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# Evaluation of Long-Term Stability of High-Precision Standard for Low-Frequency Voltage Measurement

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***Abstract* – The National measuring standards ensure the quality of measurements in different areas of science and technology. The actual errors of standards are not the only necessary characteristics to be determined. The long-term stability of the corrections also should be evaluated to guarantee the uncertainty of measurement is within the specified margin and, as a consequence, the metrological traceability is established. This paper mainly concerns the stability evaluation of the top-level standard for metrology service in low-frequency voltage measurement. The AC-DC transfer difference of high-precision voltage converter has been determined for almost 20 years. The measurements performed gave an opportunity to compare the deviations detected with the relevant combined uncertainties. The long-term stability estimate was within 20 µV/V for the frequency of 1 MHz.**

## I. INTRODUCTION

There are four secondary standards of the voltage of alternating current (AC) with 33 precision thermal converters in Ukraine that require calibration on the National standard of AC voltage. More than 700 other precision measuring instruments (MIs) for AC voltage also are operated. These are thermal converters of different types, calibration units for voltmeters, precision digital multimeters, etc. Such MIs are used in electricity, industrial technology for civil and military purposes, and other fields of science and technology. The metrological traceability of those standards and MIs is provided by the National standard of AC voltage.

Ukraine is a member of the World Trade Organization. The strategic goal of the state is to integrate into global world structures in various spheres of life. The state continues to implement a system of mutual recognition in the results of measurements of calibration and testing laboratories. A necessary condition for the recognition of measurement results is the compliance of the calibration laboratory with the criteria of the ISO/IEC 17025 standard [1], one of the requirements of which is to ensure measurement traceability in the calibration chain.

## II. BASIS FOR AC VOLTAGE MEASUREMENT

Two important factors should be kept in mind when analyzing the calibration chain to establish metrological traceability in the area of AC voltage measurements (Fig. 1). Firstly, the derived unit of voltage (V) of the redefined International System of Units is connected with two quantum constants through the Josephson constant $K_J=(2e)/h$, where $e$ is an elementary charge, $h$ is a Planck's constant [2]. Secondly, the Josephson standard [3] reproduces the unit of the voltage of direct current (DC). The AC/DC transfer standards are the high-precision standards for the difference between the root mean square (RMS) voltage and the equivalent DC voltage. Those standards are widely used to link AC and DC voltages [4-7].

It is necessary to compare two values of AC and DC voltages to determine the unit of AC voltage. The AC/DC transfer standard and DC voltage reference standard must be used for the high-precision reproduction of the AC

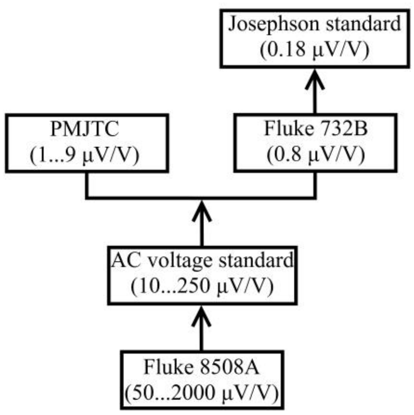


*Fig. 1. Metrological traceability of the AC voltage measurements.*

voltage unit. The metrological traceability will be branched to two primary standards (see Fig.1). The first one is Josephson voltage standard and the second one is planar multi-junction thermal converter (PMJTC).

The route of measurement traceability for AC voltage up to 1 MHz with corresponding measurement uncertainties from working standard (e.g., Fluke 8508A multimeter) to Josephson voltage standard is shown on Fig. 1. The Fluke 732B DC voltage reference instrument often is used as transportable for calibration with a primary standard.

The more stable each reproducible quantity in the chain is in the long term, the more reliable is ensuring the uncertainty of measurements matches the declared level.

## III. MAIN MATERIAL

### A. Procedure for stability determination

The focus of the current paper is the National standard of AC voltage, more precisely the AC-DC transfer standard Fluke 792A. The AC voltage standard is a complex set of MIs (voltmeters, sources, converters). It is presented in Fig. 2. For its stable operation, periodic calibration of the AC-DC voltage converter Fluke 792A [8] and DC voltage standards are carried out. The standards must have determined and confirmed characteristics (AC-DC transfer difference for Fluke 792A) with low uncertainty according to ISO/IEC 17025 standard.

The long-term stability of standards should not exceed specified values for a year. The minimum expanded uncertainty is 4 μV/V for a voltage of about 1 V and a frequency of 1 kHz following the Fluke 792A calibration certificate. The technical documentation of the National standard of AC voltage defines the interval of permissible values (from 2 to 36 μV/V) for the stability of AC-DC transfer difference.

The AC-DC voltage transfer difference is determined by sequentially applied voltage to the input of the thermal converter (an AC voltage of the required frequency, then a DC voltage of positive polarity, a DC voltage of negative polarity, and, finally, an AC voltage again). It is necessary to monitor the output voltage of the Fluke 792A reference converter.

The AC-DC voltage transfer difference $\delta_{AC\text{-}DC}$ is calculated by formula [9]:

$$\delta_{AC\text{-}DC} = \left. \frac{U_{AC} - U_{DC}}{U_{DC}} \right|_{E_{AC}=E_{DC}}, \quad (1)$$

where $U_{AC}$ and $U_{DC}$ are the input AC voltage and averaged DC voltage of a thermal converter respectively; $E_{AC}$ and $E_{DC}$ are the output thermal electromotive force (EMF) of the thermal converter, respectively, when an AC voltage or DC voltage is at the input.

PMJTC thermal converter (Germany) was used for determining the stability of the Fluke 792A instrument.

*Fig. 2. General view of the AC voltage standard.*

The calibration at 1.5 V of the PMJTC converter is approved by a PTB (Germany) calibration certificate. This voltage converter has very high long-term stability [10]. The results of the AC-DC difference comparison of the two voltage converters are the input data for the stability evaluation through the annual procedure.

The Fluke 792A instrument corrections given from the calibration certificate must be taken into account during the processing. A comparison of AC-DC voltage difference has been performed yearly since 2004 when the National standard of AC voltage was created in SE “Ukrmetrteststandard”.

### B. Results

The results of the comparison of the AC-DC difference of the PMJTC thermal converter and the Fluke 792A standard from 2004 till 2022 are presented in Table 1.

*Table 1. Comparison results at 1.5 V of AC-DC voltage difference of PMJTC and Fluke 792A from 2004 till 2022*

| Year | AC-DC difference (μV/V) depending on frequancy (kHz) | | | | | |
|---|---|---|---|---|---|---|
| | 0.01 | 0.045 | 1 | 10 | 100 | 1000 |
| 2004 | 0 | -2.2 | 2.0 | 1.5 | -5.0 | 16.0 |
| 2005 | 5.2 | 5.4 | 0 | 2.0 | -6.5 | 14.2 |
| 2006 | 3.0 | 10.3 | 2.9 | 0.2 | -7.7 | 12.7 |
| 2007 | 4.0 | 9.3 | 2.6 | 5.4 | -7.0 | 14.0 |
| 2008 | 8.0 | 14.6 | 2.7 | 3.7 | -5.0 | 9.0 |
| 2009 | 5.0 | 8.8 | 1.1 | 2.5 | -6.2 | 6.0 |
| 2010 | 2.0 | 1.6 | 0 | 0.9 | -2.4 | 8.6 |
| 2011 | 2.5 | 1.6 | 0 | 1.0 | -2.0 | 9.0 |
| 2012 | 2.9 | 2.1 | 0.5 | 1.9 | -2.9 | 10.0 |
| 2013 | 6.8 | 14.0 | 2.7 | 2.7 | -5.5 | 9.1 |
| 2014 | 8.8 | 13.6 | 2.1 | 3.0 | -5.7 | 10.9 |
| 2015 | 0.2 | 1.9 | 2.8 | 2.8 | -5.0 | 5.0 |
| 2016 | 2.0 | -2.8 | 1.7 | 3.0 | -7.0 | -4.6 |
| 2017 | 7.9 | 6.3 | 0.5 | 1.3 | -2.2 | 3.8 |
| 2018 | 3.0 | 9.7 | 0.9 | 4.5 | -3.4 | 21.5 |
| 2019 | 6.1 | 6.8 | 2.4 | 2.6 | -6.1 | 9.7 |
| 2020 | 1.9 | 11.5 | 1.8 | 3.5 | -7.3 | 1.1 |
| 2021 | 0.4 | 7.4 | 0.4 | 0.8 | -4.6 | 12.6 |
| 2022 | 4.3 | 3.9 | 1.3 | 2.9 | -3.4 | 4.6 |
| Mean | 3.9 | 6.5 | 1.5 | 2.4 | -5.0 | 9.1 |

Table 1 shows that the largest AC-DC difference from 2004 to 2022 was: 8.8 μV/V in 2014 at a frequency of 0.01 kHz; 14.6 μV/V in 2008 at 0.045 kHz; 2.9 μV/V at 1 kHz in 2006; 5.4 μV/V in 2007 at 10 kHz; -7.7 μV/V in 2007 at 100 kHz; 21.5 μV/V in 2018 at 1000 kHz. Comparing two adjacent values, one can calculate that the highest instability of National standard of AC voltage has a double margin related to the maximum permissible value (36 μV/V) by National standard of AC voltage specification.

The data in Table 1 indicate a significant dissimilarity of the distribution from the normal shape for frequencies from 0.01 to 100 kHz. But, the AC-DC difference distribution has a form similar to the normal one at a frequency of 1000 kHz.

The long-term stability associated with a high-precision voltage measurement standard of 1.5 V at frequencies of 10 Hz, 1 kHz and 1 MHz are shown in Figs 3-5.

The presented long-term instability has a chaotic character. This can be explained by the different grounding configuration of the components of the investigated National standard, dissimilar temperature of the surrounding air, probable use of different connecting conductors, non-identical operating duration of MIs.

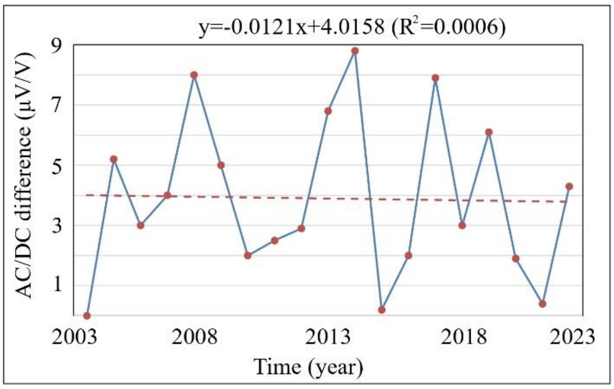


*Fig. 3. The long-term stability with corresponding drift of AC/DC transfer standard at frequency of 10 Hz.*

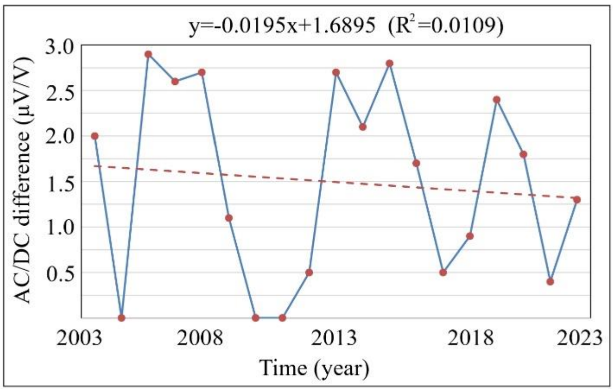


*Fig. 4. The long-term stability with corresponding drift of AC/DC transfer standard at frequency of 1 kHz.*

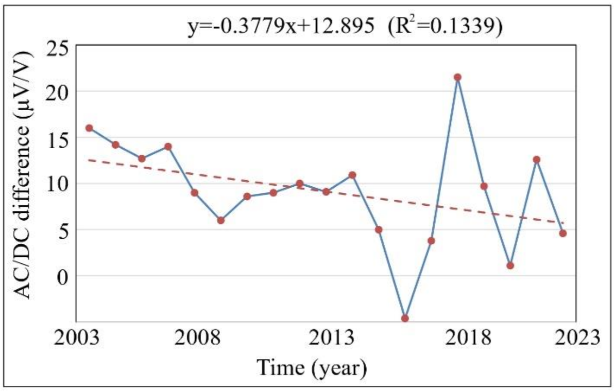


*Fig. 5. The long-term stability with corresponding drift of AC/DC transfer standard at frequency of 1 MHz.*

The accidental repair of some instruments and uncertain law of change of the AC-DC difference of both a PMJTC thermal converter and a reference Fluke 792A converter could be the reason as well.

### *C. Evaluation of measurement uncertainty*

It is possible to calculate the expanded uncertainty of the AC-DC difference measurements according to Table 1, assuming the invariance of the AC-DC voltage transfer difference of the PMJTC thermal converter during the period of a study.

According to a developed methodology, the measurement model for a single value of AC-DC difference $\delta_{ST}$ has the form

$$\delta_{ST}=\delta_{DIF}-\delta_{792A}-\delta_{NS}, \quad (2)$$

where $\delta_{DIF}$ is the value determined directly from measurements; $\delta_{792A}$ is a AC-DC transfer difference of a reference Fluke 792A standard by the calibration certificate; $\delta_{NS}$ is a combined parameter associated with short-term instability of a reference Fluke 792A instrument, voltmeters of the converter output signals, and sources of direct and alternating voltage which are parts of National standard of AC voltage. The short uncertainty budget, related to a measurement model, is compiled in Table 2.

Evaluating the long-term stability of National standard of AC voltage is a main task of the work. So, comparing the combined standard uncertainty, calculated by the original methodology, with the uncertainty contribution of the long-term scattering is of interest.

The general distribution of the random variable, combined basing on several normally distributed random variables, also tends to the normal according to the central limit theorem of probability theory. The resulting distribution can often be approximated to normal even when the component distribution deviates from normal. Type A standard uncertainty (a standard deviation) of AC-DC difference measurement can be calculated by the guide for expressing uncertainty of measurement [11].

*Table 2. Measurement uncertainty of AC-DC voltage difference measurements from 2004 to 2022*

| Characteristic | Estimate (μV/V) at frequency (kHz) | | | | | |
|---|---|---|---|---|---|---|
| | 0.01 | 0.045 | 1 | 10 | 100 | 1000 |
| Standard deviation for long-term stability $S_{DIF}$ | 0.6 | 1.2 | 0.2 | 0.3 | 0.4 | 1.3 |
| Combined uncertainty for AC-DC transfer standard $u_{792A}$ | 5.5 | 3.0 | 2.0 | 2.0 | 4.0 | 19.0 |
| Standard uncertainty of short-time instability $u_{NS}$ | 5.2 | 3.0 | 2.0 | 2.0 | 4.0 | 19.0 |
| Standard uncertainty in assuming the rectangular distribution $u_{DIF}$ | 2.5 | 5.0 | 0.8 | 1.5 | 1.6 | 7.5 |
| Combined uncertainty (normal distribution) | 7.6 | 4.4 | 2.8 | 2.8 | 5.7 | 26.9 |
| Combined uncertainty (rectangular distribution) | 8.0 | 6.6 | 2.9 | 3.2 | 5.9 | 27.9 |

Assuming a normal law of probability distribution, standard deviation is:

$$S_{DIF} = \sqrt{\frac{\sum_{i=1}^{n}\left(\delta_i - \bar{\delta}_{DIF}\right)^2}{n(n-1)}}\ , \qquad (3)$$

where $n$ is a number of measurement results of AC-DC transfer difference ($n = 19$).

The standard uncertainty of AC-DC difference $u_{DIF}$ can be calculated, if we assume a rectangular distribution low, by the formula [10]:

$$u_{DIF} = \left(\delta_{\max} - \delta_{\min}\right) / 2\sqrt{3} \qquad (4)$$

where $\delta_{\max}$ and $\delta_{\min}$ are the highest and the lowest values of AC-DC transfer difference depending on a frequency by Table 1.

The main contributions to a combined uncertainty are the expanded uncertainty for AC-DC transfer standard and the standard uncertainty of short-time instability as one can see in Table 2. These contributions of base components are made at each stage of the stability investigation. The last two components have been arising for the years.

Analyzing Table 2, one can see that the additional uncertainty contribution from instability adds a small percentage gain (at most 7 % for the worst measurement at 45 Hz) in assuming a normal distribution. A slightly different representation is in assuming a rectangular distribution law. This overestimation could lead to an increase in the combined uncertainty by more than half for 45 Hz and by one-fourth for 10 kHz.

## IV. CONCLUSION

The long-term stability of National standard of AC voltage was investigated for 1.5 V at frequencies of 10, 45 Hz, 1, 10, 100 kHz, and 1 MHz for 19 years at SE "Ukrmetrteststandard". It is likely that the recorded standard deviation of the observations reached its highest value at a frequency of 45 Hz due to the proximity to a power frequency of 50 Hz. A large difference in standard uncertainty in estimating scatter from normal and rectangular distributions has been noticed. Therefore, further careful consideration should be given to the possibility of applying a normal or other distribution law at this frequency. For other frequencies, an overestimation by a rectangular distribution law has no significant effect on the resulting combined uncertainty.

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