW = 1E6.



a) b)

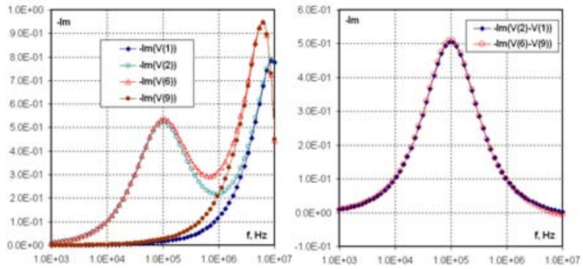
Fig. 7. Active Re voltage components (a) and their difference (b) at GBW = 1E7.

The presented research results show the complex nature of distortions, which are caused by the real parameters of operational amplifiers, and therefore, the patterns found in these studies should be taken into account in the processes of choosing an element base with the necessary frequency characteristics, circuit optimization of the measuring transducers and their calibration.



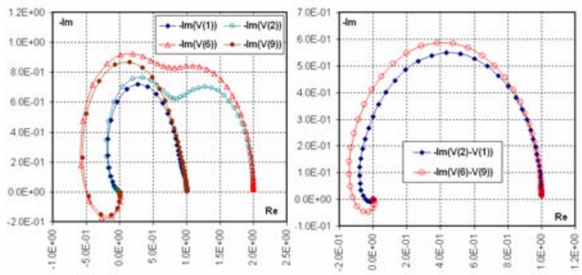
a) b)

Fig. 8. Reactive Im voltage components (a) and their difference (b) at GBW = 1E6.



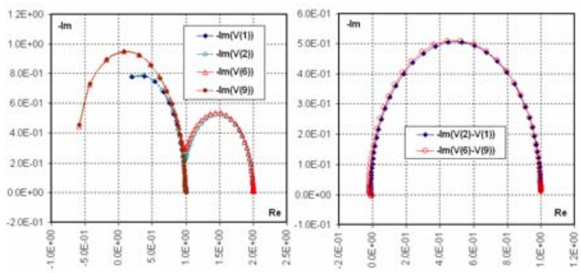
a) b)

Fig. 9. Reactive Im voltage components (a) and their difference (b) at GBW = 1E7.



a) b)

Fig. 10. The Nyquist diagram of voltage (a) and their difference (b) at GBW = 1E6.



a) b)

Fig. 11. The Nyquist diagram of voltage (a), and their difference (b) at GBW = 1E7.

To such important regularities as found out by the above results of model researches, it is necessary to include:

- Firstly, the appearance of the significant functions nonmonotonically active and reactive impedance components;
- Secondly, the emergence of secondary (parasitic) area (high frequency) impedance Nyquist diagram in thus impossible using direct output voltage operational amplifier OA1 as informative of research two-terminal signal impedance ZX;
- Thirdly, the ability to significantly improve the accuracy of measuring conversion using the difference signal conversion.

5. Modification of Galvanostatic Type Input Circles Schemes

Analyzing the problem of the above-mentioned necessity to use the differential signal transformation, we consider the modification problem of galvanostatic type input circles circuit, the output voltage of which is not the sum of the voltages on the investigated two-pole and current-consuming resistors. The solution to this problem is not problematic and is realized using an auxiliary transistor cascade (Fig. 12) or a change in the way of connecting a voltage source SG (Fig. 13, a). The only limitation here could be to assume the flow of activation current through a given source. This limitation is solved by means of the auxiliary operational amplifier as a repeater of the assigning voltage (Fig. 13, b).

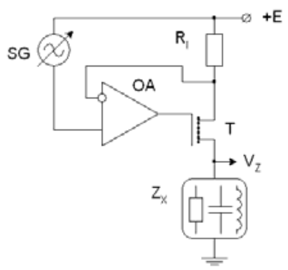
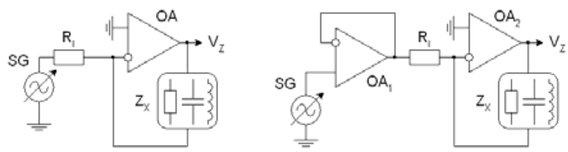


Fig. 12. Input circle circuits of galvanostatic type with transistor cascade



a) b)

Fig. 13. Modified input circles circuits of galvanostatic type.

6. Conclusions

The approaches of parametric analysis of impedance measuring transducers on the base of SPICE models and results of input circuit investigations of these transducers by means of galvanostatic measurement method are presented. In this method, the measuring transducer of the impedance form the signals on the base of the determination of the ratio and phase delay between the voltage on the investigated two-pole and the harmonic current with a given amplitude and frequency.

The research is conducted with taken in account new MicroCAP functionality possibilities of schematic design SPICE simulation package, which provides the method of impedance analysis. Such an analysis is based on the mathematical functions of the real Re and the imaginary Im component constituents embedded in the given package, by which it is possible to investigate the frequency dependences of the corresponding values of the active Re$\hat{Z}$ and the Im$\hat{Z}$ impedance, and to plot the Nyquist diagram.

The obtained results of the parametric analysis show the complex nature of the distortions, which are caused by the actual parameters of the operational amplifiers, and therefore, the patterns found in these studies should be taken into account in the processes of selecting an element base with the necessary frequency characteristics, circuit optimization of the measuring transducers and their calibration. In particular, the functions nonmonotonicity of the active and reactive impedance components and the emergence of a parasitic site on the Nyquist impedance diagram were revealed. The possibility of significant increase of the accuracy of the measuring transformation by means of the differential signal conversion is established. Modifications of input circles circuits of measuring devices of galvanostatic type impedance are presented.

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