

Wide frequency range quadrature bridge comparator Pont – comparateur a quadrator por une large bande de frequences

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Abstract. The quadrature bridge for comparison of the impedance standards in wide frequency and dynamic range was developed. The digital phase inversion of the operating signal is the single internal standard of this bridge. Technically bridge is based on the digital synthesizers of the sinusoidal signals, which are used as sources of quadrature voltages, supplying the standards to be compared. The appropriate algorithm of measurement eliminates the influence of the synthesizer's uncertainty on the results of measurement. The bridge can compare the impedance of the standards on frequency range from units of Hz to units of kHz with uncertainty better than 1 ppm and resolution better than 0.03 ppm.

Le pont en quadrature a été élaboré pour comparer les impédances sur une large bande de fréquences et valeurs de l'impédance. Le seul étalon interne du pont est l'inversion numérique de phase du signal. Dans l'aspect technique, l'étalon est se base sur les synthétiseurs numériques des signaux sinusoïdaux, utilisés comme les alimentateurs des branches du pont. L'algorithme élaboré exclut complètement l'erreur des synthétiseurs sur le résultat de la comparaison des impédances des étalons comparés. Le pont peut comparer les étalons variant entre les unités Hz et les unités kilohertz avec l'erreur de moins de 1 ppm et sensibilité de plus de 0.03 ppm.

Key Words / Mots Clés. impedance, comparison, quadrature, uncertainty, standard, digital synthesis, frequency range, algorithm, uncertainty elimination.

1. Introduction

The quadrature impedance comparison has a great importance for the fundamental and applied investigations. The investigations in this area have been expanding quickly since the 1960s. [1]. Up to present day, the quadrature impedance comparison was mostly used in fundamental investigations to trace the unit of resistance from capacitance and vice versa. To provide these investigations, transformer quadrature bridges are usually used. The main world-renowned laboratories (BIPM, NIST, NML, NPL, PTB, VNIIM, etc) in developed countries have their own primary standards, based on the Calculable Capacitor and Quantum Hall Resistance [2-9] and very accurate quadrature bridges with original constructions [10-16] for their comparison.

Classic quadrature bridge practically consists of two interrelated bridges. These bridges need one pair of the capacitive standards and one pair of the resistive ones. To balance these bridges we need to control 6-8 inductive dividers. It complicates the automation of the quadrature bridge balancing procedure.

The project 2244, financially supported by EC and USA through STCU (Scientific and Technologic Center in Ukraine) (www.stcu.int) has been launched in 2002. Project was aimed to create a set of the accurate, automatic bridges-comparators and a set of thermostated intermediary standards for traceability and reproduction of impedance units.

2. Metrologic objectives of the project.

Project 2244 resulted in the creation of two automatic bridges-comparators and a set of intermediary standards, satisfying the following requirements:

4.1. The first comparator (autotransformer bridge) disseminates units of capacitance, resistance and inductance *over a large dynamic range* and reproduces the unit of inductance from capacitance and frequency over the inductive impedance range from 10 Ω to 1 M Ω . This comparator provides measurements with dissipation factor ($tg\delta_x$) and tangent phase angle ($tg\varphi_x = 1 / tg\delta_x$) over the range of 10^{-7} to $\pm(1-2)$. Its main uncertainty is better than of $0.5 \cdot 10^{-6}$ to $2 \cdot 10^{-6}$ and sensitivity is better than 10^{-8} [17].

4.2. The second comparator (quadrature bridge) provides C \leftrightarrow R transfer over *the relatively narrow impedance dynamic range* from 100 Ω to 100 k Ω with the standards, having $tg\delta_x$ or $tg\varphi_x$ close to zero (less than $(1-2) \cdot 10^{-4}$). Its main uncertainty is better than $1 \cdot 10^{-6}$ and sensitivity is better than $3 \cdot 10^{-8}$.

4.3. Both comparators perform measurements automatically on 1.59 kHz and 1 kHz, use shared modules and are placed in the same case of weight less than 7 kg.

4.4. The set of thermostated intermediate standards contains standards, having cardinal values of the parameter (capacitance, resistance, and inductance) and special intermediate standards for R \leftrightarrow C and C \rightarrow L

transfer at 1 kHz. The ratios of the impedance of last standards to the cardinal values is equal to 1:0.4. These standards are tested by unit dissemination using first comparator.

In this paper we describe the part of the results of this project, covering the development of the quadrature bridge-comparator

3. Principle of the bridge operation

To create the quadrature bridge we usually need three voltage generators G_1 , G_2 and G_3 , having voltages (U) , $(-U)$ and (jU) respectively. Due to the different errors sources we write the real voltages of these generators in the form:

$$U_1 = U_0, U_2 = jU_0 (1 + \delta U), U_3 = -U_0 (1 + \delta_i). \quad (1)$$

were: δU is the error of the voltage ratio of the generators G_1 and G_2 , δ_i is the error of the inverter transfer coefficient. To create two counterphase voltages U_1 and U_3 in classic quadrature bridges [1] very accurate transformer divider usually are used. These bridges practically consist of two bridges. Every such bridge contains one pair of R_1 - C_1 (R_2 - C_2) standards, one quadrature voltage source U_2 and common transformer divider. Both these bridges are simultaneously balanced. In the point of common bridges balance well known equation is valid:

$$\omega^2 R_1 R_2 C_1 C_2 = 1 \quad (2)$$

Due to great efforts of many investigators today accuracy of the best (but handling) quadrature bridges achieve units of ppb. Of course, their frequency range and accuracy in this range are restricted by used transformer dividers.

In PTB, INRIM and other laboratories since the end of 70s investigators provided works, aimed to create the quadrature bridges for unlike impedance comparison on the base of the digital polyphase generators (synthesizers) [18,19]. These perspective works are provided today as well [21,22,23]. Last years a lot of works are devoted to use the synthesizers based on the Josephson array, but this very accurate solution is too expensive for commercial devices.

During the project 2244 implementation we used results, mentioned above, and improved them by calibration procedures, based on variational method [24]. First experimental tests of the quadrature bridge, developed in the frame of this project, were provided in PTB in 2005. These results were shown in [25]; the theoretical basis of these bridges was published in [26].

New quadrature bridge use only two digital generators G_1 and G_2 , which generate the sinusoidal signals, having the same magnitude and shifted on 90° . The bridge compares impedances of one capacitive and one resistive standards.

Its simplified diagram is shown on Fig.1

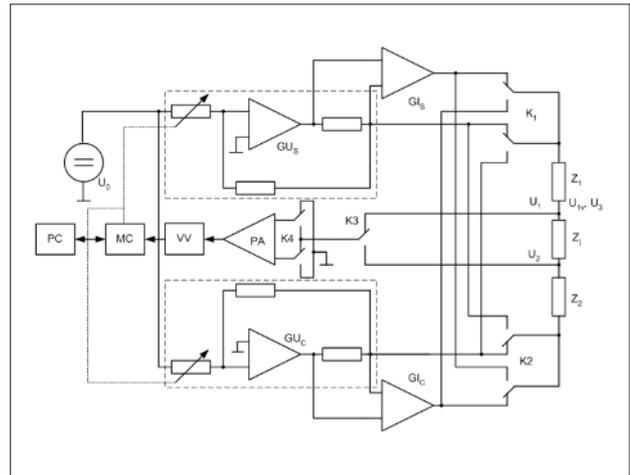


Fig.1. Simplified quadrature bridge diagram.

The bridge consists of two digital master voltage generators, GU_s and GU_c (DAC_s and DAC_c), supplied by the direct voltage standard U_0 . The slave current generators, $G1_s$ and $G1_c$, supply the standards to be compared. Two current sensors (two resistors r_s and r_c , connected in series with the outputs of the voltage generators and included into their feedback loops) create the input signals of these generators.

Master voltage generators GU_s generate quasi sinusoidal, digitally approximated signal. Master voltage generator GU_c generates quasi cosinusoidal signal. This signal can be digitally inverted or varied on the value δ_v (by its phase changing) using different memory pages.

Switchers K_1 and K_2 connect the standards to be compared to the outputs of the voltage and current generators. Separate parts of these switchers connect the potential ports of the standards to the voltage generator outputs and the current ports of the standards - to the current generator outputs. The vector voltmeter VV measures the unbalance signal. This voltmeter has conventional sensitivity better than 10^{-5} , nonlinearity – better than 10^{-4} and selectivity – better than 10^5 . Switcher K_3 connects the voltmeter input to the potential ports of the capacitive and resistive standards from the low potential side.

To get the value of the appropriate unbalance signal, MC , via the switcher K_4 , inverts the phase of the vector voltmeter input connection, so that the vector voltmeter VV measure the unbalance signal value twice. MC calculates the half-difference of these two results, so that the resulting unbalance signal doesn't depend on the possible inner VV interference.

All connections inside and outside the bridge are created using coaxial cables to ensure four pair terminal connection of the standards to be compared. Each of the current and voltage generators has a special supply source, consisting of a direct current generator and a voltage stabilizer. These supply systems divide the bridge voltage and current loops without using transformers (equalizers [27, 28]). The absence of the common currents between the voltage and current loops and the equality of the central wire and screen currents of each cable is tested by a special system (not shown on the Fig.1).

System software controls the whole process of comparison, processes the results of vector voltmeter measurements, and calculates measurement results.

The equivalent diagrams of the quadrature bridge on two stages of comparison are shown of Fig. 2a and Fig. 2b.

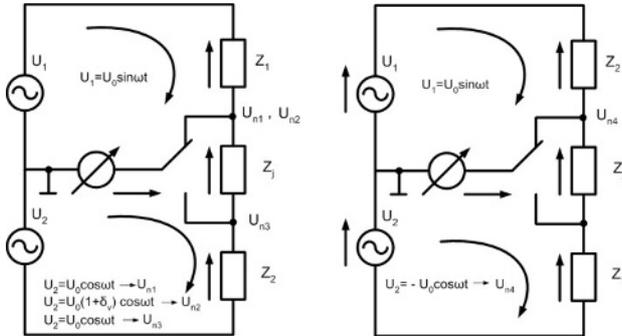


Fig.2. Quadrature bridge equivalent diagrams

Three main sources of the uncertainty influence on the result of measurement:

- ratio of two digital generators U_1/U_2 ;
- impedance of the connecting cables;
- instability of the bridge sensitivity.

To eliminate the influence of these uncertainty sources on the result of measurement we use the next approaches.

- Replacement method for unlike impedances on AC measurements [29] is used to eliminate the uncertainty δU of generators voltage ratio.
- Algorithm of two unbalance signal measurements and their processing is used to eliminate influence of the “joke” Z_j [30, 31].
- Variational method of the unbalance signal measurements [24] and processing is used to eliminate instability of the long-term bridge sensitivity.

Quadrature bridge operates by following algorithm:

1. The vector voltmeter VV measures the quadrature components of the unbalance signal U_{n1} in initial bridge state (see the Fig.2a).
2. Controlling system varies the magnitude or phase of one of the voltage generators on the well known value δ_v (it is preferable to change the phase of the generator GU_c voltage). The vector voltmeter VV measures the unbalance voltage U_{n2} .
3. Controlling system changes the state of the switcher K_3 and the vector voltmeter VV measures the new unbalance signal U_{n3} .
4. Controlling system changes the state of the switchers K_1 and K_2 , digitally inverts the phase of the generator GU_c on opposite (see the Fig.2b) and the vector voltmeter VV measures the new unbalance signal U_{n4} .

All this results of measurement are described by the next system of equations

$$\begin{aligned} U_0 - \frac{U_0 - jU_0(1+\delta U)}{Z_R + Z_j + Z_C} Z_R &= U_{n1}; \\ U_0 - \frac{U_0 - jU_0(1+\delta U + \delta_v)}{Z_R + Z_j + Z_C} Z_R &= U_{n2}; \\ U_0 - \frac{U_0 - jU_0(1+\delta U)}{Z_R + Z_j + Z_C} (Z_R + Z_j) &= U_{n3}; \\ U_0 - \frac{U_0 + jU_0(1+\delta U)}{Z_R + Z_j + Z_C} Z_C &= U_{n4}. \end{aligned} \quad (3)$$

where U_0 is the magnitude of the voltage generators, Z_R and Z_C are the impedances of the resistive and capacitive standards.

System solves the system of equation (3) accurately and finds the ratio of standards to be compared.

To analyze the influence of different factors on the result of measurement it is preferable to get the analytical solution of the system of equations (3). Such approximate solution is given by formula below:

$$\delta Z \approx -\frac{j\delta_v}{2} \left[\frac{(U_{n4} - jU_{n1}) - (U_{n3} - U_{n1})}{U_{n2} - U_{n1}} \right] \quad (4)$$

Formula (4) gets the result of comparison with uncertainty better than 10^{-7} if $\delta U \leq \delta U_{\max} = 3 \cdot 10^{-4}$, $Z_j/Z_2 \leq 3 \cdot 10^{-4}$ and $\delta Z \leq \delta Z_{\max} = 3 \cdot 10^{-4}$. It brings possibility to analyze the influence of all main factors on the result of measurement.

Formula (4) shows that the result of impedance ratio measurement depends on three differences: $(U_{n4} - U_{n1})$, $(U_{n3} - jU_{n1})$ and $U_{n2} - U_{n1}$ and variation δ_v .

4. Analysis of uncertainty sources

4.1. Difference $(U_{n4} - U_{n1})$

Difference $(U_{n4} - U_{n1})$ is proportional to the deflection δU of the generators voltages ratio from nominal value j . Usually δU doesn't exceed $(1-2)10^{-4}$ in frequency range up to units of kHz. The calculation by formula (4) eliminates the influence of this deflection on the result of measurement, but doesn't eliminate the instability of this ratio during measurement process.

Instability of the generated voltages depends on two factors: instability of the used OpAmp gain and temperature instability of the used DAC.

To decrease the influence of the OpAmp gain on the voltage instability, voltage generators have two-channel iterative structure (see Fig.3).

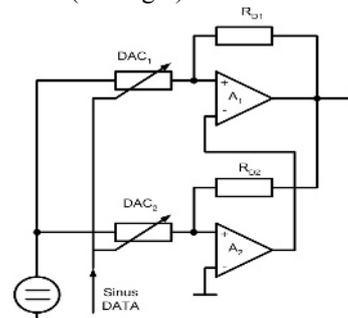


Fig.3. Generator's iterative structure.

First channel consists of OpAmp A_1 and DAC₁. This channel generates main part of the signal. The DAC₂ of the second channel forms the low signal, proportional to the error of the first channel and, through OpAmp A_2 , add it to the positive input of first channel. In this structure uncertainty, caused by limited values of the amplifiers gains can be estimated by formula $\delta_g = \frac{1}{(K_1\beta_1)(K_2\beta_2)}$, where $(K_1\beta_1)$ and $(K_2\beta_2)$ are open loop gains of the first and second channels. Let we will suppose that these values are the same for both channels and doesn't exceed 0.02%. In this case δ_g doesn't exceed $4 \cdot 10^{-8}$ and its short term instability during measurement process doesn't exceed units of 10^{-9} .

We use in both voltage generators DAC with temperature coefficient better than 2 ppm/°C. To decrease the DAC temperature instability on the result of comparison, the DAC of the second channels are set into passive thermostat, so that DAC temperature instability during the measurement process (less than 20-30 sec.) doesn't exceed 0.001-0.002 °C. In such way the generators voltage instability during the measurement doesn't exceed 5-10 ppb.

4.2. Difference ($U_{n3} - U_{n1}$)

Difference ($U_{n3} - jU_{n1}$) is proportional to the ratio Z_j/Z_R . The calculation by formula (4) eliminates the influence of this ratio on the result of measurement and ensures four terminal connection of the impedances to be compared in low potential part of comparator. But the calculation doesn't eliminate instability of the ratio Z_j/Z_R during the measurements. Usually $Z_j \leq 0.1$ Ohm (copper). Lowest impedance to be compared is 100 Ohm. Let the cable temperature instability during the measurement doesn't exceed 0.01°C. Taking into account that copper temperature coefficient is $4 \cdot 10^{-3}$, uncertainty achieves $4 \cdot 10^{-8}$ on the lowest point (100 Ohm) of the impedance range of measurement.

4.3. Difference $U_{n2} - U_{n1}$

Difference $U_{n2} - U_{n1}$ is proportional to the variation δ_v . Variation δ_v of the GU_c voltage is performed through digital phase variation on $\Delta\phi_v$. Uncertainty of this variation is negligible and is restricted by the phase noise only.

4.4. Influence of the vector voltmeter accuracy

Analysis of the formula (4) shows that multiplicative and additive parts of the VV uncertainty doesn't influence on the result of measurement. So that only VV noise and VV nonlinearity have to be taken into account.

Let we will describe the VV noise ΔU_{sn} and measured unbalance signals U_{ni} as follow:

$$\Delta U_{sn} = a_{sn} + b_{sn}; U_{ni} = a_i + jb_i;$$

where a_{sn} and b_{sn} are the quadrature components of the VV input noise, a_i and b_i are the quadrature components of the measured signals.

To get best accuracy, the magnitude of the variation has to satisfy inequality $\delta Z_{max} \leq \delta_v$ and the VV dynamic range U_m has to be fully used ($U_m/2 \geq U_{n2} - U_{n1} \geq U_{ni}$). Suppose that $a_{sn} = b_{sn}$. Using these values, named assumptions and formula (4) we get approximate formulas to estimate the measurement uncertainty, caused by the input noise of the vector voltmeter:

$$\Delta(\delta Z)_n \approx 2\sqrt{2} \frac{(\sqrt{3}+j)a_{sn}}{U_m}; \delta(\delta Z)_n \approx 2\sqrt{2} \frac{(1+j)a_{sn}}{U_m}. \quad (5)$$

Here $\Delta(\delta Z)_a$ and $\Delta(\delta Z)_n$ are the additive and $\delta(\delta Z)_a$ and $\delta(\delta Z)_n$ are the multiplicative components of the measurement uncertainty, caused by noise.

Formulas (5) show that uncertainty caused by voltmeter input noise can be almost three times bigger than the voltmeter conventional uncertainty a_{sn}/U_m (this value for our voltmeter doesn't exceed 10^{-5}). Because of it

uncertainty of the impedance comparison caused by voltmeter noise doesn't exceed $3 \cdot 10^{-8}$.

4.5. Four terminal connection

To obtain four terminal connection in high potential part of the bridge we use the system of the master voltage generator and the slave current generator, shown on Fig.4

The slave current generator and the master voltage generator outputs are connected to the high potential current and potential ports of the standard. Input of the slave current generator is connected to current sensor (resistors $R_{c(s)}$). Current sensor enters into the feedback loop of the voltage generator. Every current generator generates the current I_D , which flows through impedances to be compared. The ratio of the residual current ΔI_v , which flows through the output of the voltage generator, to the current I_D is equal to: $\frac{\Delta I_v}{I_D} = R_{c(s)} Y_{c(s)}$, where $R_{c(s)} Y_{c(s)}$ is current generator's GI open loop gain and $Y_{c(s)}$ is OpAmp A_1 and U/I converter transfer admittance.

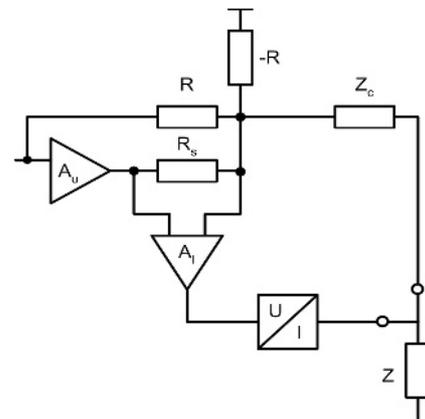


Fig.4. Four terminal connection

Assume cable impedance of $Z_c=0.1$ Ohm and the current generator's GI open loop gain $R_c Y_c=10^4$ at upper frequency range. In this case uncertainty $\delta_{uc(s)}$, caused by cable impedance $Z_{c(s)}$ described by formula $\delta_{uc} = \frac{Z_c}{Z_c R_c Y_c}$ will not exceed 10^{-7} for standard impedance $Z=100$ Ohm. Negative resistor $-R$ on Fig. 4 compensates the current, which is created by DAC feedback resistor R .

4.6. Four pair terminal connection

To get accurate impedance measurement and to exclude interferences, the currents, which flow through the central wire and screen of any connecting cable of measuring circuit has to be equal and has to have opposite direction [27, 28, 32].

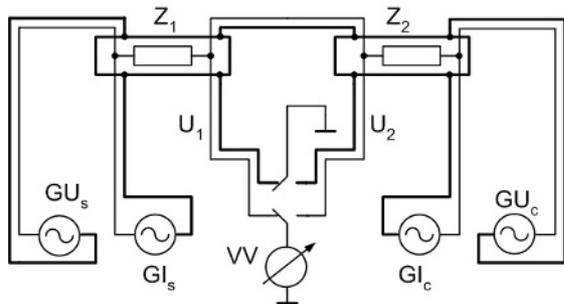


Fig.5 Four pair terminal connection

To achieve in wide frequency range equality of the direct and back currents in the cables, which connect current GI and voltage GU generators with standards to be compared, in every of these units we use the special supply, which consists of pair of DC current generators and voltage stabilizers. In this case the screens of all cables are connected in appropriate points, as it is shown on Fig 5.

To measure correctly the unbalance signals the vector voltmeter is connected to the appropriate measuring circuit outputs and appropriate cable screen is grounded. In this case equivalent circuits (Fig.2) correctly describe the measuring circuit (voltage drops between appropriate standard case and appropriate voltage generator ground is equal to zero). Equality of the currents in the cable centrals wire and screens we test using classical methods in higher part of the frequency range, where this question is most important. Tests have shown that relative inequality of currents in any cable doesn't exceeds $(1-2)10^{-4}$. Typically it decreases minimum uncertainty of measurement to units of ppb on upper frequency range.

4.7. Influence of the signal upper harmonics

The quadrature bridge compare unlike impedances, which in different ways depend on the frequency. The voltage generators contain not only operating frequency but also its higher harmonics. Because of it unbalance signal contains great level of higher harmonics, which create interference and lead to appropriate uncertainty. If generator voltage have relative harmonics level δ_{gf} and vector voltmeter have relative selectivity δ_{vf} estimated uncertainty δ_f will not exceed $\delta_f = \delta_{gf}\delta_{vf}$. Quadrature bridge uses vector voltmeter with δ_{vf} lower than $(3-4)\cdot 10^{-5}$. Voltage generators have $\delta_{gf} < 10^{-4}$. Therefore uncertainty satisfies $\delta_f < (3-4)10^{-9}$.

4.8. Influence of the digital phase inversion

To get bridge balance in both configurations – when resistive standard is connected to GU_s and capacitive standard is connected to GU_c or vice versa, we digitally reverse the phase of the generator GU_c . Accuracy of the digital phase reverse is restricted by phase noise only. This factor at highest frequencies of frequency range (units of kHz) doesn't exceed 10^{-9} .

4. Conclusion

The developed automatic quadrature bridge potentially can compare impedances in wide frequency

range. Upper frequency is limited mainly, by speed of used DAC and OpAmp and today is limited at units of kHz. Lower frequency of the frequency range is limited by time of measurement only. Uncertainty of measurement (as show uncertainty analysis) could be decreased to some parts of 10^{-8} . Experimental investigations, provided in PTB, have shown the difference in $C \rightarrow R$ transfer lower than 0.4 ppm.

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