Accurate universal set of automatic comparators for impedance parameters units reproduction and transfer

M. Surdu[1], *A. Lameko*[2], *D. Surdu*[2], *S. Kursin*[2], M. Mukharovsky, A. Akhmadov,[2] *S. Shevkun*[2]

[1] Institute of electrodynamics, Kiev, Ukraine, msurdu@nbi.com.ua
[2]Ukrmetrteststandard, Kiev, Ukraine, lameko@nbi.com.ua

1. Abstract

Comparison and unit transfer of the impedance parameter is provided using a lot of different very complicate manual bridges with numerous different standards. 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 [1,2,3,4,5] and appropriate transformer bridges [6,7,8], on the Quantum Hall Resistance [10] and appropriate bridges[11,12,13.14] and very accurate quadrature bridges for comparison of different impedance parameters [15,16,17,18,19], having original constructions. All these bridges constitute a very complicate set of devices that have long and intricate balance processes. In addition, these bridges and standards are divided into different sets and are disposed in various laboratories. The process of calibration and traceability is, therefore, complicate and very expensive. The project (№ 2244, Science and Technology Center in Ukraine, see site www.stcu.int), supported by the USA and the EU, was aimed to create the set of accurate automatic bridges-comparators and the set of thermostated intermediary standards for impedance units traceability and reproduction. Here we show the results of the implementation of this project.

Key words: impedance, measurement, traceability, unit reproduction, precision, uncertainty.

2. Metrologic requirements of the project.
3.

Technical requirements for the developed automatic bridges - comparators can be found by analysis of the diagram, shown below (Fig.1.).

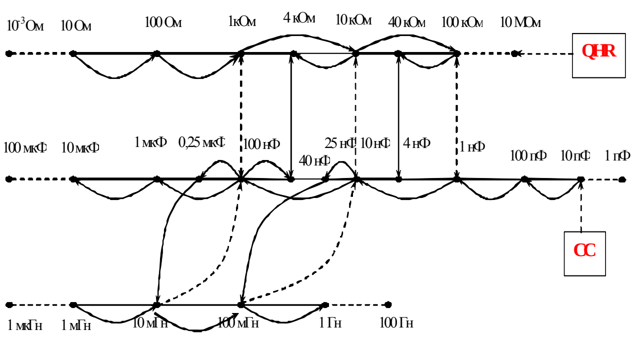


Fig.1

This diagram shows the ranges of measurement, which cover the parameters of resistance, capacitance and inductance AC standards.

The bold line showing the capacitance traceability is usually derived from a calculable capacitance standard. This line covers capacitance standards having capacitance from 10^{-3} pF to 100 μF, corresponding to impedance from 1 Ohm to 10^{9} Ohms. In some laboratories, the line of capacitive standards is traced to the Quantum Hall standard.

The bold line showing inductance is usually traced to the capacitance primary standard. This line covers inductance standards having inductance from 10^{-6} H to 100 H, corresponding to impedance from 10^{-3} Ohm to 10^{6} Ohms.

The bold line showing resistance is usually traced to a primary standard, based on the Quantum Hall Effect. This line covers the resistance standards, having resistance from 10^{-3} Ohm to 10^{9} Ohms. Sometimes the line of resistive standards is traced to the capacitance primary standard.

To perform unit transfers over a wide impedance range at 1.59 kHz using comparators without internal standards, we need a large set of intermediate standards having cardinal parameter values (capacitance, resistance, and inductance). This set can also be used for unit reproduction (R-C, C-L transfer) at the frequency 1.59 kHz.

For R-C or C-L transfer at the frequency of 1 kHz, we must use special intermediate standards. Unit transfer to these standards can create some problems because of the non-cardinal parameters required for 1 kHz. To solve this problem we proposed to use the standards with impedances, having ratio to cardinal impedances on 1 kHz equal to 0.4:1 For R-C it means capacitances 40 nF, 4 nF etc and resistances 40 kOhm, 400 kOhm, etc. For C-L transfer it means capacitances 2.5 nF, 25nF, 250 nF etc.

The entire set of intermediate standards must have very good short-term stability.

From the above approach, and considering widely used methods of impedance measurement, it is possible to achieve a nearly optimal system of comparators for impedance unit transfer and reproduction, consisting of two comparators, satisfying the following requirements:

1. The first comparator must transfer units of capacitance, resistance and inductance over the whole dynamic range.
2. The first comparator must reproduce the unit of inductance from capacitance and frequency over the impedance range from 1.0 Ω to 1 MΩ.

3. The first comparator must provide measurements with dissipation factor or tangent phase angle over the range from 0 to ±1-2.

4. The second comparator must provide C-R transfer and vise versa over the dynamic range from 100 Ω to 100 kΩ with the standards dissipation factor or tangent phase angle close to zero (less than 2-3 10^{-4}).

5. The uncertainty of the unit reproduction and transfer on the main ranges of measurement should be better than (1-3) 10^{-6} and could increase near the ends of the dynamic range up to 10^{-3}.

6. The sensitivity of the measurement on the main ranges of measurement should be better than 10^{-7} and could increase near the ends of dynamic range up to 10^{-4}.

7. The set of standards should include a thermostated set of intermediate R and C standards, ensuring short-term stability better than 10^{-7} (per ten hours).

3. Task solution.

First comparator is the autotransformer one. Its simplified diagram is shown on Fig.1.

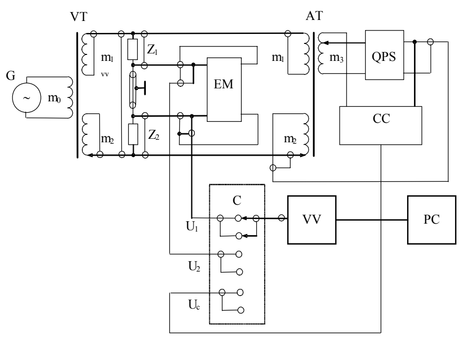


Fig.2

It consists of generator G, supply transformer VT, autotransformer AT, everyone of them caring on their core the winding m_2, and the winding m_1 used for bridge balancing on main and second parameters. Transformer VT has the screened winding m_3, connected to generator G. Self calibrated quadrature phase shifter QPS is used to balance bridge on the second parameter. Equipotential module EM, as well as appropriate algorithm of bridge balancing, excludes fully influence of the impedance of the cable, connecting impedances to be compared, on the result of measurement. Vector voltmeter VV measure two orthogonal components of the unbalance signal. Interface contain microcontroller MC, used for inner bridge procedures and used to connect comparator with PC. Two features are new here.

1. To exclude the influence of the impedance of the cable between two compared standards, the equipotential module EM is used.

1. To provide the comparator balance, VV measure **two** unbalance signals, as it is shown on Fig.1, and additional variational unbalance signal, caused by well known variation of the winding m_1 turns. Measured unbalance signals are described by next system of equations:

$$\vec{U}_1 = \vec{U}_o\left[1-\frac{Z_n}{Z_c}(1+\delta)\right]\frac{m_1}{m_1+m_2} - \vec{U}_o\frac{Z_1}{Z_c};$$

$$\vec{U}_2 = -\vec{U}_o\left[1-\frac{Z_n}{Z_c}(1+\delta)\right]\frac{m_2}{m_1+m_2} + \vec{U}_o\frac{Z_2}{Z_c}; \qquad (1)$$

$$\vec{U}_{2v} = \vec{U}_o\left[1-\frac{Z_n}{Z_c}(1+\delta)\right]\frac{m_2}{m_1+m_2+\Delta m_v} - \vec{U}_o\frac{Z_2}{Z_c}.$$

where: $Z_c=Z_1+Z_2+Z_n$;

δ - uncertainty of the equipotential module EM,

U_o – generator's voltage, Z_n- cable impedance.

Solution of the system (1) is given by formula:

$$\delta Z = -\frac{1}{2}\left(\frac{m_1+m_2}{m_2}\right)\frac{C+\dfrac{m_1-m_2}{m_1+m_2}D}{1+(C+D)\delta_v}\delta_v \qquad (2)$$

where: $C=\dfrac{\vec{U}_2+\vec{U}_1}{\vec{U}_{2v}-\vec{U}_2}$; $D=\dfrac{\vec{U}_2-\vec{U}_1}{\vec{U}_{2v}-\vec{U}_2}$;

$$\delta_v = \frac{\delta m}{1+\delta m}; \quad \delta m_v = \frac{\Delta m_{1v}}{m_1+m_2}$$

Calculation by this formula permits us to balance quickly the comparator on the first four decades and precise the balance point on the last decade, so that final result is given by 8,5 digits.

The accuracy of the measurement here depends on the accuracy of the autotransformer AT (less than 10^{-7} in the whole range of measurements, nonlinearity (better than 10^{-4}) and sensitivity (better than 10^{-5}) of the vector voltmeter, noise and interference in the voltmeter preamplifier. For the impedances, having great dissipation factor, accuracy of the measurement will depends as well, on uncertainty of QPS auto-calibration.

Autotransformer bridge is used to transfer the unit of any impedance parameter in whole range of measurement. It measures the impedances, having great dissipation factor, specific especially for inductive standards. It is used for reproduction of the inductivity unit on the base of units of capacitance and frequency as well.

To balance the bridge on the second parameter the quadrature phase shifter QPS is used. To get good accuracy the special auto-balancing and calibration procedure, described in [9], is used.

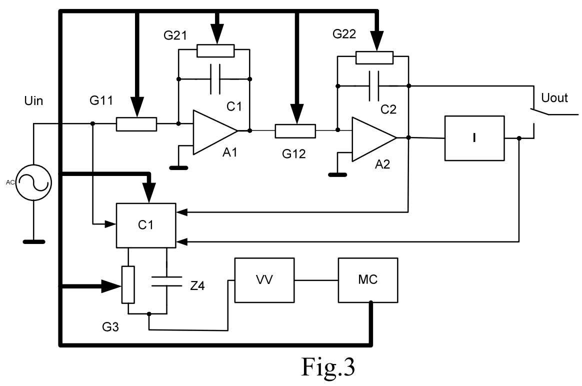


Fig.3

The phase shifter (QPS) (see Fig.3) consist s of two PS, (amplifiers A1 and A2, everyone having module of the transfer coefficient 1 and angle 45^o) and precise inverter I. The calibration circuit (CC), which consists of resistive and capacitive standards is switched by switcher C1. The vector voltmeter VV measures the output signals of the calibration circuit and transfers the results to microcontroller unit MC.

On the first stage of calibration the bridge, created by QPS and CC is balanced by control of the resistive standards in QPS and CC. The appropriate DACs are used as resistive standards in QPS and CC. As the result of this stage, the transfer coefficient of the DAC is set to value $j(1+\delta_f)$. Here δ_f is limited by DAC discreteness.

On the second stage the value of the δ_f is determined.

Three measurements are made on every stage: output signals of CC with direct and reverse connection of the CC and one of these signals, then the transfer coefficient of the QPS is varied on well known value δ_v (U_1, U_2, U_3). The process on every stage is described by equations:

$$\vec{U}_0 - \frac{\vec{U}_0 + j\vec{U}_0(1+\vec{\delta}_f)}{Z_3+Z_4}\cdot Z_3 - \vec{U}_1 = 0,$$
$$\vec{U}_0 - \frac{\vec{U}_0 + j\vec{U}_0(1+\vec{\delta}_f+\vec{\delta}_v)}{Z_3+Z_4}\cdot Z_3 - \vec{U}_2 = 0, \qquad (3)$$
$$\vec{U}_0 - \frac{\vec{U}_0 - j\vec{U}_0(1+\vec{\delta}_f)}{Z_3+Z_4}\cdot Z_4 - \vec{U}_3 = 0.$$

here: Z_4 and Z_3 – impedances of the CC; $Z_4/Z_3 = j\omega C_н R_н(1+\delta_k) = j(1+\delta_k)$,

δ_f - deflection of the QPS transfer coefficient from nominal.

δ_k- deflection of the CC transfer coefficient from nominal.

From this system we can get next approximate solution:

$$\vec{\delta}_f = (A_1 + jA_3)\delta_v/2;$$
$$\vec{\delta}_k = (A_1 - jA_3)\delta_v/2. \qquad (4)$$

where: $\vec{A}_1 = \frac{\vec{U}_1}{\vec{U}_2 - \vec{U}_1}$; $\vec{A}_2 = \frac{\vec{U}_3}{\vec{U}_2 - \vec{U}_1}$.

Second stage of the calibration procedure of the QPS is provided periodically. After second calibration procedure we know the transfer coefficient of the QPS with uncertainty of units of ppm. Appropriate data are used during the calculation of the ratio of the measured impedancies.

To transfer the units $R \leftrightarrow C$ the special quadrature bridge has been developed [9] (see Fig.4).

The quadrature bridge consists of two master voltage generators GU_s and GU_c and two slave current generators GI_s and GI_c . These two pair of generators, through the switchers K_1 and K_2, supply serially connected impedances to be compared. The voltage generators GU_s and GU_c are created using appropriate DAC_s and DAC_c. The DACs are supplied by stable source U_o of DC voltage. These DACs, under the control of the bridge MC, generate appropriate sinusoidal and positive or negative cosinusoidal signals. Two unbalance signals, generated on the low potential potential ports of the standards to be compared, are measured. These signals through switchers K_3 and K_4 are applied to preamplifier PA. To exclude the possible interference in the preamplifier, its input signal is measured twice by changing of its polarity by means of the switcher K_4.

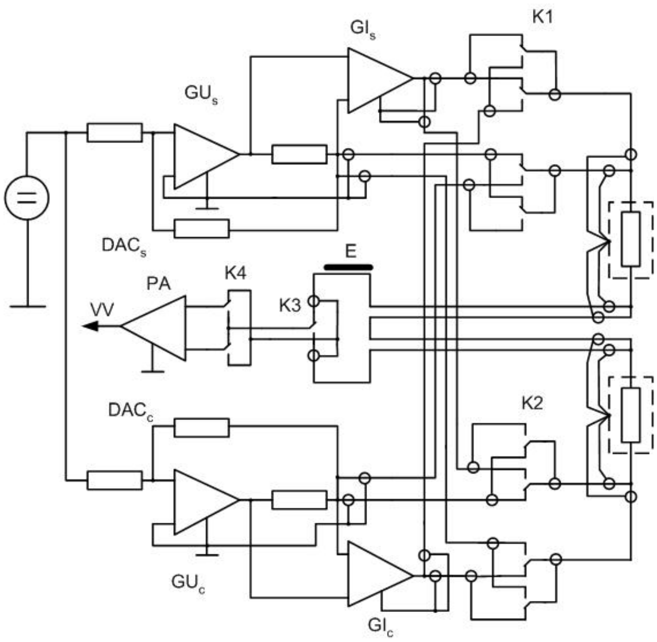


Fig.4

Every resulting unbalance signal we get by subtraction of these two results. Output signal of this preamplifier is measured by bridge vector voltmeter VV. Equalizer E is used to divide current and potential rings in low potential part of the of the quadrature bridge. Measurement algorithm contains four stages:

1. In initial position of the switches K_1 and K_2 the unbalance signal U_1, acting on the low potential potential port of the first impedance is measured.

2. In initial position of the switches K_1 and K_2 the unbalance signal U_2, acting on the low potential potential port of the second impedance is measured after the switching of K_3.

3. In initial position of the switches K_1 and K_2 the unbalance signal U_3, acting on the low potential potential port of the second impedance is measured after the well known variation of the magnitude of the sinusoidal generator GU_s on δ_v.

4. In reversed position of the switches K_1 and K_2 and of the cosinusoidal generator output signal, unbalance signal U_4, acting on low potential potential port of the second impedance is measured.

The enumerated measurements are described by next system of equations:

$$\vec{U}_0 - \frac{\vec{U}_0 - j\vec{U}_0(1+\delta\vec{U})}{Z_R + Z_C + Z_S}\cdot Z_R = \vec{U}_1;$$
$$\vec{U}_0 - \frac{\vec{U}_0 - j\vec{U}_0(1+\delta\vec{U}+\delta_v)}{Z_R + Z_C + Z_S}\cdot Z_R = \vec{U}_2; \qquad (5)$$
$$\vec{U}_0 - \frac{\vec{U}_0 - j\vec{U}_0(1+\delta\vec{U})}{Z_R + Z_C + Z_S}\cdot (Z_R + Z_S) = \vec{U}_3;$$
$$-\vec{U}_0 - \frac{-\vec{U}_0 - j\vec{U}_0(1+\delta\vec{U})}{Z_R + Z_C + Z_S}\cdot Z_C = \vec{U}_4.$$

where: Z_R, Z_C and Z_S – the impedances to be compared and the impedance of the connecting cable;

$\delta\vec{U}$ - relative complex value of the generator GU_s and GU_c voltages inequality.

Solution of this system get us next approximate formula:

$$\delta Z \approx j\frac{\delta_v}{2}\cdot\left[\frac{\vec{U}_4 - \vec{U}_3 + (1+j)\vec{U}_1}{\vec{U}_2 - \vec{U}_1}\right]. \qquad (6)$$

Last formula permits us to determine ratio of the impedances to be measured. Accuracy of determination of this ratio depends on the accuracy of the digital phase inversion of the cosinusoudal signal of the voltage generator GU_c. It could be decreased to 10^{-8} or less. It also depends on the stability of the inequality $\delta\vec{U}$ and cable impedance Z_s during the measurement process (20-30 sec). By special construction it can be decreased to units of 10^{-8} It also depends on generator's noise and high frequency interference of these ones. Accuracy of the determination of the deflection of the impedances ratio from nominal is determined by uncertainty of variation, by nonlinearity and sensitivity of the vector voltmeter etc. As the result, total resolution of the comparison is better than $0.5*10^{-7}$ and comparator zero shift don't exceed $2*10^{-7}$.

To increase speed of measurement the vector voltmeter has two parallel channel and measure two quadrature components of the signal simultaneously.

To increase selectivity of every channel detectors are created using digital voltage reference. It permits to achieve selectivity of every channel better, than 120 db and, at the same time, permits easily to change accurately the phases of the reference voltages.

Detected signals of every channel are measured by two $\Sigma - \Delta$ ADC, having the notch, set on 25 HZ. In such way products of detection are suppressed on 150 db.

To exclude complex value of the inequality of the channels on the result of measurements, the automatic calibration of the vector voltmeter is provided. To provide the calibration of the voltmeter the signal of generator U_g is applied to VV input.

Two components of generator signal (U_1 and U_2) are measured using as reference voltage sinusoidal signal in both these channels. After it the phase of the reference signal in both channels are turned on 90^0 and new output components of the detectors are measured. These measurements are described by appropriate system of equations:

$$U_1 = KU_g\sin(\omega t+\varphi_o)U_o\sin\omega t = 0.5KU_gU_0\cos\varphi_0$$
$$U_2 = U_g\sin(\omega t+\varphi_o)U_o\sin(\omega t+\Delta\varphi) = 0.5U_gU_o\cos(\varphi_o+\Delta\varphi) \qquad (7)$$
$$U_3 = KU_g\sin(\omega t+\varphi_o)U_o\cos\omega t = 0.5KU_gU_o\sin\varphi_o$$
$$U_4 = U_g\sin(\omega t+\varphi_o)U_o\cos(\omega t+\Delta\varphi) = 0.5U_gU_o\sin(\varphi_o+\Delta\varphi)$$

where: ω – operation frequency, φ_0-initial phase of the signal U_g of the generator signal, U_o- module of the reference signal, K- relative value of the ratio of the modules of channel transfer coefficient, Δφ – phase shift between vector voltmeter channels.

Solution of this system get us possibility to find inequality of the channels:

$$\begin{cases} tg\,\Delta\varphi = \dfrac{U_2\cdot U_3 - U_1\cdot U_4}{U_1\cdot U_2 + U_3\cdot U_4}; \\ K = \dfrac{\dfrac{U_1}{U_2}\cdot\left(1+\dfrac{U_3}{U_1}\cdot tg\,\Delta\varphi\right)}{\sqrt{1+(tg\,\Delta\varphi)^2}} \end{cases} \qquad (8)$$

Using last formulas we can calculate the values of the detected signal for ideal detectors by formulas:

$$U_{sk} = \frac{U_s}{K};$$
$$U_{ck} = U_{sk}\bullet tg\Delta\varphi + U_c\bullet\sqrt{1+(tg\Delta\varphi)^2}\,. \qquad (9)$$

where: U_s и U_c, U_{sk} и U_{ck} – measured by vector voltmeter real values of the input signal in both cannels and corrected, used for further calculation, values.

4. Appereance

The appearance of the set of comparators and thermostated standards is shown on Fig. 5.

Fig.5

The very short specification of the comparators set on main ranges is given below.

5. Specification

- Comparator zero shift – less than 0.5 ppm.
- Comparator decimal transfer un-ty – less than 0.5 ppm.
- Comparator sensitivity (S)– better than 0.01 ppm without average.
- C→L transfer uncertainty - 10 ppm.

Sensitivity (S)– better than 0.1 ppm without average.

$R \leftrightarrow C$ transfer uncertainty - better than 1 ppm,

Sensitivity (S)– better than 0.05 ppm without average.

$R_{k12,9k} \leftrightarrow R_{d10k}$ - direct comparison (experimental investigations).

Operating frequency – 1.0 kHz and 1, 59 kHz.

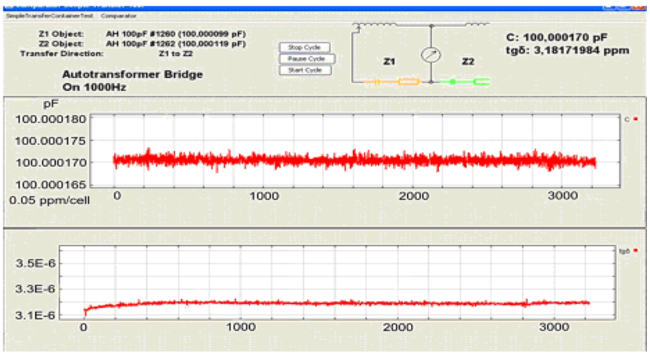
6. Delivery

Set of the comparators and thermostated intermediary standards has been delivered to GUM (Poland), NIST (USA), has been used in Ukrainian inductivity standard.

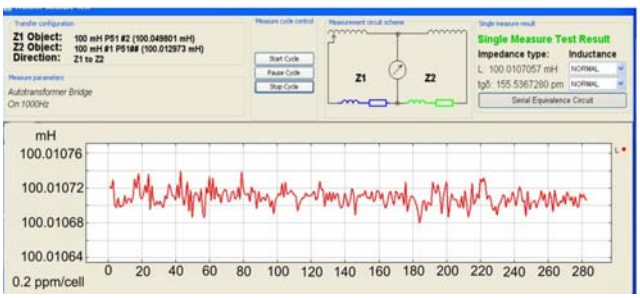
7. Some experimental results

Some experimental results of the investigation of the set of comparators in different laboratories are shown below.

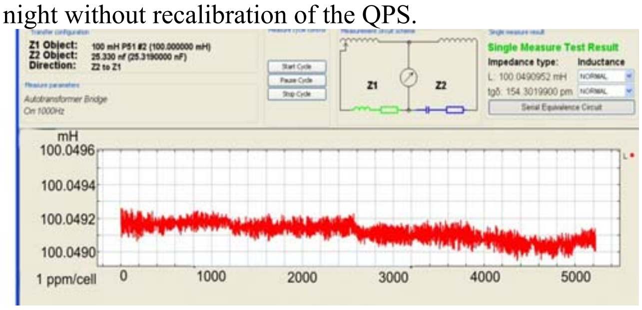
4.1 Comparison of two AH1100 capacitive standards; Ukraine, measurements during the night



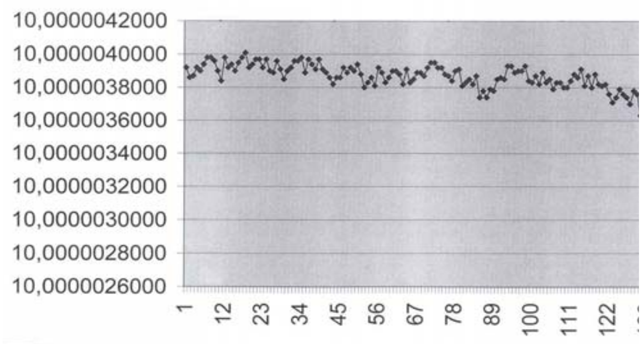
4.2 Comparison of two inductivity standards; Ukraine, measurements during one our.



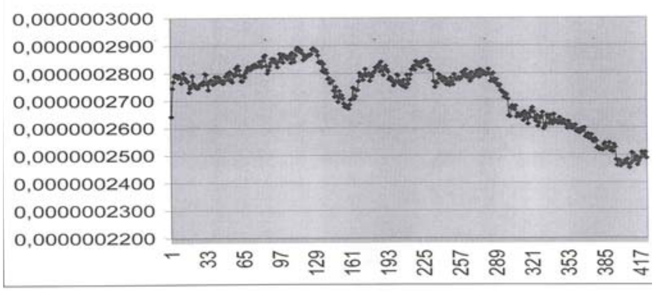
4.3 C-L unit transfer; Ukraine, measurements during the night without recalibration of the QPS.



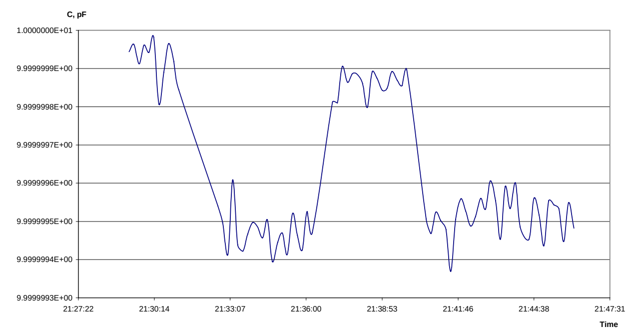
4.4 Comparison of two AH1100 capacitive standards (100 pF and 10 pF) in GUM, measurements during the night



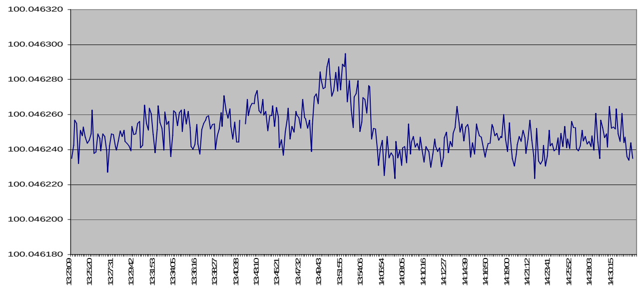
4.5. Comparison of dissipation factor of the two AH1100 capacitive standards 10 pF in GUM, measurements during the night.



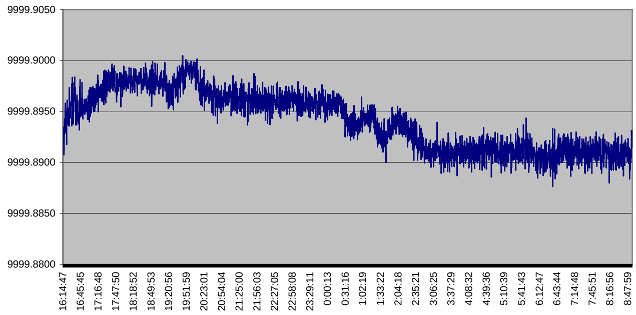
4.6. Comparison of two AH1100 capacitive standards 10 pF in NIST, substitution method, measurements during few minuts, without average, 10^{-8}/div.



4-7. C-L unit transfer; PTB, measurements during the night, 0.1 ppm/div.



R-R comparison, PTB; PTB, non thermostated standards; measurements during the night, 0.1 ppm/div.



5. Conclusion

Automatic precision measuring system, sufficiently simplify the metrologic assurance of the impedance parameters measurements. Computerization of the whole measurement process, as well as the wide measurement information processing, make whole process more accurate, sufficiently cheaper and quicker. It needs not so many personal for its exploration and decrease requirement to its skill level as well.

6. Acknowledgments

The authors are very grateful to Dr. H. Bachmair, Dr. J. Melcher and Dr. M. Klonz (PTB), to Dr. A. Koffman, Dr. J.Kinnard and Dr. Y. Wang (NIST) for their constant support and very useful advises during the project development.

7. References

1.Thompson A.M., Lampard D.G., A New Theorem in Electrostatic and its Application to Calculable Standard of Capacitance., Nature, 1956, 177, 888.

2. Clothier W. K. A ,Calculable Standard of Capacitance, Metrologia, 1965, V.1, № 36.

3. H. Bachmair, Design Criteria For Investigation on PTB Calculable Cross Capacitor. BNM-LCIE, 1998. pp. P1-P27. 1. Y. Nakamura, Capacitance Standard at ETL. BNM-LCIE. 1998. pp. R1-R16.

4. G.H Rainer. "NPL Calculable Capacitor," IEEE Trans. Instrum. Meas. Vol. I M-21, pp. 361-365. 1972.

5. Nick Fletcher. The BIPM/NMIA Calculable Capacitor Project., Conference on Precision Electromagnetic Measurements, June 13-18, 2010, Daejeon, Korea, ,pp. 318-319.

6. Bachmair, H., Funck T., Hanke, R., and Lang, H., Realization and Maintenance of the Unit of Capacitance with PTB Cross Capacitor during the Last Ten Years, IEEE Trans. Instrum. Meas., Vol. 44., No. 2., April 1995. 4. A.M. Jeffery, J. Shields, S. Shields, L.H. Lee, New Multi-frequency Bridge at NIST, BNM-LCIE, 1998, pp. G1-G37.

7. A.M. Jeffery, J. Shields, S. Shields, L.H. Lee, New Multi-frequency Bridge at NIST, BNM-LCIE, 1998, pp. G1-G37.

8. G. Small, Two-terminal-port AC bridges at NML, BNM-LCIE, 1998, pp. B1-B18.

9. F. Delahaye, AC-bridges at BIMP. BNM-LCIE. 1998. pp.C1-C6.

10. K. v. Klitzing, G. Dorda, M. Pepper., New Method for High-Accuracy Determination of the Fine-Structure Constant Based on Quantized Hall Resistance., Phys. Rev. Lett. **45**, 494., 1980.

11. Fletcher, N.E.; Williams, J.M.; Janssen, A cryogenic current comparator resistance ratio bridge for the range 10 kΩ to 1 GΩ., Precision Electromagnetic Measurements Digest, 2000 CPEM2000 y., 482 – 483 pp.

12. Bartolomé M.E.,Camón A., Sesé J., Rillo C., Flokstra J., and Rietveld G., Rogalla H., Resistance bridge based on the cryogenic current comparator in a transport dewar. IEEE Transactions on Applied Superconductivity, 2001, 11 (1). pp. 867-870. ISSN 1051

13. J M Williams, T J B M Janssen, G.Rietveld, E. Houtzager., An automated cryogenic current comparator resistance ratio bridge for routine resistance measurements., Metrologia , 2010, Volume: 47, Issue: 3, Pages: 167-174,

14. MI6800A – Quantum Hall System, technical description.

15. Thompson, A.M., An absolute determination of resistance based on calculable standard of capacitance., Metrologia, Vol. 4, № 1б, pp. 1–7, January 1969

16. G. Trapon, O. Thevenot, J. C. Lacueille, W. Poirier., Determination of the von Klitzing constant R_K in terms of the BNM calculable capacitor - fifteen years of investigations", Metrologia, Volume 40, Issue 4, August 2003, pp. 159-171.

17. B. Wood, M. Cote, AC Bridges for the R-C Chain. BNM-LCIE. 1998. pp. E1-E20.

18. 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 July 1998, ,pp. 418-419.

19. Trapon, G., Thevenot, O., Lacueille, J.C., Poirier, W., Fhimia, H., Geneves, G., Progress in linking of the Farad and the Rk to the SI Units at BNM_LCIE, CPEM 2000, Conference Digest, pp. 214-215.

20. Surdu M.N., Lameko A.L., Karpov I.V. (Ukraine), Kinard J., Koffman A. (USA). Theoretical basis of variational quadrature bridge design of alternative current // Measurement Techniques, Moscow. – 2006. – № 10. – P. 58–64.