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Establishing metrological traceability of precision measurements of electrical voltage at various levels

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Abstract

The paper outlines the features of metrological support for electrical voltage measurements in the range from 0.1 V to 520 kV. The SE "UKRMETRTESTSTANDARD" maintains three national measurement standards for alternating voltage and one for direct voltage. The electric voltage scale in the specified range shows five segments of implemented high-precision measurement standards depending on the type of voltage (alternating or direct) and the effective voltage value (up to 1000 V or above). Some aspects of transferring the unit of voltage using five high-precision measurement standards are considered. The paramount importance of metrological traceability and international comparisons of measurement results for the international recognition and national development is emphasized. In particular, some information about the comparisons of national measurement standards of electrical voltage units carried out over the past twenty years is provided. An algorithm for establishing the metrological traceability to the internationally agreed Josephson's constant within the specified range is proposed. The algorithm outlines a route for tracing measurement results using various types of electrical voltage measuring instruments, depending on the voltage level. It is schematically shown that most of these measurement results can be traced to the Josephson's constant. However, for high AC voltages – above 230 kV – the national measurement standard links the measurement results to the reference capacitors included in the reference measuring system. Nevertheless, the relations between the five applied high-precision measurement standards, schematically presented in the algorithmic flowchart, show the main steps for establishing metrological traceability depending on the type and level of electrical voltage. The paper discusses problematic aspects of metrological support in the specified range of electric voltage measurements. In particular, there is no national measurement standard of the DC voltage unit in the range from 3 to 1000 V.

Keywords: electrical voltage; national measurement standard; metrological traceability; measurement; calibration; alternating current; direct current.

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Introduction

There is an urgent need to use measuring instruments (MIs) for both direct and alternating voltages in a wide range – from millivolts to hundreds of kilovolts. This requires special approaches in the design of such devices. When measuring low voltages (microvolts, millivolts), the electrical noise and interference are the major problem. When measuring high voltages, it is necessary to use special voltage dividers (resistive or capacitive), which reduce the voltage to a level safe for the applied MIs. There are other peculiarities in measuring both direct and alternating voltages. Given such significant peculiarities, the metrological support of voltage measurement in a wide range is of utmost importance [1–3].

The recognition of measurement results of a calibration laboratory at the international level is possible only when MIs with calibration certificates are used [4]. The certificates provide information on measurement uncertainty (UM) [5] and allow establishing metrological traceability (MT) to the International System of Units (SI). The best level of UM of the final measurement result within the country is determined by metrological characteristics of national measurement standards (NMSs). NMSs shall have published calibration and measurement capabilities (CMCs) in the Key Comparison Database (KCDB) of the International Bureau of Weights and Measures (BIPM) [6–8].

One of the key functions of the NMSs is ensuring the proper level of competitiveness of national manufacturers in the global market system. To this end, the UM associated with the application of NMSs shall have values similar to the standards of other countries. NMSs represent the country at the international level during international comparisons confirming MT to the SI system [9, 10]. The results of international comparisons are published in the KCDB of the BIPM [6].

Statement of the problem and overview of publications

More than 50 countries operate NMSs of alternating voltage up to 1000 V and have received the international recognition of those [6]. One of the leading National Metrology Institutes (NMIs) in this area is the German Federal Institute of Physics and Technology (Physikalisch-Technische Bundesanstalt, PTB). PTB performed a study of the key element for the transfer from alternating current (AC) to direct current (DC) – multi-junction thermoelectric converters of the planar type. The study showed, notably, a high degree of long-term stability at the level of 0.2 μV/V at a frequency of 1 kHz [11]. The lowest level of the UM in alternating voltage segment is currently achieved using such thermal converters, given a wide acceptance of these MIs among NMIs [12]. It should be noted that DC voltage reproduced by the primary Josephson standard is the most accurate one, and it is linked to the internationally agreed Josephson's constant ($K_{J-90\,=\,483\,597.9}$ GHz/V) [13].

NMIs have to maintain NMSs at appropriate levels and to establish new scientifically capacious metrological support systems, as well as methodological research support for these measuring complexes. The purpose of the study is to ensure the integrity of the electric voltage measurement system, as well as to develop an algorithm for establishing the MT to the Josephson constant $K_{J\text{-}90}$.

Ensemble of National Measurement Standards of electrical voltage units

At the State Enterprise (SE) "UKRMETRTESTSTANDARD", four NMSs of electrical voltage were put into operation between 1998 and 2019. Establishing an adequate degree of equivalence of these NMSs in the whole range of electrical voltage with analogues from leading countries of the world indicates a large amount of research work performed [14–17]. The NMS of the AC voltage unit up to 230 kV successfully passed the procedure for establishing the degree of equivalence with the reference system of the PTB Institute [16]. The results of the comparison showed an adequate level of UM of this NMS and confirmed the MT of the measurement results to the SI system. Concerning the NMS of high DC voltage up to 180 kV, it was also verified [17], confirming the traceability to the SI system.

According to the national regulations, each NMS in Ukraine shall be periodically studied and improved. Therefore, the research and custodian institution developed the programs and regularly implements them. Recently, a NMS for metrological support of AC voltage measurements in the range from 230 to 520 kV has been established. It has too large dimensions and a lot of components, which makes the task of verifying the reproducible quantity through comparisons extremely difficult, yet there is still scope to observe its characteristics [18]. Moreover, over the past 20 years, the long-term instability of the Ukrainian NMS of AC voltage up to 1000 V has been observed. The contribution of this factor as a standard uncertainty at a frequency of 1 kHz was evaluated at the level of 0.4 μV/V [19]. Similar studies have been carried out for the DC voltage standard [20] and other standards, and there will be more in the future for all the NMSs at the SE "UKRMETRTESTSTANDARD" to verify the UM and ensure the MT.

In Ukraine, 20 NMSs operate in the field of electromagnetic measurements, and 6 of them ensure the accuracy and MT of electric voltage measurements. These NMSs of electric voltage units differ in the kind of voltage: two of them are standards of direct voltage, and four are standards of alternating voltage. The difference in the voltage level is also to be considered: three standards are of low voltage up to 1000 V, and the other three are those of high voltage above 1000 V. The last significant aspect of differentiation is the implementation of different frequency ranges in voltage reproduction: two of them are low-voltage NMSs and provide reproduction of alternating voltage with a frequency from 10 Hz to 1 GHz, and two others are high-voltage NMSs for voltages of industrial frequency only. All of the above NMSs are maintained by qualified personnel with sufficient experience to operate and verify the reliability of the created measuring systems.

The SE "UKRMETRTESTSTANDARD" maintains four NMSs of electric voltage, three of which cover a wide range from 0.1 V to 520 kV of alternating voltage, and one NMS reproduces direct voltage in the range from 1 to 180 kV. These NMSs are of particular importance for supporting the energy sector of the Ukrainian economy, which is currently experiencing difficult times of transition from excessive centralization of the electricity supply system to the creation of more autonomous and independent grids with distributed electricity sources [21]. The unification within one scientific metrological centre into one system of high-precision standards for reproducing the units of electrical voltage in different ranges opens up additional opportunities for establishing the MT.

The SE "UKRMETRTESTSTANDARD" has integrated several high-precision standards of electrical voltage units in one institution [16] and provides MT for measuring laboratories of Ukraine. Fig. 1 shows the electric voltage scale in the range covered by the NMSs established and operated at this organization. The figure has a few elements, which are the blue-crossed circle. They symbolize MIs for comparing two quantities simultaneously or in turns, which often are called comparators. Since such a device also requires calibration in most cases, this creates additional MT chains [22]. However, they are not discussed in the present paper.

Fig. 1 shows that AC voltage meters up to 1000 V, such as multi-digit multimeters, require calibration using a DC voltage standard and an AC/DC transfer standard (thermal voltage converter). Alternatively, such multimeters can be calibrated using calibrators, but in this case, the calibrators themselves require the determination of their characteristics relative to the just mentioned two standards.

The SE "UKRMETRTESTSTANDARD" has a secondary measurement standard of DC voltage unit for voltage up to 1000 V that is calibrated together with the primary Josephson standard at an external laboratory. In this way, a MI that enters the laboratory can be traced to the Josephson standard using a calibration certificate of the secondary standard. Measurements of high DC voltage are performed by reducing it with voltage dividers. The voltage magnitude shall be observed through the readout of the meter of the divider output signal, which together make up a high DC voltage meter. They establish the MT through the calibration using the DC voltage standard of up to 180 kV.

Voltage transformers, which perform a downward scaling function, have been recently widely used for high AC voltage measurements. The low voltage of the secondary winding of the transformer is measured, for example, by a voltmeter, which are in concert a version of implementation of a high AC voltage meter. Such a combined instrument establishes the MT through the calibration of a voltage transformer linked to the NMS of the high AC voltage that has a few elements which are also calibrated using the NMS of AC voltage up to 1000 V.

As for measuring the AC voltage above 230 kV, capacitive voltage transformers are usually used, which are essentially a combination of a high-voltage capacitor and a reduced-voltage transformer unit. Indeed, voltmeters are also connected to the secondary windings of such transformers to observe the voltage value accounting for a transformation ratio. However, it should be noted that the NMS for AC voltage above 230 kV is the standard for large-scale voltage reduction, which is probably due to the lower prevalence of high-voltage meters up to 520 kV.

Algorithm of establishing metrological traceability to the Josephson's constant

Any measuring laboratory uses multimeters, voltmeters, kilovoltmeters, voltage transformers, voltage dividers, etc. to measure electrical voltage. Depending on the type of voltage and its nominal value, MIs shall be calibrated using a corresponding high-precision measurement standard to establish the MT to the Josephson's constant.

The SE "UKRMETRTESTSTANDARD" has established and maintains four NMSs of electrical voltage units of various types and ranges:

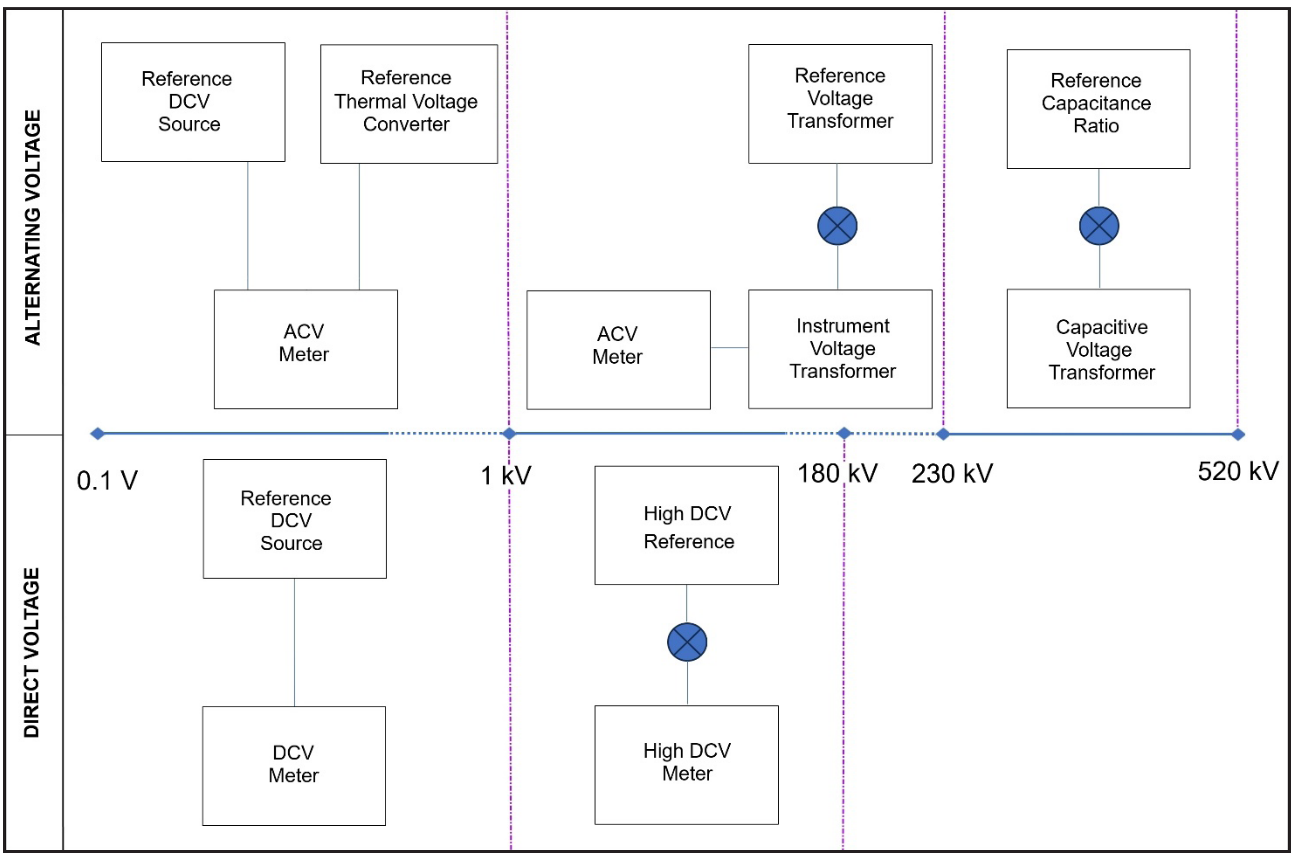

Fig. 1. Electric voltage scale for the MT established at the SE "UKRMETRTESTSTANDARD"

• National Measurement Standard of alternating voltage from 0.1 to 1000 V in the frequency range from 10 Hz to 1 MHz (DETU 08-07-02);

• National Measurement Standard of direct voltage from 1 to 180 kV (DETU 08-04-99);

• National Measurement Standard of alternating voltage and scale transformation coefficient from 1 to 230 kV (DETU 08-05-99);

• National Measurement Standard of scale transformation coefficient up to 520 kV (NDETU EM-01).

The SE "UKRMETRTESTSTANDARD" also maintains a secondary measurement standard of a direct voltage up to 1000 V (DCV WS). All of these high-precision standards within the same institution are connected within the system of establishing MT to the SI system, in particular, to the internationally agreed Josephson's constant. The best UM in calibrating MIs using the ensemble of the standards would be: with DETU 08-07-02 – 0.002%; with DETU 08-04-99 – 0.05%; with DETU 08-05-99 – 0.05%; with NDETU EM-01 – 0.05%; with DCV WS – 0.001%.

The algorithm for establishing MT to the Josephson's constant $K_{j\text{-}90}$ is presented in Fig. 2.

The MIs mainly have a measurand indication device, which is the initial data source for obtaining the measurement result. Fig. 2 shows that firstly, such a result shall be characterized against the actual voltage value: up to 1000 V or above 1000 V. The next step is to characterize the type of voltage: alternating (ACV) or direct (DCV). After specifying these two basic features at a voltage up to 1000 V, the chain of MT traces to the standards of the lowest uncertainty (to DETU 08-07-02 if the voltage is ACV, or to DCV WS if the voltage is DCV). Otherwise, the measurement result is traced to the high-voltage NMSs (to DETU 08-04-99 if the voltage is DCV; to DETU 08-05-99 if the voltage is ACV up to 230 kV; and to NDETU EM-01 if AC voltage is in the range from 230 to 520 kV).

The next step in tracing to the Josephson constant is to match the voltage (V) levels as the primary Josephson standards reproduce a direct voltage under 3 V or 10 V. An intermediate stage of tracing from the DETU 08-04-99 standard to the DCV WS is the calibration of a few components of the first one using the more accurate low-voltage standard. In turn, the DCV WS undergoes the matching calibration linked to the DC voltage standard by a special voltage divider [23]. The final step is to calibrate the DC voltage standard against the Josephson standard [24].

Returning to the DETU 08-05-99 and NDETU EM-01 standards, the difference in quantities that the two standards keep should be noted. The first NMS is a standard of a high AC voltage unit, and the second one is a standard of both the scale transformation coefficient and the phase displacement. As a result, the DETU 08-05-99 has MT to the DETU 08-07-02 through the calibration of precision voltmeters as part of the standard. In contrast, the NDETU EM-01 is

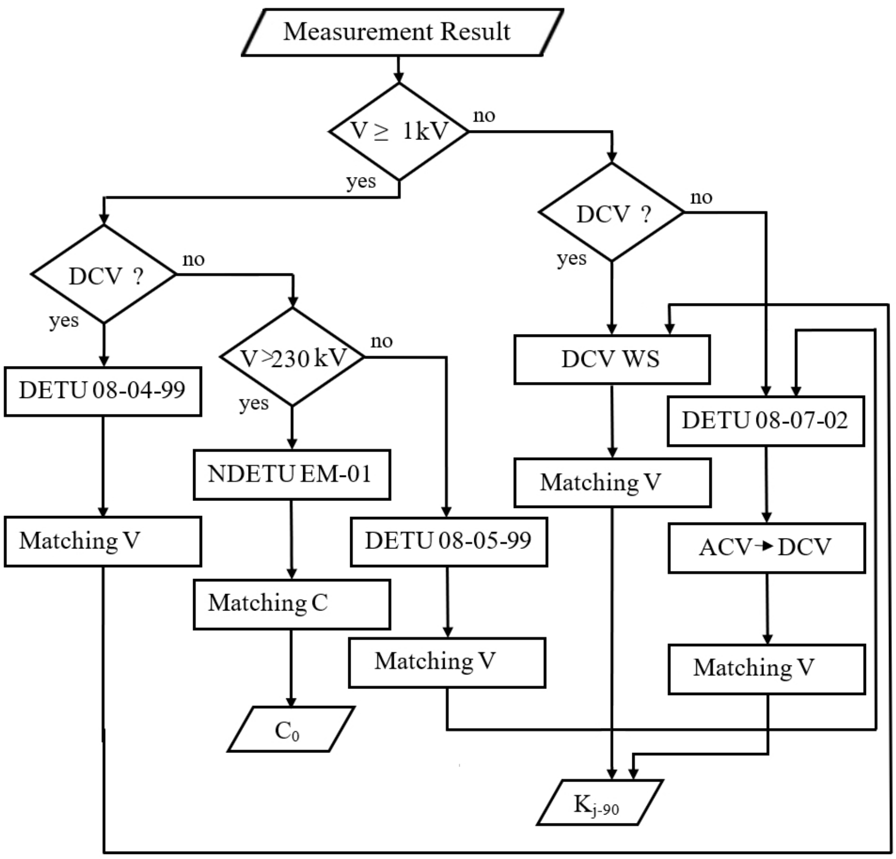

Fig. 2. Algorithm for establishing the MT to the Josephson's constant $K_{j\text{-}90}$

fundamentally designed in such a way that it requires the use of reference capacitor C_0. Moreover, the ratio between the primary and secondary voltages of voltage transformers is determined by the reference ratio of currents flowing in the reference measuring system. Due to this circumstance, the results of the voltage measurement during calibration against NDETU EM-01 are traced to the reference capacitance, or, more precisely, to the ratio of two ones with matching the voltage levels.

Over the past twenty years, the SE "UKRMETRTESTSTANDARD" has participated in numerous international comparisons. Regarding the NMSs of electrical voltage units, the international comparisons were: the DETU 08-04-99 – in 1998 [16] and bilateral comparisons in 2008; the DETU 08-05-99 – in 1998 [16] and 2020 (GULFMET.EM-S6, where three countries participated) [25]; the DETU 08-07-02 two times participated in comparisons in 2005, in a bilateral comparison (COOMET.EM-S1), and in multilateral comparison in 2013 (COOMET.EM-K6a where five countries participated) [15]. The SE "UKRMETRTESTSTANDARD" was a pilot laboratory in COOMET.EM-K6a and GULFMET.EM-S6 comparisons.

It should be added that the State Primary Measurement Standard of the Unit of AC Voltage in the Frequency Range from 30 to 1000 MHz (DETU 09-05-04) and the State Primary Measurement Standard of the Unit of Electromotive Force and DC Voltage (DETU 08-03-07) also participate in the establishment of MP in Ukraine. In particular, the DETU 09-05-04 standard has CMCs in the KCDB database and thus the linkage of the reproduced unit of AC voltage in the range from 0.1 to 3 V at frequencies from 30 MHz to 1 GHz to the SI system is confirmed. The DETU 08-03-07 standard shall periodically participate in international comparisons to confirm the linkage of the reproduced unit of DC voltage to the SI system.

To date, Ukraine does not maintain internationally recognized measurement standards of the unit of electrical DC voltage in the range from 3 to 1000 V. This means that there is no MT for measurement results in this DC voltage range, and there is a need to establish a corresponding high-precision measurement standard. Similarly, there is no NMS of alternating voltage unit in the frequency range from 1 to 30 MHz, and, accordingly, the MT of measurement results is not established.

Conclusions

The introduced ensemble of high-precision measurement standards for the reproduction, preservation, and transfer of electrical low and high voltage units allows ensuring the uniformity of measurements in the field. The ensemble of high-precision measurement standards of the SE "UKRMETRTESTSTANDARD" allows establishing the metrological traceability: in the range of direct voltage from 1 to 180 kV; in the range of alternating voltage from 0.1 V to 520 kV. The developed algorithm for establishing the metrological traceability offers a scheme of connections between high-precision standards within the SE "UKRMETRTESTSTANDARD", which links most of these standards to the Josephson constant. The conducted international comparisons of national standards allow confirming the metrological traceability of electric voltage units in a wide range (from 0.1 V to 230 kV of alternating voltage and from 1 to 180 kV of direct voltage) to the SI system.

Встановлення метрологічної простежуваності прецизійних вимірювань електричної напруги різних рівнів

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Анотація

Статтю присвячено висвітленню особливостей метрологічного забезпечення вимірювань електричної напруги в діапазоні від 0,1 В до 520 кВ. На Державному підприємстві "УКРМЕТРТЕСТСТАНДАРТ" створено три національні еталони напруги змінного струму та один національний еталон високої напруги постійного струму. Побудована шкала електричної напруги в зазначеному діапазоні відображає п'ять сегментів реалізованих високоточних еталонів залежно від роду напруги (змінна чи постійна) та діючого значення напруги (до чи понад 1000 В). Розглянуто деякі аспекти передавання одиниці напруги за допомогою п›яти високоточних еталонів. Підкреслено особливе значення метрологічної простежуваності та міжнародних звірень результатів вимірювань для визнання та розвитку країни. Зокрема, подано деякі відомості про проведені звірення національних еталонів одиниць електричної напруги протягом останніх двадцяти років. Запропоновано алгоритм встановлення метрологічної простежуваності до міжнародно узгодженої сталої Джозефсона в межах заданого діапазону. Він окреслює маршрут простежування результатів вимірювань засобами вимірювання електричної напруги різних типів залежно від рівня напруги. Схематично показано, що більшість таких результатів вимірювання можуть бути простежені до сталої Джозефсона. Однак для високої напруги змінного струму понад 230 кВ національний еталон пов'язує результати вимірювань з еталонними конденсаторами, що є в складі цієї вимірювальної системи. Проте зв'язки між п'ятьма застосованими високоточними еталонами, схематично представлені в алгоритмічній блок-схемі, показують основні кроки для встановлення метрологічної простежуваності залежно від роду та рівня електричної напруги. У статті зазначено проблемні моменти метрологічного забезпечення у визначеному діапазоні вимірювання електричної напруги. Зокрема, констатовано відсутність національного еталона одиниці напруги постійного струму від 3 до 1000 В.

Ключові слова: електрична напруга; національний еталон; метрологічна простежуваність; вимірювання; калібрування; змінний струм; постійний струм.

References

1. Jones R.G. Calibration of high voltage transformers. *Proceedings of Conference on Precision Electromagnetic Measurements Digest (Cat. No.98CH36254)*, 1998, pp. 207–208. doi: https://doi.org/10.1109/CPEM.1998.699869
2. Schon K. High Voltage Measurement Techniques. Fundamentals, Measuring Instruments, and Measuring Methods. Springer Nature, Switzerland AG, 2019. 466 p. doi: https://doi.org/10.1007/978-3-030-21770-9_1
3. Küchler A. High Voltage Engineering. Fundamentals – Technology – Applications. Springer Vieweg, Berlin, 2018. 650 p. doi: https://doi.org/10.1007/978-3-642-11993-4
4. ISO/IEC 17025:2017. General requirements for the competence of testing and calibration laboratories. Available at: https://www.iso.org/ISO-IEC-17025-testing-and-calibration-laboratories.html
5. JCGM 100:2008. Evaluation of measurement data – Guide to the expression of uncertainty in measurement. Available at: https://www.bipm.org/documents/20126/2071204/JCGM_100_2008_E.pdf
6. The BIPM key comparison database (KCDB). Available at: http://kcdb.bipm.org
7. CIPM-MRA-G-13. Calibration and measurement capabilities in the context of the CIPM MRA: Guidelines for their review, acceptance and maintenance. BIPM, 2024. Available at: https://www.bipm.org/documents/20126/43742162/CIPM-MRA-G-13.pdf
8. CIPM-MRA-P-12. Coordination within the CIPM MRA: Consultative Committees, Regional Metrology Organizations. JCRB, BIPM, 2021. Available at: https://www.bipm.org/documents/20126/43742162/CIPM-MRA-P-12.pdf
9. CIPM-MRA-G-11. Measurement comparisons in the CIPM MRA: Guidelines for organizing, participating and reporting. BIPM, 2021. Available at: https://www.bipm.org/documents/20126/43742162/CIPM-MRA-G-11.pdf/
10. Velychko O., Gordiyenko T. Metrological Traceability at Different Measurement Levels. Standards, Methods and Solutions of Metrology, IntechOpen, 2019. doi: https://doi.org/10.5772/intechopen.84853
11. Klonz M. CCEM-K6.a: key comparison of ac-dc voltage transfer standards at the lowest attainable level of uncertainty. *Metrologia*, 2002, vol. 39, no. 1A. doi: https://doi.org/10.1088/0026-1394/39/1A/2
12. Velychko O., Isaiev V. A comparative analysis of AC/DC transfer standards for comparison of national standards. *Eastern-European Journal of Enterprise Technologies*, 2018, vol. 6, no. 5 (96), pp. 14–24. doi: https://doi.org/10.15587/1729-4061.2018.150459
13. CCEM/2005-28. Mohr P.J., Taylor B.N. Present Status of SI Values of KJ and RK. BIPM, 2005. Available at: https://www.bipm.org/documents/20126/28438604/working-document-ID-1573/3f667289-5d66-a77f-f978-209154f548c6
14. Telitchenko G.P. Supplementary bilateral comparison of the national AC/DC voltage transfer references between VNIIM (Russia) and Ukrmetrteststandard (Ukraine) (COOMET.EM-S1). *Metrologia*, 2017, vol. 54, no. 1A, 01004. doi: https://doi.org/10.1088/0026-1394/54/1A/01004
15. Velychko O., Darmenko Yu. Final report on COOMET key comparison of AC/DC voltage transfer references (COOMET.EM-K6.a). *Metrologia*, 2016, vol. 53, no. 1A, 01011. doi: https://doi.org/10.1088/0026-1394/53/1A/01011
16. Kopshyn V.V. et al. Intercomparison between PTB and UkrCSM of the calibration of standard current transformers and standard voltage transformers. *Digest of Conference on Precision Electromagnetic Measurements*, Sydney, Australia, 2000. doi: https://doi.org/10.1109/CPEM.2000.850878

17. Kopshyn V.V. et al. The international comparison of the DC high voltage and AC voltage ratio standards between VNIIMS and UKRCSM. *Digest of Conference on Precision Electromagnetic Measurements,* Ottawa, ON, Canada, 2002. doi: https://doi.org/10.1109/CPEM.2002.1034723
18. Anokhin Yu., Velychko O. Research of the State Primary Standard of the unit of scaling factor of AC voltage up to 750/√3 kV. *Ukrainian Metrological Journal*, 2021, no. 1, pp. 9–14. doi: https://doi.org/10.24027/2306-7039.1.2021.228174
19. Velychko O., Isaiev V. Evaluation of Long-term Stability of High-Precision Standard for Low-Frequency Voltage Measurement. *Digest of 26th IMEKO TC4 Symposium and 24th International Workshop on ADC and DAC Modelling and Testing (IWADC),* Pordenone, Italy, 2023. doi: https://doi.org/10.21014/tc4-2023.05
20. Velychko O., Vendychanskyi R. Research of Long-Term Drift of the National High-Voltage DC Standard. *Digest of 25th IMEKO TC4 Symposium and 23nd International Workshop on ADC and DAC Modelling and Testing (IWADC)*. Brescia, Italy, 2022. doi: https://doi.org/10.21014/tc4-2022.19
21. Levchenko S. Detsentralizatsiia systemy elektropostachannia ta yii vplyv na ekonomichnu bezpeku enerhetychnykh kompanii [Decentralization of the electricity supply system and its impact on the economic security of energy companies]. *Sustainable Development of Economy*, 2023, no. 1(46), pp. 84–91 (in Ukrainian). doi: https://doi.org/10.32782/2308-1988/2023-46-11
22. Isaiev V., Anokhin Iu. Methodological Aspects of Using Comparators for Metrological Traceability of Instrument Transformers. Applied Aspects of Modern Metrology. IntechOpen, 2021. doi: https://doi.org/10.5772/intechopen.100508
23. Everett W.A. Calibration: Philosophy in Practice, 2nd Edition. Fluke Corporation, 1994. Available at: https://ru.scribd.com/document/623567252/Fluke-Calibration-Philosophy-in-Practice
24. Maruyama M. et al. Calibration System for Zener Voltage Standards Using a 10 V Programmable Josephson Voltage Standard at NMIJ. *IEEE Transactions on Instrumentation and Measurement*, 2015, vol. 64, issue 6, pp. 1606–1612. doi: https://doi.org/10.1109/TIM.2015.2411998
25. Velychko O. et al. Final report on GULFMET supplementary comparison of high voltage transformer measuring systems (GULFMET.EM-S6). *Metrologia*, 2022, vol. 59, no. 1A, 01011. doi: https://doi.org/10.1088/0026-1394/59/1A/01011