ВИМІРЮВАННЯ ЕЛЕКТРИЧНИХ ТА МАГНІТНИХ ВЕЛИЧИН
MEASUREMENTS OF ELECTRICAL AND MAGNETIC QUANTITIES

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Study of autotransformer bridges for measurements of the impedance parameters

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Abstract

The analysis of the existing impedance measurement methods showed that for the establishment of precision comparators that operate in a wide range of values in the audio frequency range, it is best to use transformer and autotransformer bridges. Autotransformer bridges are used for measurements in a wide range of the impedance values. The use of autotransformer bridges allows reducing the measurement error to 10^{-7}–10^{-9}.

High metrological characteristics of transformer bridge circuits make it possible to use them in commercial devices and precision measuring equipment. Simple autotransformer bridges do not provide the opportunity to measure the impedance parameters in a wide range of values of the tangent of the loss angle (phase shift). For the synthesis of measuring circuits of bridges and their balancing, it is necessary to have a precision quadrature channel that will ensure high accuracy of the transmission coefficient both by phase and by module.

The structures of universal autotransformer comparators and their properties are determined by two main factors: by the method of forming the source of the complex balancing signal and by the types of schemes for replacing the impedances of the compared objects. To determine ways to improve universal precision impedance comparators based on autotransformer bridges, it is necessary to develop and analyze mathematical models of universal comparators.

The conducted theoretical analysis showed that in the process of comparison, it is possible to compare impedances with different substitution schemes with a direct reading of reactive and active parameters. By choosing the appropriate transmission direction, with a simple reconstruction of the measuring circuit, it is possible to compare two impedances with a parallel substitution scheme, two impedances with a series substitution scheme, or two impedances with a different substitution scheme. The obtained results made it possible to implement them in a universal autotransformer-comparator bridge.

Keywords: autotransformer bridge; impedance; quadrature channel; substitution scheme; equilibrium equation.

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Introduction

The analysis of the existing impedance measurement methods showed that for the establishment of precision comparators that operate in a wide range of values in the audio frequency range, it is best to use transformer and autotransformer bridges [1, 2]. Autotransformer bridges are used for measurements in a wide range of the impedance values. The use of these bridges allows reducing the measurement error to 10^{-7}–10^{-9}.

The theory of these bridges is quite well-developed, and high metrological characteristics of transformer bridge circuits make it possible to use them in commercial devices and precision measuring equipment [3–7]. Simple autotransformer bridges do not provide the opportunity to measure the impedance parameters in a wide range of values of the tangent of the loss angle (phase shift). For the synthesis of measuring circuits of bridges and their balancing, it is necessary to have a precision quadrature channel that will ensure high accuracy of the transmission coefficient both by phase and by module [8, 9].

Modern research demonstrates the high accuracy of the unit size transfer from measurement standards based on the Calculation Capacitor and Quantum Hall Effect using transformer bridges [10–14]. However, such bridges do not provide the transmission over the entire range of reference impedance measurements. In the case of the quadrature transmission (from resistance to capacitance and vice versa), the size, accuracy of forming the phase, and modulus of the transmission

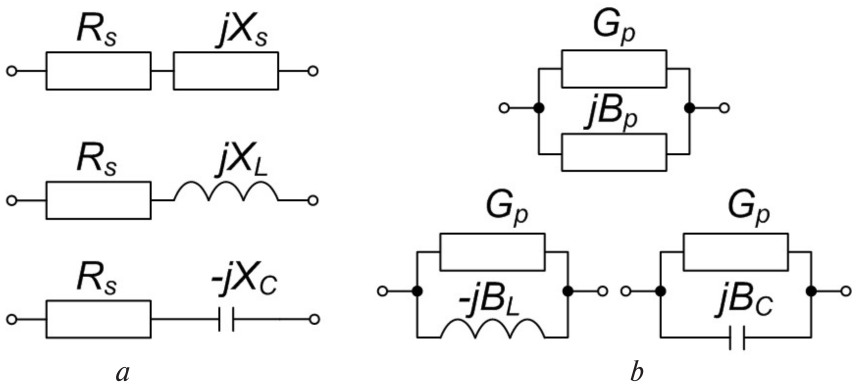


Fig. 1. Serial and parallel presentation of impedance parameters

coefficient of the quadrature channel affect the accuracy of measuring the impedance parameters [15].

To determine ways to improve universal precision impedance comparators based on autotransformer bridges, it is necessary to develop and analyze mathematical models of universal comparators and, based on this, to develop methods of their variational automatic balancing.

Structures of universal autotransformer bridges

The structures of universal autotransformer comparators and their properties are determined by two main factors: by the method of forming the source of the complex balancing signal and by the type of equivalent circuit for the impedances of the compared objects.

Electrical impedance (resistance) or admittance (conductivity) are general characteristics of the component of an alternating current electrical circuit and being complex quantities represent the sum of active and reactive resistances or conductances represented by parallel or series equivalent circuits, shown in Fig. 1.

The impedance best represents the connection (series equivalent circuit) of active (R_s) and reactive resistances (X_s). For a parallel connection, admittance is often used, where G_p and V_p are active and reactive conductances. The concepts of impedance and admittance can also be used to describe parallel and series circuits, respectively, but a mathematical model of the object is significantly complicated.

The autotransformer comparator shall perform a comparison of the impedances of two measures according to two parameters. For this, the comparator shall be balanced according to these two parameters. Balancing according to one of the impedance parameters (which is the main one) is usually carried out by changing the ratio of the number of turns of the windings of the autotransformer divider. For balancing according to the second parameter, it is necessary to create and accordingly enter the second source of quadrature amplitude-regulated voltage. Separate structures of autotransformer bridges, within which this issue is resolved, are given in [1].

Depending on what is the signal source for the quadrature regulated voltage source, comparators can be divided into three main groups. In each group, the structures of the comparators differ in the place of input of the quadrature signal – adjustable or non-adjustable arm.

In the structures of the first group, the signal source for the quadrature channel is the output voltage of the generator (Fig. 2, where *a* is a quadrature signal input into the non-adjustable arm, *b* is a quadrature signal input into the adjustable arm).

In the structures presented in Fig. 2: *Gen* is a voltage generator, Z_1 and Z_2 are compared impedances,

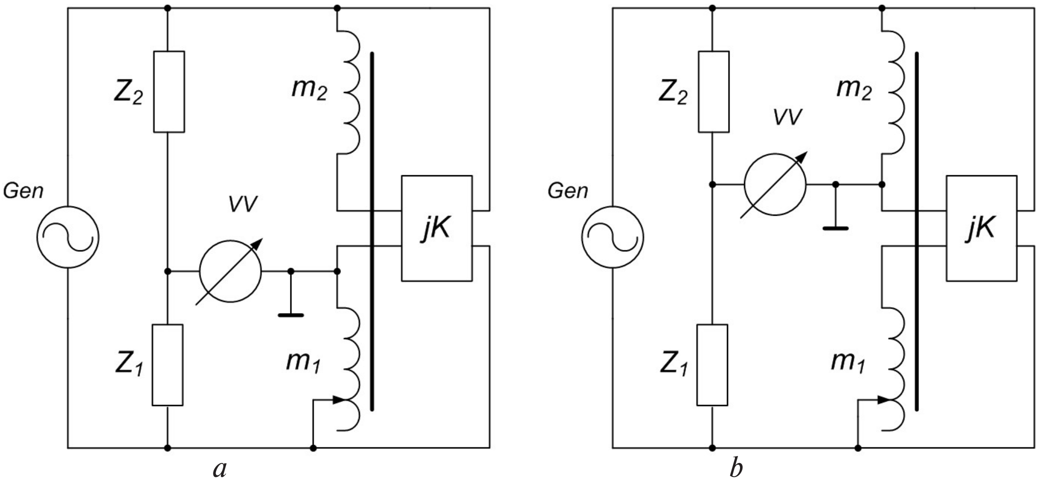
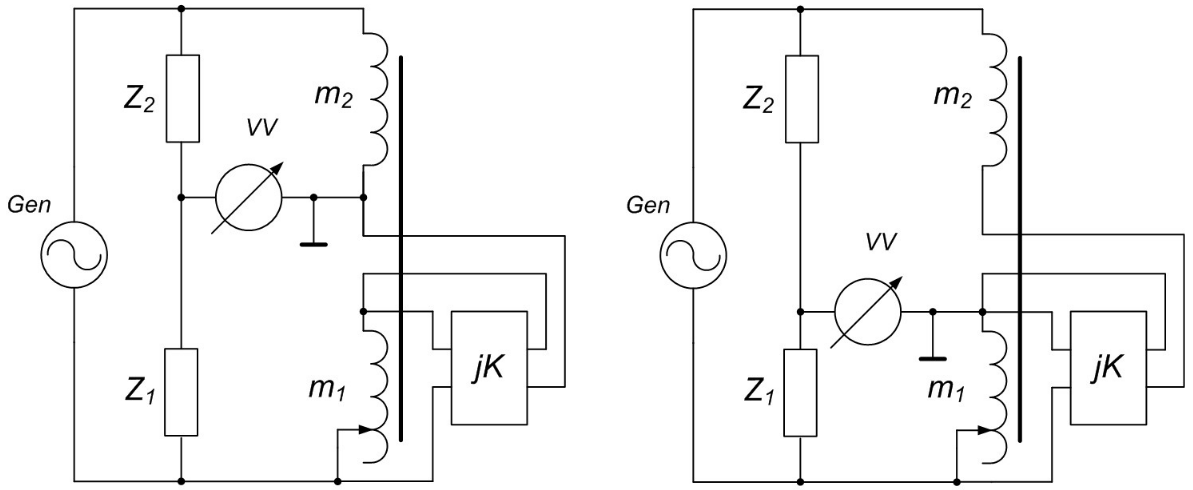


Fig. 2. Structures of autotransformer comparators where the voltage source for the balancing system of the quadrature channel is the generator voltage



a *b*

Fig. 3. Structures of autotransformer bridges where the voltage source for the balancing system of the quadrature channel is the arm winding voltage m_1

m_1 and m_2 are autotransformer windings, *VV* is a vector voltmeter. The input of the quadrature channel *jK* (*K* is a transmission coefficient of the quadrature channel) is connected to the voltage generator *Gen*. Winding m_1 has a variable number of turns that implement the first decade of balancing and is used to balance the bridge.

The equilibrium equation for the schemes in Fig. 2, is as follows:

- for the structure in Fig. 2, *a*:

$$\frac{Z_1}{Z_2}=\frac{1-jK}{\frac{m_1}{m_2}+jK}; \tag{1}$$

- for the structure in Fig. 2, *b*:

$$\frac{Z_1}{Z_2}=\frac{\frac{m_1}{m_2}+jK}{1-jK}. \tag{2}$$

For the second group of structures, the source of the input signal of the quadrature channel is the voltage on the m_1 winding of the autotransformer divider (Fig. 3, *a* is a quadrature signal input into the adjustable arm, *b* is a quadrature signal input into the non-adjustable arm).

The equilibrium equation for the schemes in Fig. 3, is as follows:

- for the structure in Fig. 3, *a*:

$$Z_1=Z_2\frac{m_1}{m_2}\left(1+jK\right); \tag{3}$$

- for the structure in Fig. 3, *b*:

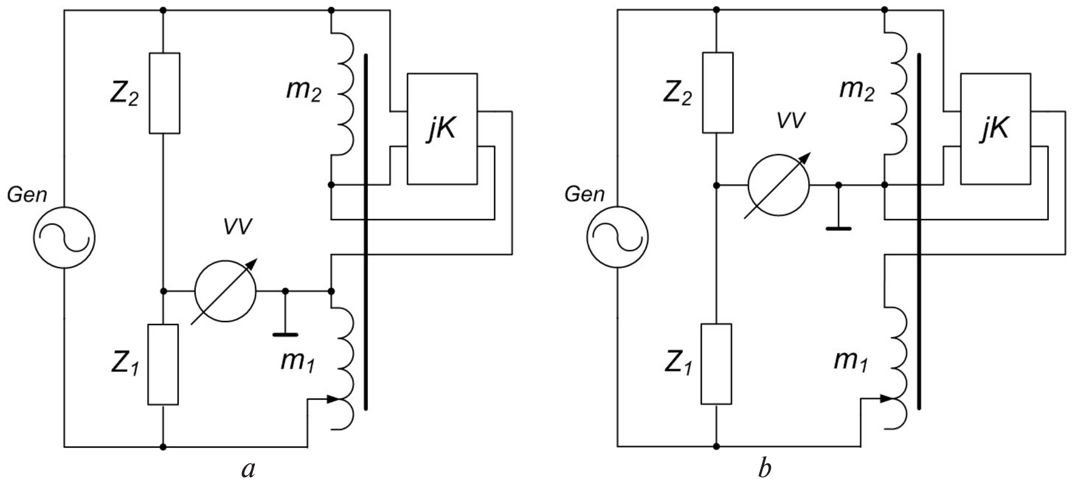
$$Z_2=Z_1\frac{m_2}{m_1}\left(1+j\frac{m_1}{m_2}K\right). \tag{4}$$

In the structures of the third group, the quadrature channel is powered by the voltage on the winding m_2 (Fig. 4, *a* is a quadrature signal input into the non-adjustable arm, *b* is a quadrature signal input into the adjustable arm).

The equilibrium equation for the schemes in Fig. 4, is as follows:

- for the structure in Fig. 4, *a*:

$$Z_2=Z_1\frac{m_2}{m_1}\left(1+jK\right); \tag{5}$$



a *b*

Fig. 4. Structures of autotransformer bridges where the voltage source for the balancing system of the quadrature channel is the arm winding voltage m_2

- for the structure in Fig. 4, *b*:

$$Z_1 = Z_2 \frac{m_1}{m_2}\left(1 + j\frac{m_2}{m_1}K\right). \qquad (6)$$

The analysis of the given equations shows that when the generator voltage is used in the quadrature channel as an input, the equilibrium equations have a rather complicated form. At the same time, the proportionality of the reading of the parameters of one impedance to the parameters of another one cannot be ensured even in those simple cases when one of the compared impedances is solely active or solely reactive. Therefore, let us focus on the analysis of other configurations.

Schemes of the second group do not provide any constant sensitivity for balancing the quadrature parameter in the entire range of compared impedances [16].

Analysis of balance equations for autotransformer bridges

Let us analyze the equilibrium equation of the structure shown in Fig. 4, *a*. The compared impedances can be represented by both parallel ($G+jB$) and series ($R+jX$) equivalent circuits. The unit size of the impedance parameters can be transferred both from the object Z_1 and from the object Z_2.

Equilibrium equations for possible substitution schemes of compared objects when transferring from Z_1 to Z_2 are given in Table 1.

Equilibrium equations for possible substitution schemes of compared objects during transfer from Z_2 to Z_1 are given in Table 2.

Table 1

Equilibrium equation when transferring the size of the unit from Z_1 to Z_2

Substitution scheme		General balance equation
Z_1 series	Z_2 parallel	$G_2 + jB_2 = \frac{m_1}{m_2}\left(\frac{R_1 - KX_1}{\left(1+K^2\right)\left(R_1^2 + X_1^2\right)} - j\frac{KR_1 + X_1}{\left(1+K^2\right)\left(R_1^2 + X_1^2\right)}\right)$
	Z_2 series	$R_2 + jX_2 = \frac{m_2}{m_1}\left(j\left(X_1 + KR_1\right) - \left(KX_1 - R_1\right)\right)$
Z_1 parallel	Z_2 parallel	$G_2 + jB_2 = \frac{m_1}{m_2}\left(\frac{G_1 + KB_1}{1+K^2} + j\frac{B_1 - KG_1}{1+K^2}\right)$
	Z_2 series	$R_2 + jX_2 = \frac{m_2}{m_1}\left(\frac{G_1 + KB_1}{G_1^2 + B_1^2} + j\frac{KG_1 - B_1}{G_1^2 + B_1^2}\right)$

Table 2

Equilibrium equation when transferring the size of the unit from Z_2 to Z_1

Substitution scheme		General equilibrium equation
Z_2 series	Z_1 parallel	$R_1 + jX_1 = \frac{m_1}{m_2}\left(\frac{G_2 - KB_2}{\left(1+K_2\right)\left(G_2^2 + B_2^2\right)} - j\frac{B_2 + KG_2}{\left(1+K_2\right)\left(G_2^2 + B_2^2\right)}\right)$
	Z_1 series	$R_1 + jX_1 = \frac{m_1}{m_2}\left(\frac{R_2 + KX_2}{1+K_2} - j\frac{X_2 - KR_2}{1+K_2}\right)$
Z_2 parallel	Z_1 parallel	$G_1 + jB_1 = \frac{m_2}{m_1}\left(\left(G_2 - KB_2\right) + j\left(B_2 + KG_2\right)\right)$
	Z_1 series	$G_1 + jB_1 = \frac{m_2}{m_1}\left(\frac{R_2 + KX_2}{R_2^2 + X_2^2} - j\frac{X_2 - KR_2}{R_2^2 + X_2^2}\right)$

Similarly, let's analyze the equilibrium equation of the structure shown in Fig. 4, *b*. The compared impedances can be represented by both parallel and series equivalent circuits. The unit size of the impedance parameters can be transferred both from the object Z_1 and from the object Z_2.

The balance equation for possible substitution schemes of the compared objects when transferring from Z_1 to Z_2 is general and for the active and reactive components are given in the Table 3.

Equilibrium equations for possible equivalent circuits of compared objects during transfer from Z_2 to Z_1 are given in Table 4.

According to the analysis of the expressions given in Tables 1–4, it is obvious that the schemes in Fig. 4, *a* and Fig. 4, *b* can provide direct reading and constant sensitivity not for all substitution schemes of compared objects. In this regard, we shall analyze the expressions representing the result of measurement under the condition of small tangents of objects, which is characteristic when comparing reference measures.

Simple dependencies that provide a direct reading for the circuit in Fig. 4, *a*, are possible with the following substitution schemes when transferring the unit size provided that there are small tangents in the objects from which the transfer is carried out:

- from Z_1 with a series substitution scheme to Z_2 with a series equivalent circuit:

$$R_2 + jX_2 = \frac{m_2}{m_1}\left(jKR_1 - R_1\right); \qquad (7)$$

- from Z_1 with a parallel substitution scheme to Z_2 with a series equivalent circuit:

Table 3

Equilibrium equation when transferring the size of the unit from Z_1 to Z_2

Substitution scheme		General balance equation
Z_1 series	Z_2 parallel	$G_2 + jB_2 = \frac{R_1 m_1 + KX_1}{m_2\left(R_1^2 + B_1 X_1^2\right)} + j\frac{KR_1 - X_1 m_1}{m_2\left(R_1^2 + B_1 X_1^2\right)}$
	Z_2 series	$R_2 + jX_2 = \frac{m_2\left(R_1 m_1 + KX_1\right)}{m_1^2 + K^2} + j\frac{m_2\left(X_1 m_1 - KR_1\right)}{m_1^2 + K^2}$
Z_1 parallel	Z_2 parallel	$G_2 + jB_2 = \frac{G_1 m_1 - KB_1}{m_2} + j\frac{B_1 m_1 + KG_1}{m_2}$
	Z_2 series	$R_2 + jX_2 = \frac{m_2\left(G_1 m_1 - KB_1\right)}{\left(m_1^2 + K^2\right)\left(G_1^2 + B_1^2\right)} - j\frac{m_2\left(B_1 m_1 + KG_1\right)}{\left(m_1^2 + K^2\right)\left(G_1^2 + B_1^2\right)}$

Table 4

Equilibrium equation when transferring the size of the unit from Z_2 to Z_1

Substitution scheme		General balance equation
Z_2 series	Z_1 parallel	$R_1 + jX_1 = \frac{G_2\frac{m_1}{m_2} + KB_2}{G_2^2 + B_2^2} + j\frac{KG_2 - B_2\frac{m_1}{m_2}}{G_2^2 + B_2^2}$
	Z_1 series	$R_1 + jX_1 = R_2\frac{m_1}{m_2} - KX_2 + j\left(X_2\frac{m_1}{m_2} + KR_2\right)$
Z_2 parallel	Z_1 parallel	$G_1 + jB_1 = \frac{G_2\frac{m_1}{m_2} + KB_2}{\left(\frac{m_1}{m_2}\right)^2 + K^2} + j\frac{B_2\frac{m_1}{m_2} - KG_2}{\left(\frac{m_1}{m_2}\right)^2 + K^2}$
	Z_1 series	$G_1 + jB_1 = \frac{R_2\frac{m_1}{m_2} + KX_2}{\left(\left(\frac{m_1}{m_2}\right)^2 + K^2\right)\left(R_2^2 + X_2^2\right)} - j\frac{X_2\frac{m_1}{m_2} + KR_2}{\left(\left(\frac{m_1}{m_2}\right)^2 + K^2\right)\left(R_2^2 + X_2^2\right)}$

$$R_2 + jX_2 = \frac{m_2}{m_1}\left(\frac{1}{G_1} + j\frac{K}{G_1}\right); \tag{8}$$

- from Z_2 with a series substitution scheme to Z_1 with a parallel equivalent circuit:

$$G_1 + jB_1 = \frac{m_2}{m_1}\left(\frac{1}{R_2} - j\frac{K}{R_2}\right); \tag{9}$$

- from Z_2 with a parallel substitution scheme to Z_1 with a parallel equivalent circuit:

$$G_1 + jB_1 = \frac{m_2}{m_1}\left(G_2 + jKG_2\right). \tag{10}$$

Simple dependencies that provide a direct reading for the circuit in Fig. 4, *b* are possible with the following substitution schemes when transferring the size of the unit provided that there are small tangents in the objects from which the transfer is carried out:

- from Z_1 with a series substitution scheme to Z_2 with a parallel equivalent circuit:

$$G_2 + jB_2 = \frac{m_1}{m_2 R_1} + j\frac{K}{m_2 R_1}; \tag{11}$$

- from Z_1 with a parallel substitution scheme to Z_2 with a parallel equivalent circuit:

$$G_2 + jB_2 = \frac{G_1 m_1}{m_2} + j\frac{KG_1}{m_2}; \tag{12}$$

- from Z_2 with a series substitution scheme to Z_1 with a series equivalent circuit:

$$R_1 + jX_1 = R_2\frac{m_1}{m_2} + jKR_2; \tag{13}$$

- from Z_2 with a parallel substitution scheme to Z_1 with a series equivalent circuit:

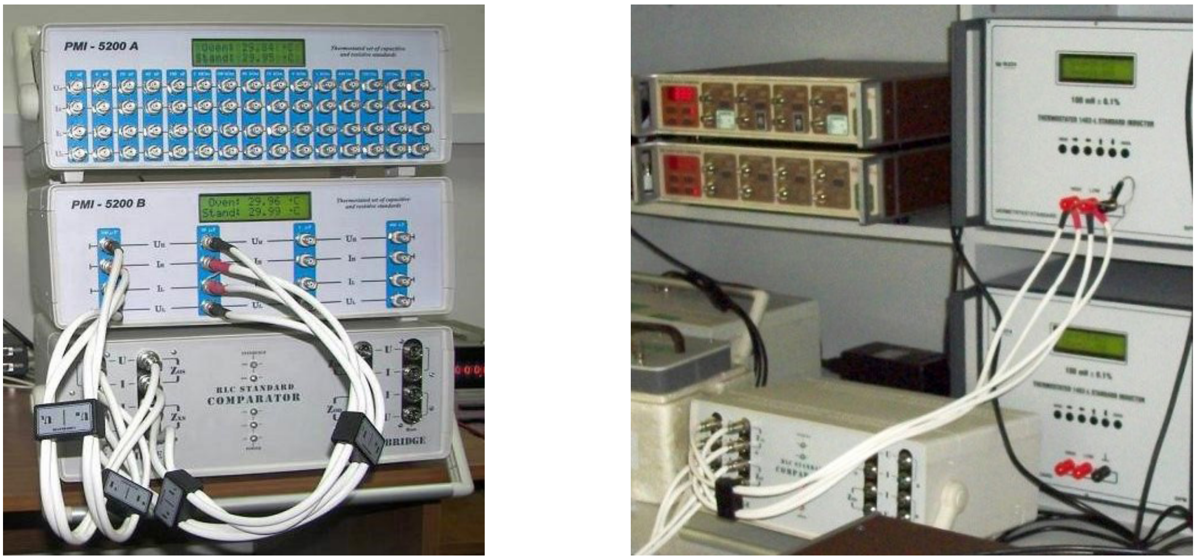
$$R_1 + jX_1 = \frac{m_1}{G_2 m_2} + j\frac{K}{G_2}. \tag{14}$$

Practical implementation of the autotransformer bridge-comparator

From the obtained theoretical results, it is clear that by choosing the appropriate direction of transmission, with a simple rearrangement of the measuring circuit, namely, changing the arm of the bridge to introduce a quadrature signal, it is possible to obtain a direct reading for the active and reactive components of the impedance. Thus, to establish a universal autotransformer-comparator bridge, the diagrams in Fig. 4, *a*, *b* shall be used, which makes it possible to compare two impedances both with the same and different equivalent circuits.

Based on the proposed solutions, a universal precision impedance comparator was developed. Experimental studies of the comparator carried out in the specified laboratories showed the following metrological characteristics of the developed universal comparator:

- zero offset of the comparator on the main measurement ranges is less than 0.5×10^{-6};
- decimal transmission error in the main ranges is less than 0.5×10^{-6};
- the sensitivity of the comparator is higher than 0.01×10^{-6};
- $C \to L$ transmission error is less than 10×10^{-6};
- the sensitivity of $C \to L$ transmission is higher than 0.1×10^{-6};
- zero offset of comparator $R \leftrightarrow C$ is less than 1×10^{-6};
- the sensitivity $R \leftrightarrow C$ of the comparator is higher than 0.05×10^{-6};
- operating frequencies are 1.0 kHz and 1.59 kHz;
- the smallest relative error of resistance measurement is 0.5×10^{-6} in the range from 100 Ω to 100 kΩ;
- the smallest relative error of capacitance measurement is 0.5×10^{-6} in the range from 10 nF to 100 pF;



a *b*

Fig. 5. Design of the impedance comparator

- the smallest relative inductance measurement error is 10×10^{-6} in the range from 10 mH to 1 H;
- impedance measurement range is from 10^{-7} Ohms to 10^{18} Ohms;
- the highest value of the voltage applied to high-resistance objects is 50 V;
- the maximum current through the low-resistance measuring object does not exceed 50 mA.

The weight of the comparator does not exceed 7 kg with the dimensions of 400×300×150 mm.

The impedance comparator as part of a complex of measuring equipment was delivered to the National Institute of Standards and Technologies (NIST) (Fig. 5, *a*) and to the Central Office of Measures of Poland (GUM) (Fig. 5, *b*). The State Primary Measurement Standard of Inductance Units and Loss Angle Tangent (DETU 08-09-09) was developed based on the universal precision impedance comparator (SE “UKRMETRTESTSTANDARD”).

Summary

The conducted theoretical analysis showed that in the process of comparison it is possible to compare impedances with different equivalent circuits with a direct reading of reactive and active parameters. By choosing the appropriate transmission direction, with a simple reconstruction of the measuring circuit, it is possible to compare two impedances with a parallel equivalent circuit, two impedances with a series equivalent circuit, or two impedances with a different equivalent circuit. The obtained results made it possible to implement them in a universal autotransformer-comparator bridge.

Дослідження автотрансформаторних мостів для вимірювання параметрів імпедансу

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Анотація

Аналіз існуючих методів вимірювання імпедансу показав, що для створення прецизійних компараторів, які працюють у широкому діапазоні значень у діапазоні звукових частот, оптимальним є використання трансформаторних і автотрансформаторних мостів. Автотрансформаторні мости застосовуються при вимірюваннях у широкому діапазоні значень імпедансів. Застосування автотрансформаторних мостів дозволяє знизити похибку вимірювань до 10^{-7}–10^{-9}.

Високі метрологічні характеристики трансформаторних мостових схем надають можливість використовувати їх у комерційних приладах і прецизійній вимірювальній апаратурі. Прості автотрансформаторні мости не надають можливості вимірювати параметри імпедансу в широкому діапазоні значень тангенсу кута втрат (фазового зсуву). Для синтезу вимірювальних кіл мостів та їх зрівноважування необхідно мати прецизійний квадратурний канал, який забезпечить високу точність коефіцієнта передачі як за фазою, так і за модулем.

Структури універсальних автотрансформаторних компараторів та їхні властивості визначаються двома основними факторами: способом формування джерела комплексного зрівноважувального сигналу і видом схем заміщення імпедансів порівнюваних об’єктів. Для визначення шляхів удосконалення універсальних прецизійних компараторів імпедансу на основі автотрансформаторних мостів необхідно розробити і проаналізувати математичні моделі універсальних компараторів.

Проведений теоретичний аналіз показав, що у процесі компарування можна порівнювати імпеданси з різною схемою заміщення при прямому відліку за реактивними та активними параметрами. Вибираючи відповідний напрям передач, при нескладній перебудові вимірювального кола можна порівнювати два імпеданси з паралельною схемою заміщення, два імпеданси з послідовною схемою заміщення або два імпеданси з різною схемою заміщення. Отримані результати дозволили їх впровадити в універсальному автотрансформаторному мості-компараторі.

Ключові слова: автотрансформаторний міст; імпеданс; квадратурний канал; схема заміщення; рівняння рівноваги.

References

1. Surdu M.N., Lameko A.L., Surdu D.M., Kursin S.N. An automatic precision system for the metrological backup of measurements of impedance parameters. Part 1. Operating principles. *Measurement Techniques*, 2012, vol. 55, no. 7, pp. 816–825. doi: 10.1007/s11018-012-0045-5
2. Kibble B.P., Rayner G.H. Coaxial AC Bridges. Bristol, Adam Hilger Ltd., 1984. 203 p.
3. Delahaye F. AC-bridges at BIMP, BNM-LCIE, 1998, pp. CI–C6.
4. Wood B., Cote M. AC Bridges for the R-C Chain. BNM-LCIE, 1998, pp. El–E20.
5. Silveira F. 2-Terminal Coaxial Capacitance Measurements and Cable Corrections. *arXiv*:2211.00757, 2022. doi: 10.48550/arXiv.2211.00757
6. Pimsut Y. et al. Development and implementation of an automated four-terminal-pair Josephson impedance bridge. *Metrologia*, 2024, vol. 61, no. 2, doi: 10.1088/1681-7575/ad2539
7. Kürten Ihlenfeld W.G., Vasconcellos R.T.B. A digital quadrature bridge for impedance measurements. *Proceedings of 29th Conference on Precision Electromagnetic Measurements (CPEM 2014)*, Rio de Janeiro, Brazil, 2014, pp. 106–107. doi: 10.1109/CPEM.2014.6898281
8. Kučera J., Kováč J. A reconfigurable four terminal-pair digitally assisted and fully digital impedance ratio bridge. *Proceedings of 2017 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, Turin, Italy, 2017, pp. 1–6. doi: 10.1109/I2MTC.2017.7969769
9. Musiol K. Experimental Study of Digitizers Used in High-Precision Impedance Measurements. *Energies*, 2022, vol. 15(11), 4051. doi: 10.3390/en15114051
10. Tran N. et al. Calibration of 10 nF capacitance standard from DC quantum Hall resistance using a digital impedance bridge. *Measurement Science and Technology*, 2023, vol. 34, no. 7. doi: 10.1088/1361-6501/acc6e2
11. Musiol K. et al. Experiences with a new sampling-based four-terminal-pair digital impedance bridge. *Measurement*, 2022, vol. 205, 112159. doi: 10.1016/j.measurement.2022.112159
12. Musiol K. et al. The Role and Importance of Digital Impedance Bridges in Contemporary Metrology. *Pomiary Automatyka Robotyka*, 2024, vol. 28(1), pp. 49–54. doi: 10.14313/PAR_251/49
13. Marzano M. et al. Primary Realization of Inductance and Capacitance Scales With a Fully Digital Bridge. *IEEE Transactions on Instrumentation and Measurement*, 2022, vol. 71, 1503008. doi: 10.1109/TIM.2022.3214498
14. Wang Y., Schlamminger S. A digital four-arm bridge for the comparison of resistance with capacitance. *Metrologia*, 2024, vol. 61, no. 5. doi: 10.1088/1681-7575/ad7590
15. Isaiev V. Metod vymiryuvannya kuta zsuvu faz mizh dvoma napruhamy za dopomohoyu pretsyziynoho vymiryuvacha zminnoyi napruhy [Method of measuring the angle of phase shift between two voltages using a precision meter of the voltage]. *Ukrainian Metrological Journal*, 2017, no. 2, pp 3–7 (in Ukrainian). doi: 10.24027/2306-7039.2.2017.109620
16. Kursin S.M. et al. Analiz struktur avtotransformatornykh mostiv dlya vymiryuvannya parametriv impedansu [Analysis of the structures of autotransformer bridges for measuring impedance parameters]. *All-Ukrainian science and technology conf. young scientists in the field of metrology "Technical Using of Measurement-2016"*, February 1–5, 2016: abstracts of reports. Kyiv, 2016, pp. 74–76 (in Ukrainian).