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PECULIARITIES OF THE ACCURATE AC PHASE CONTROLLED BRIDGE REALIZATION (ОСОБЕННОСТИ ПОСТРОЕНИЯ ПРЕЦИЗИОННЫХ МОСТОВ ПЕРЕМЕННОГО ТОКА С ФАЗОВЫМ РЕГУЛИРОВАНИЕМ)

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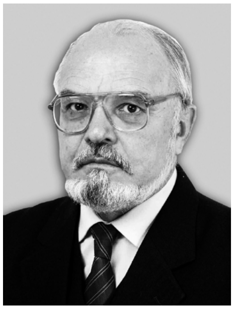

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Рассматривается новый метод построения мостов переменного тока, в которых используются делители напряжения с фазовым управлением, основанные на синтезе сигнала с регулируемой амплитудой посредством суммирования сигналов с регулируемой фазой.

The new method of building of AC bridges, in which phase-controlled voltage dividers are used, based on the synthesis of a signal with a controlled amplitude by summing signals with a controlled phase.

Introduction

Transformer bridges are widely used for impedance measurements on audio frequencies in the range of uncertainties from 10^{-3} to 10^{-7} or less.

Main metrologic laboratories use simple [1–3] or quadrature [4,5] transformer bridges for impedance measurement with uncertainty better than 10^{-6}–10^{-8} on audio frequency range. These bridges have a long history and are described in a lot of publications. In spite of high dimension and cost, transformer bridges have no competitors in this uncertainty area.

During last decades developers sufficiently improved methods of the impedance measurement, based on the digital signal synthesis, synchronous sampling systems, autobalance bridges [6–9]. These devises now measure impedance in frequency range from 10 Hz to 30 MHz with uncertainty up to 0.01 % [7,9] or less and practically extruded transformer bridges from this area.

In the area of uncertainty 10^{-4}–10^{-6} on audio frequencies transformer bridges remain practically single solution. Such bridges contain, as main part, some (2–6 or more) precision transformer dividers. It leads to big dimensions, narrow frequency range and high cost of the devices. These disadvantages sharply increase on the lower frequencies and make impossible creation of the transformer bridges for very low frequencies. But devises for measurement in this uncertainty area are very important for metrology, for electrical components measurements, for accurate temperature measurements [10] and other nonelectric quantities using, for example, capacitive [11] or other sensors etc. The devise cost and dimension in this case are critical for successful marketing and sale. This is the reason why replacing of the inductive divider in impedance measurements by another device could be very useful.

Phase controlled voltage divider

The fig. 1 shows on the plane of complex numbers (1, j) basic signal (vector U_0), which coincide with real axis and two additional vectors U_{11} and U_{21}. The bisectrix, divides in half angle between vectors U_{11} and U_{21}. This bisectrix is turned relatively real axis on the angle φ. Basic and additional signals (vectors U_0, U_{11} and U_{21}) could have different magnitudes $|U_{11}|$, $|U_{21}|$ and phases Ψ_{11} and Ψ_{21} between them and bisectrix, but it is preferable to use the signals, satisfying to the equality:

$$|U_0| = |U_{11}| = |U_{21}|; \quad \Psi_{11} = -\Psi_{21}. \tag{1}$$

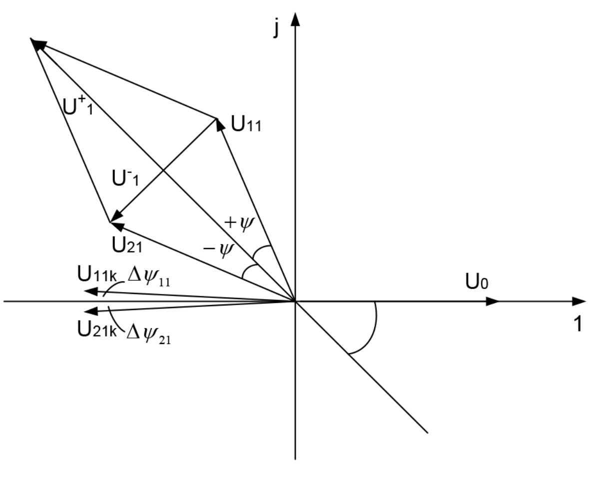

Fig. 1. Phase control vector diagram

Let's sum or subtract additional vectors U_{11} and U_{21}. Equations (2) and (3) describe the total balancing vectors U_1^+ or U_1^-:

$$U_1^+ = 2|U_0|\cos\psi \cdot \sin(\omega t + \varphi) = \rho_c e^{-j\varphi}. \qquad (2)$$

$$U_1^- = 2|U_0|\sin\psi \cdot \sin(\omega t + \varphi) = \rho_s e^{-j(\varphi+\pi/2)}. \qquad (3)$$

Let's change the angles Ψ_{11} and Ψ_{21} simultaneously from zero to the same current value $|\Psi|$. The equations (2) and (3) show that in both the cases, we change the magnitude of the blancing signal U_1 by controlling of the phases Ψ_{11} and Ψ_{21} only. The magnitude of the signal U_1 can be changed in the range from 0 to $\pm\, 2U_0$. Its phase can be changed in the range from 0 to $\pm$ 180º.

Using the signals U_0 and U_1 we can create universal balanced bridges for measurements of any type of impedances. Such bridge will be balanced by changing of the signals phases only. This approach was proposed in [12]. It should be noted that control of the electromagnetic field magnitude by phase control is widely used on high frequencies in radio-instruments for astronomic observations, in ground-based and airplane radar systems, etc [13,14], but not for accurate impedance measurements.

Signals U_0, U_{11} and U_{21} could be easily created using modern digital technique — by synthesis circuit (synthesizers). This technique was developed, for example, in [15].

Synthesizers in audio frequency range have rather big uncertainty of the DC/AC conversion- usually around 10^{-4} or worse. But synthesizer could have rather good short term (during one measurement — one minute or less) stability of its parameters.

Let's determine and eliminate the initial difference of the vectors $U_{11}/\,U_0$ and U_{21}/U_0 ratios from the nominal values. In this case only short term instability of these ratios and accuracy in phase changing of the vectors U_{11} and U_{21} will influence on uncertainty of measurement (We do not consider here many other uncertainty sources, specific for impedance measurements).

Using proper components and structures, temperature stabilization, etc. we can reduce synthesizer short term instability to value of 10^{-7}–10^{-8} or less. Accuracy of the phase changing is limited by synthesizer phase noise only. On audio and lower frequencies, this value is lower than 10^{-9}. It opens up possibilities to develop accurate bridges for impedance measurements.

Bridge balance procedure

Let's consider the simplest bridge with current comparison, based on the phase control and shown on figure 2. Bridge consists of three synthesizers — S_0, S_{11} and S_{21}, which are supplied by standard DC source U_{DC}. Synthesizers generate the sinusoidal voltages U_0, U_{11} and U_{21}. The adder Σ sums the voltages U_{11} and U_{21} and creates the balancing voltage U_1.

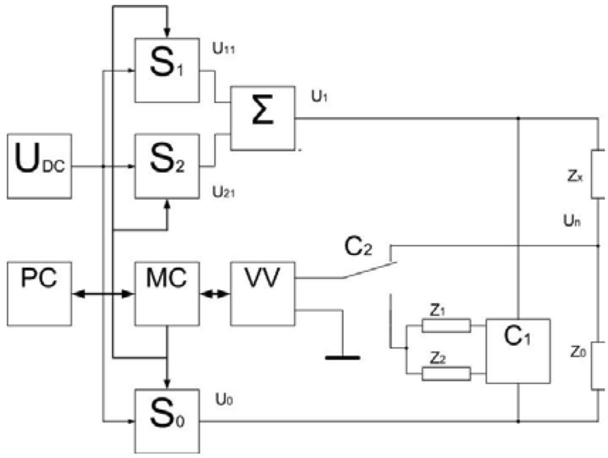

Fig. 2. High impedance bridge with phase controlled balance

The high potential ports of the standards being compared, Z_x and Z_0, are connected to the voltage sources U_1 and U_0. Low potential ports of these standards are connected together and through the switcher C_2, to the input of the vector voltmeter VV. Last one measures bridge unbalance signal and transfers results of measurements to microcontroller MC (or PC). MC processes results of vector voltmeter measurement and balances the bridge by appropriate algorithm. MC also controls the operation of all synthesizers and their output signals phase change.

To balance the bridge we use variation method [16]. Let's consider specific feature of this method for phase controlled bridges. Equation (4) describes the balance condition of the bridge:

$$\frac{z_x}{z_0} = \frac{U_{1b}}{U_{0b}} = (2\cos\psi_b)\cdot e^{-j\varphi_b}, \qquad (4)$$

where: U_{1b}, U_{0b}, ψ_b, φ_b are the values of the voltages U_1 and U_0 and their phases at the point of the bridge balance.

We can get direct reading, if we will describe ratios Z_x/Z_0 and U_{1b}/U_{0b} as follow:

$$\frac{Z_x}{Z_0} = \rho_x e^{-j\varphi_x}; \quad \frac{U_{1b}}{U_{0b}} = \rho_b e^{-j\varphi_b}.$$

In this case the balancing equation (4) divides into two simplest ones:

$$p_x = p_b = 2\cos\psi_b \text{ and } \varphi_x = \varphi_b\,. \qquad (5)$$

In this case we measure the initial bridge unbalance signal U_{n1} first. After that we provide the variation of the bridge balancing parameters, (the angles ψ or φ), and measure the new unbalance signal U_{n2}. For certainty check, let's change the angle ψ, adding variation $\Delta\psi_v$ (change of the U_{n1} magnitude ρ by $\Delta\rho_v$). Following system of equations describes this process:

$$\left[(\rho)\right]_x e^{-j\varphi_x} - \rho e^{-j\varphi})U_0 = \frac{U_{n1}(Z_x + Z_0)}{Z_0};$$

$$\left[(\rho)\right]_x e^{-j\varphi_x} - (\rho + \left[\Delta\rho_v)e\right]^{-j\varphi})U_0 = \frac{U_{n2}(Z_x + Z_0)}{Z_0}. \qquad (6)$$

Using Euler transformations for exponential functions from (6) we get formulas to calculate the distance δρ and Δφ between the current bridge point (ψ, φ) and the point of the bridge balance (ψ_b, φ_b):

$$\delta\rho = -1 + \sqrt{1 + \mathrm{B}} \approx \delta_v |\mathrm{A}| \cos\varphi_a;$$

$$\sin\Delta\varphi = -\delta_v |\mathrm{A}| (1 + \delta\rho) \sin\varphi_a. \qquad (7)$$

where:

$$\mathrm{B} = 2\delta_v \frac{|\mathrm{A}| \cdot \cos\varphi_a}{1 - 2\delta_v |\mathrm{A}| (\cos[\varphi_a - \frac{|\mathrm{A}|\delta_v}{2})]} = \approx 2\delta_v |\mathrm{A}| \cos\varphi_a;$$

$$\mathrm{A} = \frac{U_{n1}}{U_{n2} - U_{n1}} = \left|\frac{U_{n1}}{U_{n2} - U_{n1}}\right| e^{-j\varphi_a} = |\mathrm{A}| e^{-j\varphi_a}$$

and

$$\Delta\rho_v = \frac{\cos(\psi + \Delta\psi_v)}{\cos\psi} - 1 \approx -tg\psi \sin\Delta\psi_v.$$

Using (7) we calculate the coordinates ψ_b and φ_b, set them in the synthesizers S_1 and S_2 and achieve the bridge balance.

Two main factors determine the uncertainty δ_b of the bridge balance:

- Uncertainty δ_{vv} of the VV measurement (its relative nonlinearity and sensitivity) which could vary from 10^{-5} to 10^{-4}.
- Relative discreteness δ_d of the phase control.

Discreteness δ_d depends on the number of the steps on the period of the signal (accuracy of signal approximation). It usually lies in the range from 10^{-5} to 10^{-3} or more. Such balance discreteness is the peculiar property of the phase control.

This uncertainty of the bridge balance is too large. Because of it, the balance procedure in our case consists of two steps:

1. *On the first step* the variation δ_v is large. It could represent, for example, the change of the balancing voltage U_1 from 0 to its maximal value. The VV provides two measurements before and after the variation with minimal sensitivity S_{min}, and transfer these data to MC. Last one calculates values δρ and Δφ, set these results in synthesizers S_{11} and S_{21} and change the voltage U_1 to its balancing value U_{1b}. If the uncertainty of the VV measurement is $\delta_{vv} \leq \delta_d / 2$, the uncertainty δ_b of the bridge unbalance will have, practically, the value δ_d

2. *On the second step* MC increases the sensitivity S_{vv} of the VV to the value and varies the voltage U_1 by the one unit δ_d of its discreteness. VV measures again two unbalance signal as earlier. MC calculates by formulas (7) the new δρ and Δφ values. PC digitally add these date to the data, written on the first step in synthesizers S_{11} and S_{21} and uses these summed data to calculate the real value of the ratio Z_x/Z_0. The uncertainty δ_{be} of such equivalent bridge balancing and calculation of the ratio Z_x/Z_0 does not exceed $\delta_{be} \leq 2\delta_d\delta_{vv}$

Let's assume that the δ_d is less than and the δ_{vv} is less than $1{\cdot}10^{-4}$. In this case the δ_{be} is less than $2{\cdot}10^{-8}$.

Bridge calibration procedure

The shown above uncertainty, does not take into account the synthesizers uncertainty. Synthesizer uncertainty can achieve (depends on the used DAC) values 10^{-3}—10^{-4}. To eliminate this uncertainty we provide bridge calibration.

Let's perform balance equation. Additional signals U_{11} and U_{21} could be described by formulas:

$$U_{11} = U_{11n} + \Delta U_{11} = U_{11n}(1 + \delta_{11})$$

and

$$U_{21} = U_{21n} + \Delta U_{21} = U_{21n}(1 + \delta_{21}).$$

These signals have nominal values U_{11n} and U_{21n} and constant relative deviations δ_{11} and δ_{21} from nominal value. Using these formulas we could rewrite balance equation (4) into following equivalent form:

$$\frac{Z_x}{Z_0} = \frac{U_{11n}}{U_0}(1 + \delta_{11}) + \frac{U_{21n}}{U_0} = (1 + \delta_{21}). \qquad (8)$$

Bridge calibration have to eliminate deviations δ_{11} and δ_{21}. One possible automatic calibration procedure was described in detail in [12]. In compliance with this procedure VV measures initial unbalance signal of the calibration divider (impedances Z_1 and Z_2), connected between voltage sources U_0 and U_1 through switcher C_1. After it switcher C_1 replaces connection of the calibration divider (see Fig. 2). VV measures new unbalance signal. Finally, we vary on well known value voltage U_1, measure last unbalance signal, provide appropriate calculations and get deviations δ_{11} and δ_{21}. To correct the result of the ratio Z_x/Z_0 measurement, the voltage ratios U_{11n}/U_0 and U_{21n}/U_0 have to be divided by $(1 + \delta_{11})$ and $(1 + \delta_{21})$ accordingly (see formula (8)).

Residual uncertainty of measurement after the calibration procedure depends on the short time instability of the synthesizers and adder. Last ones depend on instability of the gain of used amplifiers (instability of the system statism) and the temperature instability of the DAC and resistive standards.

To decrease influence of the gain instability we use iterative structures for both synthesizers and adder (see Fig. 3).

Simplified diagram of every synthesizer consists of rough channel ($DAC_{1(2)r}$), its feedback resistor $R_{1(2)r}$ and amplifier $A_{1(2)r}$) and accurate channel ($DAC_{1(2)a}$, its feedback resistor $R_{1(2)a}$ and amplifier $A_{1(2)a}$). Rough channel creates main part of the synthesizers signal. $DAC_{1(2)a}$ of the accurate channel is connected in parallel to the

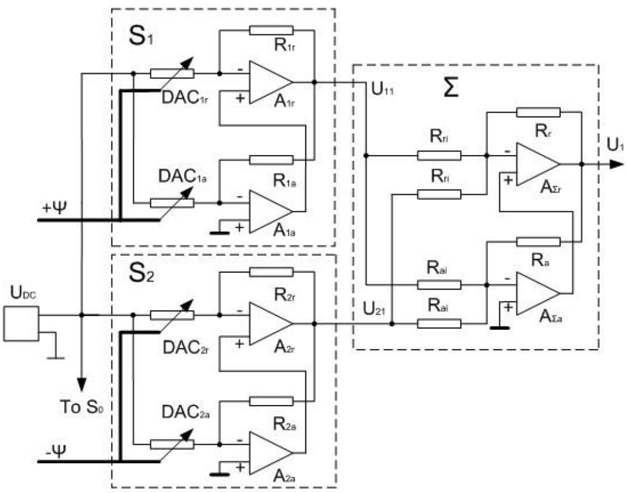

Fig. 3. Structure of the phase controlled voltage source U_1

rough channel, so that the signal, proportional to the uncertainty of the rough channel, acts on the output of this DAC. Amplifier $A_{1(2)a}$ gains this signal, adds it to the signal of the rough channel and in this way compensates its uncertainty. If the feedback gain in every channel is 10^4 (real value up to units of kHz), the equivalent feedback gain of the iterative structure exceed 10^8. The statism uncertainty of the iterative structure in this case doesn't exceed 10^{-8} and its short term instability in the temperature range ± 1 °C is lower than 10^{-9}.

Adder Σ consists of rough channel (resistors R_{ri}, feedback resistor R_r and amplifier $A_{\Sigma r}$) and accurate channel (resistors R_{ai}, feedback resistor R_a and amplifier $A_{\Sigma\alpha}$). Rough channel creates main part of the adder signal. Resistive divider (resistors R_{ai} and R_a) of the accurate channel is connected in parallel to the rough channel, so that the signal, proportional to the uncertainty of the rough channel, acts on the input of this divider. Amplifier $A_{\Sigma\alpha}$ gains this signal, and adds it to the signal of the rough channel. The statism uncertainty of the adder in this case also doesn't exceed 10^{-8}.

Iterative structure practically eliminates influence of the gain of used amplifiers on the synthesizers and adder stability. But heating influences on the $DAC_{1(2)a}$ and adder resistive standards stability. To decrease this effect we use DACs and VISHIY resistors with low temperature coefficients (better than 10^{-6}/°C). DACs and resistors dissipate all the time the constant power and have the constant self-heating. They are set in the passive thermostat with temperature instability better than 0.01 °C during the measurement. Because of it the drift of the DACs and resistors during the measurement is negligible (lower than 10^{-8}). Adder feedback resistors R_r and R_a operate in wide range of the dissipated power (practically, from 100 uWatt to 10 mWatt). Because of it self-heating changes the temperature and value of these resistors and in such way create inertial adder nonlinearity. To eliminate this effect we use for R_a “Megatron” resistors with temperature coefficient (1–3) ppm and high power-dissipation capability (up to 10 Watt). This resistor is set on the heat sink which dissipates applied power and acts as passive thermostat as well.

Bridge four pair terminal connection

Bridge, described above, accurately measures ratio of high impedance standards with two (three) terminal connections. For lower impedance measurements, bridge has to measure impedances using four terminal connections. Structure of the bridge with phase control balance and four terminal connections was described in detail in [17]. For accurate impedance measurement, with uncertainty, lower than units of ppm, on *AC* we have to perform bridge with described above four terminal connection into bridge with four *pair* terminal connection of the standards being compared [3,4]. In accordance to this connection, the currents, which flow through central wire and screen of any connecting cable of measuring circuit, have to have the same value and to flow in opposite directions [3]. Figure 4A shows the measuring circuit with phase control and four pair connection.

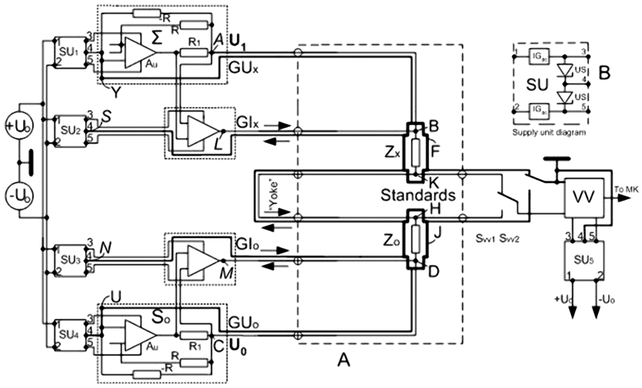

Fig. 4. Four pair terminal bridge diagram (without correction divider)

Measuring circuit consists of two voltage generators GU_x and GU_o and two current generators GI_x and GI_o which supply serially connected standards Z_x and Z_0.

Voltage generators GU_x and GU_o represent output stages of the adder Σ and synthesizer S_o (OpAmps A_u with feedback resistors R (see Figure 2 and 3). The current sensor R_1 is serially connected with output of the voltage generator's amplifiers A_u. Feedback current which flows through the feedback resistor R do not flows though the current sensor R_1 due to the negative resistor — R, connected to the output of the voltage generator. Negative resistor can be realized in different well known ways. Here it is realized using simple transistor superpair with equivalent gain, higher than 10^4. Supply units SU_1 and SU_4 supply voltage generators GU_x and GU_o correspondingly.

Every current generator GI_x and GI_o represents the voltage /current converter with input, connected to the current sensor R_1. Due to the feedback through central wires of the current and potential cables the operating current flows through the current cable (section L-B) and does not flow through the voltage cable (section A-B). Supply units SU_2 and SU_3 supply current generators GI_x and GI_o correspondingly.

Vector voltmeter VV measures appropriate unbalance signals. To eliminate influence of the impedance of both central wire and screen of the "Yoke" cable on the result of measurement, switcher S_{vv}, through the screen of the low voltage potential cables, grounds appropriate cases F or J of the standards Z_x and Z_o and connects the VV input to the points *K* or *H* correspondingly. Algorithm, described in [17], let us to calculate the accurate result of impedance measurement on the base of VV measurements. Supply unit US_5 supply the vector voltmeter VV.

Request for four pair terminal connections in the bridge shown on figure 4, would be satisfied, if all current generators, voltage generators and vector voltmeter would have fully separated supply sources and the measurement circuit will be grounded in one point only. Usually the same source supplies all generators, so that all generators have common ground. To divide all bridge contours transformer equalizers are used [2,3]. Such solution restricts frequency range and complicates measuring circuit. Because of it we use quasi-separated supply sources US_1-US_5 for every generators and voltmeter which, in turn, are supplied by main supply source (see Figure 4A). Structure of quasi-separated supply source is shown on figure 4B. Quasi-separated supply source consists of two *DC* current generators IG_{dc} and two voltage stabilizers *US*. *DC* current generators IG_{dc} have high output impedance Z_{out} (more than 10^5 Ohm) and are realized by well known circuit diagram based on super pair transistors. *DC* voltage stabilizers use simple Zenner diodes with input impedance Z_{in} lower than 10 Ohm. Voltage and current generators *GU* and *GI* and their load in measuring circuit as well as VV, acts as *AC* load for own *US* and create appropriate *AC* current I_l, which flows through stabilizers. Only a little part δI_l of this current ($\delta I_l = I_l Z_{in}/ Z_{out}$) flows through generators IG_{dc}, main supply sources and, in addition to operating current, through screens of the cables. Due to the quasi-separated *SU*, currents which flow in central wire and screen of every connecting cables are the same: currents in cable wires *A-B* and *E-F*, *L-B* and *S-F*, *C-D* and *T-J, M-D* and *N-J*. Relative difference of these currents is lower than $\delta I_l \leqslant (2–3)10^{-4}$ and only slightly violates four pair terminal connection. Violation of four pair terminal connection we tested using three-winding current comparator, switched on in every connecting cable sequentially. Tests were provided on 1 kHz. They have shown that relative current difference in central wire and screen of any connecting cable never exceeds mentioned above value.

Experinental results

The set of resistive standards MC3005 and the set of capacitive standards R597 were used during bridge experimental investigation, as well as other standards. Frequency dependence of the resistive standards MC3005, through the set of resistive standards MAS-2, was traced to VNIIM in the frequency range from *DC* to 100 kHz. These standards were used for investigation in dynamic and frequency range of measurements. Table 1 shows some results of these investigations, based on replacing method.

Data shows that the best uncertainty we have got on frequency 1 kHz. Synthesizer's noise increases measurement uncertainty on frequency 3 kHz and on lower impedances. On lower frequency the time instability of the synthesizer increases due to increasing of the time of measurement. It increases proper uncertainty of measurement. Worse results of capacitance measurement are explained by worse temperature instability of the standards R597.

Phase controlled voltage divider was used in quadrature bridge for C-R unit transfer [18]. This bridge was experimentally tested in PTB. These tests have shown that during the C-R transfer the bridge uncertainty δR was 0.41 ppm and Δtgφ was 15 ppm.

Conclusion

A new method of the accurate signal magnitude control for bridge balance was proposed and analyzed. The bridge with current comparison on this basis was developed and investigated. Balance and calibration procedures of this bridge, which determines measurement accuracy, were developed and investigated. Bridge investigations have shown that discreteness of the phase controlled balancing is rough. Because of it the proper algorithm of bridge accurate quasi — balancing procedure was implemented. Bridge main components, which determine its accuracy, were created. Accuracy of these bridge components was investigated. The standards four terminal and four pair terminal connection, its experimental investigation, was provided. Experimental investigations of the developed bridge in frequency and dynamic range are given. These investigations have shown that the bridge uncertainty could be reduced to units of ppm or less. Main factors, which restrict measurement accuracy, were revealed.

Table 1

	12.5 Hz		125 Hz		375 Hz		1 kHz		3 kHz	
	δR (δC) (ppm)	Δtgφ(δ) (ppm)	δR (δC) (ppm)	Δtgφ(δ) (ppm)	δR (δC) (ppm)	Δtgφ(δ) (ppm)	δR (δC) (ppm)	Δtgφ(δ) (ppm)	δR (δC) (ppm)	Δtgφ(δ) (ppm)
10 Ohm	4.4	8.3	3.2	6.8	2.6	4.1	2.7	5.2	3.4	7.8
1 kOhm	2.9	4.7	1.6	2.8	1.4	2.9	0.81	3.2	2.3	5.2
10 kOhm	3.7	6.1	1.7	3.1	1.8	3.4	0.62	2.9	4.4	6.6
10 nF	6,2	9.4	3.3	5.6	2.9	4.1	2.6	3.9	5.2	8.8

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References

1. *Jeffery A.M.*, Shields J., Shields S., Lee L.H. New Multi-frequency Bridge at NIST, BNM–LCIE, pp. G1–G37, 1998.
2. *Kibble B.P.*, Rayner G.H. Coaxial AC Bridges., Adam Hilger Ltd., Bristol, pp. 203, 1984.
3. *Shakil Awan*, Bryan Kibble, Jurgen Schurr, Coaxial Electrical Circuits for Interference-Free Measurements, The Institution of Engineering and Technology, London, United Kingdom, 321 pp., 2011.
4. *Thompson A.M.* An absolute determination of resistance, based on calculable standard of capacitance, Metrologia, Vol. 4, № 1б, pp. 1–7, 1969.
5. *Chua S.W.*, Kibble B.P., Hartland A. Comparison of Capacitance with AC Quantized Hall Resistance. Conference on Precision Electromagnetic Measurements, Washington DC, USA, 6–10, pp. 418–419, July, 1998.
6. *Cabiati F. and Bosco G.C.* “LC comparison system based on a two-phase generator”, IEEE Trans. Electron Devices, Vol. 34, no. 2, pp. 344 –349, 1985.
7. *Callegaro L.*, D’Elia V., Trinchera B. Realization of the Farad from the DC quantum Hall effect with digitally assisted impedance bridges,, Metrologia, 47, 464, 2010.
8. *Overney F. and Jeanneret B.* RLC Bridge based on an automated synchronous sampling system, IEEE Trans on Inst., Vol. 60, 7, 2393–2398, 2011.
9. Agilent E4980, data sheet, http://literature.cdn.keysight.com/litweb/pdf/5989–4435EN.pdf?id=776077
10. ASL digital thermometers, http://www.electri-temp.com/asl.html
11. 24-Bit Capacitance-to-Digital Converter, http://www.analog.com/media/en/technical-documentation/data-heets/AD7745_7746.pdf
12. *Surdu M.*, Surdu D., Koffman A. Precision universal AC bridges with phase controlled dividers, CPEM-2010, Korea, 2010.
13. *Robert J.* Mailloux, Phased array antenna, Handbook, Second Eddition, Artech House, Boston/London, 509 pp., 2005.
14. Fundamentals of Phased Arrays, Parbhu D. Patel, Astron, The Netherlands, lecture, 26th November, 2007, http://www.astron.nl/other/workshop/MCCT/MondayPatel.pdf
15. *Callegaro L.*, D’Elia, Bava E., Galzerano, Svelto C. Polyphase Synthesizer for Unlike-Impedance Intercomparison System. CPEM2002. Conference Digest, pp. 176–177, 2002.
16. *Grinevich F.B.*, Surdu M.N. Precision variational AC measuring systems. — Kiev, Scientific Thought, 209 pp., 1989.
17. *Surdu M.*, Surdu D. Wide Range Bridge-Comparator for Accurate Impedance Measurements on Audio- and Low Frequencies, CPEM-2014, Digest, Rio-da-Janeiro, 23–26 August, 2014.
18. *Surdu M.*, Lameko A., Karpov I., Koffman A., Kinard J., Klonz M., Melcher J., Tarlowsky A. Complex of bridge comparators for impedance unit traceability and impedance measurements // Digest of 2006 Conference on Precision Electromagnetic Measurement. — Torino, Italy, Digest, pp. 520–521, 2006.