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A COMPARATIVE ANALYSIS OF AC/DC TRANSFER STANDARDS FOR COMPARISON OF NATIONAL STANDARDS

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Розвиток еталонів на основі квантових ефектів, зокрема синтезаторів змінної напруги, поки що не дозволяє визначати метрологічні характеристики засобів вимірювання змінної напруги до 1000 В частотою до 1 МГц. Тому порівняльний аналіз міжнародних звірень національних еталонів дозволив підсумувати можливості метрологічного забезпечення із застосуванням еталонів перетворення змінної напруги у постійну.

Проведені аналітичні та експериментальні дослідження дають підставу констатувати визначальний внесок національних метрологічних інститутів у формування сучасного рівня еквівалентності еталонів перетворення змінної напруги у постійну. Порівняльний аналіз досягнутої провідними національними метрологічними інститутами невизначеності вимірювань дозволив виділити найточніший тип термоперетворювача напруги на основі серії послідовно з'єднаних термопар. Такий засіб вимірювання дозволяє вимірювати різницю перетворення змінної напруги у постійну з невизначеністю менше 1 мкВ/В у певних точках діапазону.

Розгляд можливостей транспортованих еталонів забезпечувати стабільне відтворення різниці перетворення змінної напруги у постійну засвідчив перевагу термоперетворювача попередньо відзначеного типу відносно інших застосованих у звіреннях засобів порівняння. Розрахунок коефіцієнтів стабільності для еталонів різних типів показав приблизно дворазову перевагу термоперетворювачів на основі термопари проти багатодіапазонних термокомпараторів на основі сенсору середньоквадратичної напруги. Результати розглянутих звірень показали відсутність переваги будь-якої з використаних лабораторіями схем вимірювання, оскільки не виявлено зв'язку між заявленою невизначеністю вимірювання й схемою.

Результати оцінювання впливу частоти вхідної напруги на коефіцієнт передавання засобів компарування змінної й постійної напруги двох типів дають підставу знехтувати коригуванням внеску цього джерела невизначеності. Запропонований підхід до вимірювання різниці перетворення змінної напруги у постійну зі збереженням зв'язку з прямим визначенням дозволяє більш достовірно оцінювати цю метрологічну характеристику в два способи

Ключові слова: звірення, термоперетворювач напруги, перетворення напруги, транспортований еталон, невизначеність вимірювання

1. Introduction

With the introduction of the scientific discovery of the Josephson Effect into the applied metrology, the researchers reached the quantum accuracy of reproduction of a direct voltage of up to 10 V [1]. Such reproduction systems have a good capability for metrological support of solid state DC voltage standards, for example, on the basis of Zenner's diode, with an uncertainty of measurements (UM) less than 1 μV/V. In order to improve the operational properties and implementation in a wider use by many laboratories, experts continue to search for sources of uncertainty and ways to reduce these sources [2]. In recent years, the validation of the engineering design development of the standards on the basis of the mentioned quantum effect has been performed. It showed the level of equivalence of the two standards with different methodological approaches at the level of 10 nV/V [3].

The possibilities of using standards based on the Josephson Effect are not limited to direct voltage. Also, high-precision synthesizers of periodic signals for 1 V voltage have been created, the urgency of which is due to the presence of a huge number of precision meters of the alternating voltage [4]. The results of the comparison of two standards of the alternating voltage unit on the basis of the quantum effect at 1 V voltage at a frequency of 100 Hz, when a level of equivalence of less than 0.1 μV/V was achieved, have been recently published [5].

To date, in the field of high-precision measuring of alternating voltage, the persistent work on improving the metrological support of a higher level continues. The current summary of this work shows the relevance of the use of precision voltage converters as the basis of national standards (NS) for the vast majority of countries [6]. The range of amplitude and frequency of reproducible voltage synthesized by apparatuses based on the Josephson Effect does not allow them to be used for metrological support of the entire spectrum of measuring instruments (MI) of the alternating voltage. As a result, international key comparisons of such standards have not been carried out by this time.

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More than a quarter of the century has passed from the beginning of defining and comparing the calibration and measurement capabilities (CMC) of the national metrology institutes (NMI) from different countries of the world with the help of thermal converters. This process began with the comprehensive reporting of the Australian and German NMIs in the mid-90s of the last century. During this time, six international key comparisons were carried out (designation K6.a). They were coordinated within the framework of the projects of the Consultative Committee for Electricity and Magnetism (CCEM) of the International Committee for Weights and Measures (CIPM) and the Regional Metrology Organizations (RMO) – SIM, EURAMET, COOMET, and APMP. At this time, the leading, most technically and economically developed countries were able to achieve the degree of equivalence of NSs at the level of several tenths of μV/V [7].

The three fundamentally different types of thermal converters were used as a travelling standard. Single-junction voltage thermal converters based on one thermocouple (SJVTC) have a low level of an output signal, and by this time are still used in many calibration laboratories [8]. Planar multi-junction thermal converters (PMJTC), consisting of connected in series thermocouples, have a more convenient output signal to measure [9]. Finally, the multi-range thermal comparators are based on the use of a sensor of the input root-mean-squared (RMS) voltage and have the highest magnitude of the output signal and the least expressed short-term drift [10].

2. Literature review and problem statement

Nowadays, more than 50 countries of the world have declared and confirmed during the audit and international comparison their CMCs in the field of the alternating voltage measurement [11]. This calibration service of the highest precision provides metrologically three categories of MIs in the directions: AC voltage ratio; measurement and reproduction of alternating voltage; direct and alternating voltage transformation (AC/DC voltage transfer).

The latest scientific and engineering developments in the field of precision measuring of alternating voltage using the quantum effect ensured the ability to measure alternating voltage with magnitude from 0.1 to 7 V and frequency from 1 to 500 Hz with standard uncertainty from 0.2 to 8 μV/V [12]. Determination of the metrological characteristics (MC) of the thermal converter was performed using a Josephson alternating voltage synthesizer and a buffer amplifier, and the level of the measurement results (MR) concordance with the traditional standard did not exceed 1 μV/V [13]. The results of the first bilateral Dutch-Canadian comparison of Josephson alternating voltage standards in the range from 12 to 100 mV in a frequency range from 2.5 to 100 kHz were published in 2012, and it showed a level of equivalence of 1 μV/V [14]. Specialists from the Swiss NMI studied the possibility of determining the AC/DC voltage transfer difference of the thermal converter using a Josephson alternating voltage synthesizer in the range from 0.1 to 1 V at a frequency of 1 kHz. At this time, it was possible to achieve measurement uncertainty, which did not exceed 1.2 μV/V [15].

Despite the significant progress in such developments, the use of non-quantum measurement methods for alternating voltage does not cease to be actual. Comparison of the methods of calibrating the source of the alternating voltage from 0.5 to 5 V in the frequency range from 0.001 to 100 Hz confirms the possibility of reaching UM at the level of about 1 μV/V [16]. Among the methods, which provide the metrological support of the MIs in the widest range of voltage and frequency, comparing the output signals using the voltage thermal converter is the most widespread. Such standards are an important link for ensuring the metrological traceability of the MRs of the alternating voltage to the Josephson's constant.

Just the thermal converters were chosen to compare the CMCs of the NMIs in the field of measuring the alternating voltage in order to achieve the highest level of MRs concordance [7]. The experimental part of the CCEM-K6.a key comparison was completed in 1999, and the reference value was determined with UM of 0.4 μV/V at a frequency of 1 kHz and 6.7 μV/V at a frequency of 1 MHz. At the same time, the maximum UM of the degree of equivalence was 2.7 μV/V at a frequency of 1 kHz, and 100 μV/V at 1 MHz. During the comparison, two travelling standards were replaced due to damage, all of them were multi-junction thermal converters based on the thermocouple.

The second largest by a number of participants was the comparison in the Pacific region from late 2000 to almost 2004, and the results were linked to the first key comparison. UM of the deviation from the reference value of the first comparison was 9.0 μV/V at a frequency of 1 kHz and 79.1 μV/V at a frequency of 1 MHz. At this time, a single-junction converter based on the thermocouple was used as a travelling standard [17].

In this comparison, the Fluke 792A precision thermal comparator, manufactured in the USA, on the basis of an input voltage RMS-sensor was chosen as a travelling standard. The reference value was calculated with UM of 1.2 μV/V at a frequency of 1 kHz and 12.4 μV/V at a frequency of 1 MHz. At the same time, the maximum UM of the degree of equivalence was 11.3 μV/V at a frequency of 1 kHz and 62.4 μV/V at a frequency of 1 MHz [18].

Another international comparison in this area took place in 2013-2014 within the framework of the RMO – COOMET project. A single-junction thermal converter based on the thermocouple was selected as a travelling standard in this comparison, and the reference value was calculated with UM of 3.5 μV/V at a frequency of 1 kHz and 31.8 μV/V at a frequency of 1 MHz. The maximum UM of the degree of equivalence was 24.3 μV/V at a frequency of 1 kHz and 51.1 μV/V at a frequency of 1 MHz [19].

Given the differences in the design of the travelling standards, the question arises of the absence of influence of this factor on the results of comparisons. The differences in the complex of applied MIs and methods for determining the AC/DC voltage transfer difference (AC/DC difference), which also probably influenced MRs, should be added to this. Particular interest is aroused by the opportunity to assess the advantages and disadvantages of using standards of different design and operating principle.

The analysis showed that the appropriate level of reproduced voltage by means of such standards for the metrological support of laboratory MIs has not yet been achieved, despite the significant progress in the development of primary standards on the basis of the Josephson Effect. Since the middle of the '90s of the last century, international comparisons of NSs still remain the only benchmark for the assessment of CMCs of a particular country. It is evident that the study of metrological peculiarities of existing NSs is actual for today as there are still countries that did not declare their CMCs in Key Comparison Database (KCDB) [11]. In addition, the transfer of an alternating voltage unit through calibration laboratories requires the dissemination of the experience gained by leading NMIs to rectify the uncertainty budgets for the measurements carried out.

3. The aim and objectives of the study

The aim of the study is the analysis of the results of international comparisons of many countries in the field of measurement of alternating voltage and extraction of the metrological peculiarities of the application of various AC/DC transfer standards. There is also an urgent need to consider the question of measuring the AC/DC transfer difference with respect to the generally accepted definition of this characteristic. In our opinion, the procedure should contain a description of the method of determining the applied input voltage.

The following objectives were set to achieve the stated aim:

– conducting a comparative analysis of the results of international key comparisons of NSs in the part of the reference value formation for these comparisons;

– determining the reference thermal converter, by which it is possible to reach the lowest level of UM in determining the MCs of other precision thermal converters, and the travelling standard, capable of providing the best MC for long-term stability;

– conducting a comparative analysis of methods and measurement circuits for the determination of the AC/DC difference at a voltage of 1.5 V or 3 V in the frequency range from 1 kHz to 1 MHz;

– estimating the influence of the frequency of the input voltage on the transfer coefficient of a planar type voltage thermal converter on the basis of the thermocouples connected in series and a thermal comparator based on the sensor of the input RMS voltage.

4. Methods of studying the comparisons of national standards and ensuring the correct measurement of the AC/DC voltage transfer difference

Using comparative analysis, it is advisable to distinguish NSs of NMIs that played a leading role in the formation of the reference values of key comparisons, and that defined independently the values of UMs when researching the reference thermal converters and that provided the smallest UMs of MRs. During the analysis, three variants of measuring circuits were worked out, depending on the method of comparison of output signals of thermal converters. Three variants of mathematical models were made and the sources of uncertainty were compared with taking into account the sequence of the applied voltage. Travelling standards and stability assessment results were compared, as well. There was considered NSs modernization between the comparisons when comparing UMs given by NMIs. Since some NMIs used different working standards to determine the AC/DC difference at different frequencies, this was also taken into account. Besides, attention was paid to the experimental study of the absence or presence of frequency influence on the final MR of the output signals of comparable thermal converters.

When analyzing the measurement schemes of laboratories, due to the lack of measuring information about the input voltage, a question arose about the degree of influence of the non-ideality of the transformation coefficient of the thermal converter. The transformation coefficient in the periodic signal applying depends on the values of the reactive elements of the thermal converter, including parasitic elements. Since the reactive resistance varies with the frequency change, then the change in the output signal should not be the same. It is necessary to study experimentally this aspect to check the hypothesis of a noticeable level of the frequency impact.

Forming the output signal of the Fluke 5720A calibrator in the range of values corresponding to the AC/DC difference change of 1, 5, 10 μV/V, it is necessary to observe the readout of the Agilent 3458A multimeter when applying the input direct or alternating voltage. Also, an attention should be drawn to the difference in dependencies when applying a voltage of different frequencies.

The nominal input voltage is 1.5 V for the PMJTC planar type thermal converter manufactured by PTB/IPHT (Germany). The input voltage for the Fluke 792A thermal comparator was also selected the same, i. e. 1.5 V. It was calculated that the change in the input voltage to 1 μV/V for a nominal voltage of 1.5 V is 0.0000015 V, to 5 μV/V is 7.5 μV, and to 10 μV/V is 0.15 μV. It was decided to observe the magnitude of the change in the output signal at frequencies of 1, 20 and 100 kHz.

Having determined the relation between the changes in input and output signals, one can calculate the increase of the input signal by measuring the output of the thermal electromotive force (thermo-EMF), thus ensuring a connection with the direct definition of the AC/DC difference. Fig. 1 shows the dependencies on the input voltage for the output thermo-EMF of the thermal converter on the basis of the thermocouple.

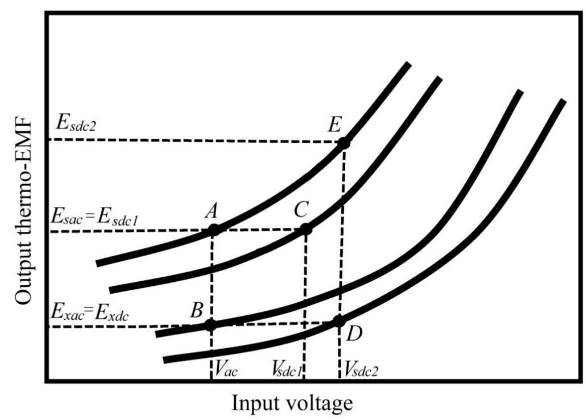

Fig. 1. Dependence on input voltage of output thermo-EMF for thermal converter on the basis of thermocouple

It is necessary to consider the sequence of measurement operations in order to achieve the correctness of the measurement procedure in relation to the generally accepted definition of the AC/DC difference. At the first stage of one cycle of determination of the AC/DC difference, measurements of the output signals of the reference E_{sac} and calibrated E_{xac} thermal converter (points *A* and *B* in Fig. 1) are performed when applying the input alternating voltage V_{ac} of required frequency.

At the second stage, the output signal E_{sdc} is measured when applying an input direct voltage of a positive polarity (point C in Fig. 1), and then the same for the negative polarity. Finally, the direct voltage MRs should be averaged.

The next step is providing such a positive direct voltage when the output signal E_{xdc} will coincide with E_{xac} (point D), simultaneously it is necessary to fix the readout of the E_{sdc2} output signal meter of the reference thermal converter at the point E. Then the difference ($V_{sdc2}-V_{sdc1}$) must be calculated taking into account the difference ($E_{sdc2}-E_{sdc1}$). In this case, the AC/DC difference of the calibrated thermal converter must be determined as

$$\delta_X = \delta_S - \frac{V_{sdc2} - V_{sdc1}}{V_{nom}}, \quad (1)$$

where δ_S is the AC/DC difference of the reference voltage thermal converter; V_{nom} is the value of the input voltage for determining the AC/DC difference of the calibrated thermal converter.

An alternative approach for determining the AC/DC difference with respect to the direct definition requires an additional measurement of the input direct voltage and corresponds to the following sequence of operations. In this case, the reference thermal converter must be previously calibrated with the help of sources of the alternating and direct voltage with UM of several tenths of μV/V. In the first stage of one measuring cycle, two signals of the output thermo-EMF of the reference and calibrated thermal converters are measured for the given input alternating voltage of the required frequency (points A and B in Fig. 1). After that, the voltage V_{sdc1} is applied and its value must be measured in the center of the tee-connector, as well as the output signal E_{sdc1} of the reference thermal converter (point C in Fig. 1) which should be equal E_{sac}. Further, the direct voltage V_{xdc} is applied so that the output thermo-EMF of the calibrated thermal converter would be equal to the value at point B and the value of the input voltage must be noted.

After eliminating the drift of the output signal of the thermal converter, the AC/DC difference can be calculated as

$$\delta_X = \frac{V_{sdc} \cdot (1+\delta_S)}{V_{xdc}} - 1. \quad (2)$$

Thus, both of the above-discussed approaches for determining the AC/DC difference allow us to provide a connection with the direct definition of this characteristic. The only difference is that in the first variant multiple investigations of the transformation coefficient during maintenance are required, and in the second – the measurement of the input voltage.

5. The main results of the study of the AC/DC transfer standards

5. 1. Research of main characteristics of key comparisons

The six key comparisons were conducted from 1996 to 2014, with a total number of participants equal to 50, and ten of them were double-compared, but German NMI (PTB) – even triple-compared. Since the thermal converters, which were used during the first key comparison, had the nominal voltage of 1.5 or 3 V, then the next comparisons also were with an application of the similar nominal voltage (four comparisons were with a voltage of 3 V and one – with 1.5 V). The results of the comparative analysis of mentioned comparisons of the AC/DC transfer standards are summarized in Table 1.

Table 1

Main characteristics of key comparisons of AC/DC transfer standards

Organization	Pilot laboratory	Travelling standard	Level of input/output	Impact of NMI into reference value	Traceability to NMI
CCEM	PTB	3-d MJTC 2 PMJTC pieces	2.8 V/100 mV 1.5 V/100 mV	NPL, IEN, NRC, NIST, NPLI, CSIRO, PTB, VSL (1 MHz)	PTB, VSL, NIM, VNIIM, NPLI, NIST, NRC
APMP	NMIA	SJTVC holt model 11	4 V (3 V)/7 mV (4 mV)	NMIA, PTB, NMIJ	NMIA, PTB, NMIJ, NPL, NPLI
SIM 1	CENAM	Fluke 792A	3 V	NIST, NRC, INTI	PTB
SIM 2	INMETRO	PMJTC 180-3	1,5 V/86 mV	LNE	PTB
EURAMET	PTB	Fluke 792A	3 V	PTB	PTB
COOMET	UMTS	SJTVC PNTE-6	3 V/5 mV	All participants	PTB, VNIIM

The pilot laboratories chose the travelling standard and performed an estimation of its stability. It should be noted that multi-junction thermal converters were applied for two times during these six comparisons, the single-junction thermal converters were used twice, and the Fluke 792A transfer standard was applied twice. In the case of applying a single-junction thermal converter, each NMI had to pay particular attention to ensure the resolution (at least 1 nV) of the meter of the low-voltage output signal to reduce UM of this factor.

For all comparisons, the measurement of the AC/DC difference was performed in accordance with its direct definition that requires applying the input voltage in the center point of the contact tee-connector. The impact of the input tee-connector on MR was estimated and this value was used as an adjustment for NMI results depending on the applied device in the second comparison [17].

Regarding the reference value, at least one NMI was chosen for a calculation of this value in each key comparison in the way where UM of NMI provided a significantly lower level than the other NMIs. It is important that the reference thermal converter must have an absolute independent implementation. According to these features, the data of eight NMIs were used in the first comparison and in the second and in the third comparisons the number of such NMIs was equal to three for each one. The data of NMIs, which participated in the first comparison, were used in bilateral comparisons to determine the reference value in order to link the results to the first comparison. It was decided to use the data of all NMIs during the comparison which was conducted in the framework of COOMET project. The linking of MRs to the first comparison was carried out through the data of VNIIM (Russia) which also participated in the first comparison [19].

The metrological traceability of all participants can be divided into ten directions to ten NMIs (Table 1). Moreover, nine NMIs participated in the first comparison. Thus, at this stage of the analysis one can distinguish the nine leading laboratories of the world in the first approximation. These laboratories have reached the highest accuracy and confidence in calibration capabilities and external recognition due to obtaining the AC/DC difference value by the NSs of the less experienced laboratories of other NMIs.

A more meticulous analysis allows us to distinguish the main laboratories among the nine leading NMIs in the direction of measurement of the alternating voltage. According to the results of the analysis, one could conclude about the prevailing contribution of the four following laboratories in the formation and determination of the reference value and the linking of MRs of the comparisons around the world: NRC (Canada), NIST (USA), NPLI (India) and PTB (Germany). The leading positions of these NMIs were provided, first of all, due to the application of relatively independent AC/DC difference standards that were implemented by these laboratories earlier than other labs. But it is not worth considering these achievements of the NMIs only from the technical point of view because the personnel's scientific potential of a particular laboratory plays a prominent role in the development of the standard base of each NMI.

The AC/DC standard can be considered to be a relatively independent one in the case of applying the research data of other organizations during the implementation of this complex of MIs. Examples of such partially independently created standards are NSs of metrology laboratories of IEN (Italy), NPL (United Kingdom), CSIRO (Australia) and NIST (USA). The developments of NRC, NPLI, and PTB can be considered to be fully independent AC/DC transfer standards. These laboratories have their own standards across the whole working range with some degree of external organization participation during standard creation. NIM (China) and VNIIM (Russian Federation) were not chosen as the core NMIs. The reason for this was a significant UM, a presence of significant deviation of the results when comparing or an absence of MRs.

Taking into account the number of items of reference thermal converters developed and manufactured with the direct participation of PTB, one can consider the German NMI as an undisputed driver of the formation of a modern level of equivalence of NSs all over of the world [7]. When calculating the results of the first comparison obtained by the laboratories that worked with the MJTC4 and PMJTC 230 type of the thermal converters, the values proposed by PTB were taken as the basis of the highest confidence with the consent of the participants of the comparison.

5. 2. Measurement accuracy of comparison in determining AC/DC transfer difference of different types of thermal converters

The several leading NMIs that participated in more than one key comparison and provided significantly less UM than the other labs were selected for comparing. First of all, it was PTB (took part in the three comparisons), NRC and NIST. It is advisable to add NMIA (Australia) [20] and INMETRO (Brazil) to these three NMIs. The latter labs improved their own NSs and significantly enhanced the standard complement and UM. It is also advisable to add LNE (France) and IEN as NMIs that used more sophisticated methods based on bridge measurement schemes.

Comparing the MCs of travelling standards was made using the values of UM indicated by NMIs in the key comparisons reports. Comparing the UM achieved by the indicated NMIs, one can conclude about the degree of suitability of a specific type of thermal converters for use as a working standard for the determination of MCs. UM of the results of the AC/DC difference determination of the travelling standards, chosen from the reports for the indicated NMIs depending on the frequency, are given in Table 2.

Table 2

Measurement uncertainty of results of AC/DC difference determination of travelling standards

NMI	Travelling standard	1 kHz	20 kHz	100 kHz	1 MHz
NRC	PMJTC	0.4	1.2	2.0	13.0
NIST		0.9	1.3	2.0	21.0
PTB		0.4	1.0	2.0	24.0
NMIA		1.5	2.2	4.6	24.0
INMETRO		2.2	2.2	5.1	12.1
IEN		0.6	0.8	2.0	13.0
LNE		1.0	2.2	4.6	41.0
NRC	Fluke792A	1.2	2.8	7.2	17.0
NIST		3.2	3.2	8.5	17.2
PTB		2.0	2.0	3.0	–
INMETRO		4.0	4.0	5.0	32.0
PTB	SJTC	0.8	0.8	2.8	25.0
NMIA		0.8	1.9	5.0	18.0

It is seen in Table 2 that the lowest level of UM using three types of measuring circuits was achieved in determining the MCs of PMJTC thermal converters. This is probably due to the fairly high level of an output signal, predictability of drift, low level of internal noise, and also due to the small degree of complexity of the structure of such reference standards. These aspects allow calculating the MCs of the thermal converters. However, the question about the relatively high UM for a frequency of 1 MHz, provided by PTB with the help of the differential measurement method, still remains.

Unlike the previous type of thermal converter, the Fluke 792A transfer standard has a complex design, internal active elements that require a separate power source, a higher level of internal noise and scattering of the output signal. These circumstances lead to a higher UM in determining MCs of this MI, even though there is a significantly smaller short-term drift of this thermal comparator. The decrease of the level of UM, obtained by NIST, is, perhaps, due to the improvement of UM evaluation methodology when using the reference standard of this laboratory [21].

The change in the reference standard of INMETRO, as can be seen when comparing the reports of multilateral North American [18] and bilateral American-European [22] comparisons is also worth noting. This factor, probably, affected MRs of MCs of the PMJTC thermal converter in the direction of increasing accuracy. Obviously, the latest NMI noted the disadvantages of using Fluke 792A or analyzed CMCs of NMIs of the world and decided to implement the PMJTC as the reference standard. This circumstance raises further doubts when taking into account the MRs of this NMI. However, in spite of this, the latest laboratory received one and the same level of UM for a frequency of 100 kHz.

With regard to the SJTC, it should be noted that a work on improving the reference standard of NMIA complicates the formulation of the relevant conclusion. But the first problem is the low level of the output thermo-EMF (about 4–5 mV), forms additional requirements for the measurement. The higher accuracy obtained by NMIA in the second participation should be considered to be a result of improving the reference laboratory base [20] according to the results of the first comparison. This is also indirectly evidenced by the predominant deterioration of UM obtained by the PTB lab relatively to the first key comparison.

Thus, the comparative analysis showed the possibility of achieving the lowest level of UM in the application of PMJTC comparing with other types of AC/DC transfer standards.

5. 3. Comparison of long-term stability of travelling standards

In order to analyze the data about the long-term stability of the travelling standards, one must consider the results of the repeated determination of the AC/DC difference by pilot labs of the key comparison.

Such analysis can prove expediency of the implementation of one or another thermal converter as a part of NS. The four reports of comparison of AC/DC transfer standards contain information about the stability of the travelling standards within a comparison. The results of 14-years studying MCs of NS of the alternating voltage unit, which have been kept at SE "Ukrmetrteststandard" (Ukraine) since 2002 [23], should be also used as an information source.

Table 3 summarizes the results of the determination of stability of the travelling standards of the different types within comparisons yielded by the pilot labs. The maximum intervals between MRs fixed during researching the stability of the Fluke 792A AC/DC transfer standard, which is a part of NS of the alternating voltage unit of Ukraine, are also shown in Table 3.

Table 3 shows that thermal converters based on one thermocouple or few thermocouples connected in series have the best stability coefficients. Obviously, the complexity of the process of the analytical evaluation of MCs of the investigated subject directly depends on the design complexity. This statement can be applied with regard to the thermal converters that contain one or more thermocouples. But in the case of a multi-junction item, this complexity is compensated due to the improvement of the operating properties, in particular by the increased level of the output signal. This rule can be spread on Fluke 792A which consists of a large number of electronic components inside, and each component has own features of change of the internal properties for a lasting time. In order to provide more objective comparing, a calculation of the ratio of the maximum interval between MRs to UM was yielded in a stability estimation of the travelling standards, since UM of the pilot labs varies (ten times as much in some points). A range of the received values of the stability coefficient was divided into two areas, and the relative numbers for each area points were defined (Fig. 2).

It is shown in Fig. 2 that all of the stability coefficients of Fluke 792A get the value at the range above 0.375, and the stability coefficients of the thermal converters based on the thermocouple were allocated as follows: 58.3 % are within the area before 0.375, and 41.7 % are within the area above 0.375.

Table 3

Results of determination and analysis of stability of travelling standards

NMI, travelr ling standard	Characteristic	MC value depending on frequency			
		1 kHz	20 kHz	0,1 MHz	1MHz
PTB, PMJTC	Maximum inx terval, μV/V	0.3	0.3	0.8	4.0
	UM, μV/V	0.4	1.0	2.0	24.0
	Stability coefficient	0.75	0.30	0.40	0.17
CENAM, Fluke 792A	Maximum inx terval, μV/V	3.8	2.5	5.0	27.0
	UM, μV/V	6.0	6.0	8.0	38.0
	Stability coefficient	0.63	0.42	0.63	0.71
NMIA, SJTC	Maximum inx terval, μV/V	0.3	1.0	0.5	5.5
	UM, μV/V	0.8	1.9	5.0	18.0
	Stability coefficient	0.38	0.53	0.10	0.31
INMETRO, PMJTC	Maximum inx terval, μV/V	0.3	0.4	0.3	6.1
	UM, μV/V	2.2	2.2	5.1	12.1
	Stability coefficient	0.14	0.18	0.06	0.50
SE "Ukrmetrteststandard", Fluke 792A	Maximum inx terval, μV/V	2.9	–	5.0	20.6
	UM, μV/V	4.8	–	11.4	53.8
	Stability coefficient	0.60	–	0.59	0.45

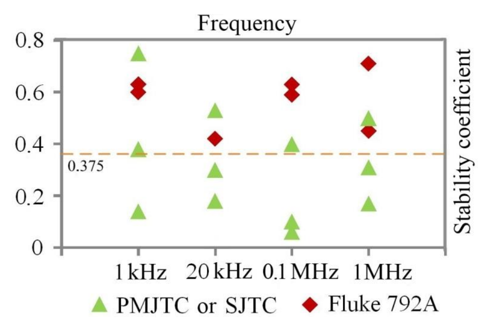

Fig. 2. Travelling standards stability coefficients comparing

Thus, the analysis of the results of defining the stability of the thermal converters of a different design has shown a significant superiority of the thermal converters based on the thermocouple regarding this MC.

5. 4. Comparison of methods of measuring AC/DC transfer difference

In order to compare the methods of measuring the AC/DC difference, it is necessary to consider variants of the measurement schemes used during the NS comparison. One can distinguish three methods indicated in [7]: differential measurement; 2-channel measurement; measurement using equilibrium bridge circuits.

Fig. 3 represents a diagram of the method of differential measurement, where the designations are: TVC_S is a reference thermal converter; TVC_X is an investigated thermal converter.

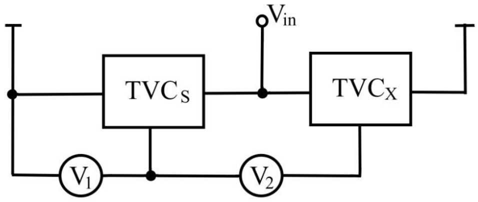

Fig. 3. Differential measurement method

If a measuring circuit is used for measuring the difference between the output signals of the thermal converters, then UM of this difference arises. The functional relationship will look like

$$\delta_X = \frac{\Delta E_{dc} + \Delta_{V1} + (d_X - d_S) - \Delta E_{ac} - \Delta_{V2}}{E_{sdc} + \Delta_{V1} + d_S}, \quad (3)$$

where ΔE_{ac} is the difference between the output signals of the reference and the investigated thermal converters during applying the input alternating voltage of the required frequency; ΔE_{dc} is the difference between the output signals of the reference and the investigated thermal converters during applying the input direct voltage; Δ_{V1}, Δ_{V2} are the corrections to the readout of the direct voltage meters; d_X, d_S are the drifts of the output signals of the reference and the investigated thermal converters during the time between measurements.

In this method, it is necessary to take into account the readout corrections of the meters when measuring the output signal of the reference thermal converter and the outputs difference, since the values measured have an absolutely different order of magnitude. An additional deviation occurs in the case where the transformation coefficients and the degree of dependence of the output thermo-EMF on the input voltage of the comparable thermal converters differ noticeably. This is due to the disproportionate increase in the output signals (for example, when the degree of dependence of the reference thermal converter n_S is equal to 2, and for the investigated thermal converter n_X is equal to 2.3). If the working standard has a small AC/DC difference, then one can ignore the specified additional deviation in the disproportionate increase in output signals.

Fig. 4 shows a diagram of the 2-channel measurement method.

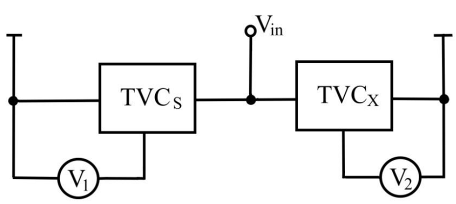

Fig. 4. 2-channel measurement method

If multimeters are used, and one of these MIs measures one and the same voltage value, then the readout corrections of the multimeters are not required in determining the AC/DC difference, since these corrections are reduced both in the numerator and in the denominator. UM due to the readout scattering of the multimeter occurs in any case, and the functional relationship will look like

$$\delta_X = \frac{E_{sac} + \Delta_{V1}}{E_{sdc} + \Delta_{V1} + d_S} - \frac{E_{xac} + \Delta_{V2}}{E_{xdc} + \Delta_{V2} + d_X}. \quad (4)$$

The equation (4) may not contain the drift components because of excluding these characteristics after the measurements, and the readout corrections can be excluded from the above expression.

A more sophisticated method for determining the AC/DC difference is used by NMIs in the application of the bridge schemes. Fig. 5 shows the features of the measurement method with the use of the bridge scheme on the example of the system of the automatic comparison implemented at LNE [24].

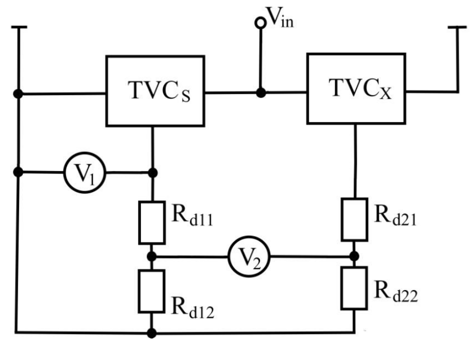

Fig. 5. Method with the use of bridge equilibrium circuits

Analyzing and transforming the scheme of Fig. 5 with the application of methods based on Kirchhoff's laws for calculating electrical circuits, one can obtain a set of mathematical expressions. It is necessary to convert R_{d12}, R_{d22}, and R_{Vd} (internal resistance of the voltmeter V_2) with the star connection into the triangle for the analytical determination of the potentials at the connection points of the voltmeter V_2. In this case, the values of equivalent resistance R_1, R_2, R_3 are determined by expressions

$$R_1 = \frac{R_{d12} \cdot R_{Vd}}{R_{d12} + R_{Vd} + R_{d22}}; \quad (5)$$

$$R_2 = \frac{R_{d12} \cdot R_{d22}}{R_{d12} + R_{Vd} + R_{d22}}; \quad (6)$$

$$R_3 = \frac{R_{Vd} \cdot R_{d22}}{R_{d12} + R_{Vd} + R_{d22}}. \quad (7)$$

After such a transformation, forming a system of equations according to Kirchhoff's laws, one can obtain the following three equations with three unknowns and seven input quantities in accordance with Fig. 5.

$$E_X = I_X \cdot (R_{d11} + R_3 + R_2) + I_S \cdot R_2; \quad (8)$$

$$V = I_S \cdot (R_{d11} + R_2 + R_1) + I_X \cdot R_2; \quad (9)$$

$$\Delta V = I_S \cdot R_1 + I_X \cdot R_3, \quad (10)$$

where I_S, I_X are the values of the currents through the resistances R_{d11} and R_{d21}, respectively; V, ΔV are the readouts of the voltmeters V_1 and V_2, respectively; E_X is the value of the output thermo-EMF of the calibrated thermal converter.

For the final determination of the AC/DC difference, one has to use, as usual, an expression

$$\delta_X = \frac{1}{n} - \frac{E_{xac}}{n \cdot E_{xdc} + d_X}. \quad (11)$$

There are additional sources of uncertainty of the bridge circuit resistance values in this method. Another question is related to the device for measuring the absence of a potential difference in the bridge circuit. If the galvanometer detects zero with an uncertainty of less than 1 nV, then its contribution is much smaller than the previous measuring circuits. However, UM due to the other voltmeter remains and the advantages of such a measuring circuit are lost in the evaluation of the combined UM, as can be seen by the data of the comparison [7]. The combined UM in the application of the method based on the bridge measuring scheme is not lower as can be seen by the data in Table 2.

Consequently, the next conclusion is that there is no advantage of any of the three measurement schemes used by different NMIs during the comparison.

5. 5. Investigation of transformation coefficient influence

Measurement information on the degree of the transmission coefficient influence on MR of the AC/DC difference was obtained for the values of this characteristic of 1, 5, 10 and 50 μV/V. MRs of the changes in the output signal of PMJTC thermal converter depending on the change in the input voltage is presented in Table 4.

Table 4

Measurement results of output signal change of PMJTC depending on input voltage change

Characteristic	AC/DC difference depending on relative change in the input signal, μV/V			
	1	5	10	50
Input voltage, V	1.4990015	1.4990075	1.4990150	1.4990750
Input change, μV	1.5	7.5	15.0	75.0
Output signal, mV	86.01802	86.01605	86.01403	86.01196
Output change, μV	–	–	near 1.7	near 8.3
Relative output change, μV/V	–	–	19.8	98.5

The changes of the output signal, estimated for frequencies 0, 1, 20 and 100 kHz with UM of about 0.7 μV/V, did not show the differences in the values of this characteristic. That is, as can be seen from Table 4, there was approximate twice the relative change in the output signal regardless of the frequency. There were significant difficulties in adjusting the output signal of Fluke 5720A calibrator at a frequency of 1 MHz. With regard to UM in estimating the transformation coefficient, this MC was evaluated through the scattering of Agilent 3458A meter readout of the direct voltage, that is, through the standard deviation.

When studying the PMJTC thermal converter, difficulties arose in estimating UM through scattering due to the presence of the drift. The drift was estimated at about 2.2 μV per minute, and the pulsation of the output signal was estimated at a level of about 0.1 μV. During the estimation time of approximately 5 s, the output signal changed by almost 0.2 μV, so the relative standard UM could be taken as 0.7 μV/V. In general, when fixing 10 observations of the output signal within 1 s, it is possible to estimate the change of this signal with a standard UM of 0.4 μV/V and to determine the change of the output thermo-EMF.

The results of measuring the change in the output voltage of the Fluke 792A transfer standard are shown in Table 5.

Table 5

Measurement results of the output signal of Fluke 792A depending on input voltage change

Characteristic	AC/DC difference depending on relative change in the input signal, μV/V			
	1	5	10	50
Input voltage, V	1.4990015	1.4990075	1.4990150	1.4990750
Input change, μV	1.5	7.5	15.0	75.0
Output signal, V	1.265775	1.265777	1.265789	1.265855
Output change, μV	near 1.0	near 6.0	near 12.5	near 63.2
Relative output change, μV/V	0.8	4.7	9.9	49.9

The changes of the output signal were estimated for frequencies 0, 1, 20 and 100 kHz without a noticeable difference in the value of this characteristic. That is, the same relative change in the output signal occurred regardless of the frequency. Concerning UM, in the case of Fluke 792A application, the scattering of Agilent 3458A multimeter readout in a direct voltage measurement mode was evaluated depending on the frequency of the output voltage of Fluke 5720A calibrator, as indicated in Table 6.

Table 6

Scattering of Agilent 3458A multimeter readout

Characteristic	Output frequency of Fluke 5720A calibrator			
	0 Hz	1 kHz	20 kHz	0.1 MHz
Scattering, μV	0.7	1.8	1.2	3.1
Standard UM, μV/V	0.2	0.5	0.4	0.9

Table 6 shows that the average value of the relative change in the output signal of Fluke 792A transfer standard was determined with UM which did not exceed 0.9 μV/V.

6. Discussion on direct definition of AC/DC transfer difference in the context of obtaining measurement information

The direct definition of AC/DC transfer difference is as follows: "the relative difference of the ac voltage in relation to the dc voltage at the reference point in the T-connector for the same output voltage of the transfer standard" [25]. Thus, in the direct definition, the voltage at the input of the thermal converter must be measured at the tee-connector point which is usually chosen by its center.

From the reports of all comparisons, it is unclear whether the potential possibility of using some additional connectors by any NMI was considered in some way. Applying of such an additional item should lead to the displacement of the middle point of the tee-connector. This task was assigned to each participating laboratory, and the result depended on the skill and experience of the performers. If some NMI applied an additional connector to match its equipment, then a shift of the middle point should have occurred. That is, the center point should have shifted from the position *A* to the position *B* (Fig. 6) if the resistance changes proportionally to the length growing.

If the value of the input resistance of the reference and the investigated thermal converters were significantly different, then an asymmetry of the potential distribution in the tee-connector should have occurred. The input signal must be applied to point *C* from the voltage source, and it is more convenient to measure this quantity at the same point. If one does not take special measures, for example, to improve the tee-connector to achieve the possibility of joining the meter to point *A*. But it is difficult to predict all variants of a connection of a thermal converter in each laboratory, and therefore the distribution of potential difference is rather going to be deprived of symmetry. Also, there is an additional question regarding the measured input voltage. It consists in the presence of an additional source of uncertainty since it is necessary to control the output signals of each thermal converter, as well as to measure, additionally, the input voltage.

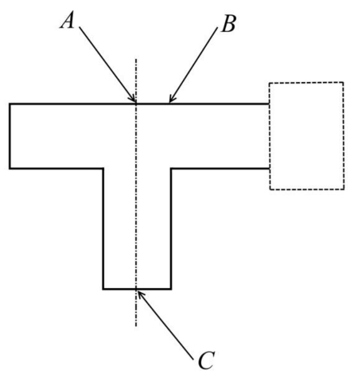

Fig. 6. Characteristic connecting points for applied voltage

None of the NMIs used the procedure of measuring the AC/DC difference according to the direct definition. In any case, it follows from the reports on key comparisons [7, 17, 18] and other sources that the measuring circuits did not contain the input voltage meters, that is, comparing of the output signals of the thermal converters was done. If the measuring procedure, when comparing the signals, is executed without obtaining the same value of the output signal of the reference thermal converter each time, then the connection with the direct definition of the AC/DC difference will be lost in the absence of a well-defined transformation coefficient.

Also, this connection will be lost when the drift of the reference thermal converter is not well investigated. Consequently, the question arises of the expediency of using a direct definition. If the NMI loses a connection with a direct definition, then, probably, it is necessary to give a real definition. For instance, "the difference between the output values of the thermo-EMF when the input voltages differ by the AC/DC difference of the reference thermal converter". In the case of the magnitude of this AC/DC difference less than 0.5 μV/V, one can speak of the equality of the input voltages. But, in any case, this is not a direct definition. The definition can be direct in the case of involving the direct or indirect determination of the values of the input voltages in the measuring procedure. For instance, when a well-defined transformation coefficient of the reference thermal converter is within the limits of the measured AC/DC difference of the calibrated thermal converter. Then, taking into account this MC, it is possible to determine the values of the input voltages through the difference that occurs at the output of the reference thermal converter.

It is necessary to have the two voltage sources with uncertainty at the level of 0.1 μV/V in order to determine indicated MC by direct definition. Such a condition was achieved at a frequency of 100 Hz [5] on the basis of Josephson's standards, but today there are still questions about the values which differ from the voltage of 1 V in the growing [12] and decreasing [15] direction. Otherwise, it is necessary to have a calculated AC/DC difference with an uncertainty of about 0.1 μV/V. But the subsequent dissemination of the unit size leads to the transition to the use of output signals to calculate MCs, considering the transformation coefficient of the thermal converter as a determined characteristic. If a transformation coefficient of a working standard is well-defined, then one can measure the AC/DC difference according to the direct definition.

When the voltage of 1 V is applied to the input of the reference thermal converter, it is possible to get the AC/DC difference within several tenths of μV/V. Consequently, the equivalent change in measuring the input voltage of the thermal converter by means of a precision meter will be at the level of the least significant digit. Under this condition, the AC/DC difference of the reference thermal converter can be considered absent.

In general, the results of the study allow laboratories, including NMIs which do not yet have NSs of an alternating voltage unit, to avoid mistaken steps when selecting working standards. The conducted studies of a long-term stability of both the high-precision voltage thermal converters and their lowest level of UM allows us to make the right choice of such converters. The detected insignificant influence of the frequency of the input signal on the coefficient of transformation of the thermal converter allows us to neglect reasonably this source of uncertainty.

Since the key comparisons considered were carried out for nominal voltages of 1.5 and 3 V in the frequency range from 1 kHz to 1 MHz, the conducted study has been limited to the indicated parameters of the alternating voltage. Reducing or increasing the nominal voltage leads to an increase in UM and a deterioration in the stability of working standards through the use of the additional scaling elements of a measurement information.

A certain disadvantage of the conducted study can be considered a limited number of MRs of AC/DC difference when estimating the stability of the travelling standards. This circumstance forms the direction of the further progress of studying the MCs of the high precision voltage thermal converters for using in the complement of NSs of an alternating voltage unit.

7. Conclusions

1. The four laboratories have been identified which created the most independent reference standards and had a decisive influence on the determination of the reference values of the key comparisons. These laboratories ensured the linking of the results of comparisons through re-participation in the multilateral and bilateral comparisons around the world to the first key comparison. The undisputed leader in the formation of the current degrees of equivalence of national standards of the world should be considered German NMI because many participants of the comparisons had metrological traceability to this laboratory.

2. By comparing, the type of reference thermal converter has been defined, which allow us to achieve the lowest level of the uncertainty of measurements: 0.4 μV/V at a frequency of 1 kHz, 0.8 μV/V at a frequency of 20 kHz, 2.0 μV/V

at a frequency of 100 kHz and 12.1 μV/V at a frequency of 1 MHz. This type is a thermal converter of a planar type on the basis of the thermocouples connected in series. The results of defining the stability of the travelling standards of various designs have shown a significant advantage of the thermal converters based on the thermocouple. The analysis of the coefficients of stability of such thermal converters showed an almost double advantage over thermal comparators constructed with the use of a sensor of root mean square voltage. This fact makes thermal converters on the basis of a thermocouple more attractive for the use in a complement of national standards.

3. It can be stated that there is no advantage of any of the three measurement schemes applied by different NMIs during the key comparisons of the AC/DC transfer standards. The uncertainties of measurements at a frequency of 1 kHz had practically the same level, about 0.5 μV/V, and it coincided completely in IEN, PTB and NRC laboratories at the level of 2.0 μV/V at 100 kHz. As a result, the overwhelming majority in the implementation of national standards received the simplest two-channel method.

4. The influence of the input signal frequency on the transformation coefficient of a planar type thermal converter has been investigated with the uncertainty of measurement at a level of about 0.7 μV/V. The evaluation results indicate that the corrections for compensating this factor depending on the frequency are inappropriate. A similar result was obtained when evaluating the effect of frequency on the change of the output signal of Fluke 792A thermal comparator with an uncertainty of measurements in the range from 0.2 to 0.9 μV/V. The approach to the measurement of the AC/DC transfer difference with providing a connection with the direct definition has been proposed, and two variants of procedural realization of such an approach have been analyzed. In particular, it has been suggested to measure additionally the input voltage or to determine precisely the relationship between the change of input and output signals.

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