

# Evaluating Uncertainty of Alternating Current Reproduction Using National Standard

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**Abstract** – The research work was aimed at improvement of metrological service of Ukraine, i.e., to solve a problem of metrological support of the production and operation of the thermoelectric converters, precision meters and sources of alternating current. A method of comparing alternating current with equivalent direct current using the precision thermal converter and shunts was selected to build the standard, and the composition of the standard was established. A functional diagram of the standard was developed to disseminate an alternating current unit. The main sources of measurement uncertainty of this unit are a combination of Type B standard uncertainty of both a thermoelectric converter and a precision shunt. A contribution to combined measurement uncertainty of both the set of measures of electrical resistance and the meters of an output voltage of both a measure of electrical resistance and a thermal converter was analyzed.

## I. INTRODUCTION

The State Enterprise (SE) “Ukrmetrtestestandard” has carried out research and development work “Creation of the state primary standard of an alternating current unit” from 2016 to 2019 [1]. An analysis of the calibration and measurement capabilities (CMC) of the National Metrology Institutes showed that the vast majority of methods for implementing national standards have been realized using thermoelectric conversion. This allows us to achieve measurement uncertainty in units, tens or hundreds of  $\mu\text{A/A}$  depending on the frequency [2]. It should be noted that mentioned standards are primarily the standards of AC/DC transfer, but the SI Base Unit of electrical physical quantity is an ampere.

The desire of scientists to achieve the lowest possible measurement uncertainty to demonstrate the best CMCs is one of the reasons for the large number of publications

describing the complex systems for calibrating the current thermal converters. Such procedure does not implement the process of dissemination of a unit of ampere directly because there are no means of measuring or reproducing a current. As a result, covering the peculiarities of high-precision reproduction of a unit of ampere and evaluating the measurement uncertainty with the analytical expressions is difficult to find among scientific papers.

According to Ohm's law, a unit of alternating current can be reproduced if the voltage drop is determined with the highest accuracy on a well-characterized measure of complex resistance. It is well-known that a measurement uncertainty of calibration of the resistance measure to an alternating current is many times greater than the similar characteristic for the resistance measure to a direct current. A similar statement is also suitable for the calibration of precision voltage meters. Therefore, for the high-precision reproduction of ampere unit for an alternating current, DC resistance measure and a precision direct voltage meter are also required.

This paper aims to highlight the aspects of a reproduction of alternating current unit using the national standard. In particular, based on the already conducted scientific and technical work, a mathematical model of the process of reproduction of an ampere unit of alternating current has been obtained.

A feature of the presented model is the introduction into the analytical expression of variables that characterize the scattering of readings of the precision direct voltage meters. One of the direct voltage meters is intended to measure the output signal of the reference thermal comparator, and the other is intended to measure the output signal of DC resistance measure.

Since each mathematical model is unique, respectively, the sensitivity coefficients for each input quantity will have the peculiarities due to the model expression. The analytical expressions for the calculation of these sensitivity coefficients are also presented in the paper.

## II. BASIS FOR OPERATION OF STANDARD

The alternating current always flows in the conducting medium with voltage drops occurring in different sections of the current circuit. This phenomenon provides a close unbroken link between current and voltage characterized by Ohm's law. The method of comparing the root-mean-square (RMS) value of a harmonic electrical signal with the equivalent value of a constant signal is the basis for the asynchronous comparison of both voltage [3] and current [4]. It is necessary to control the invariance of the value of the output thermo-electro-motive force (thermo-EMF) of the reference thermoelectric converter, and the value of AC/DC transfer difference  $\delta_{AC/DC}$  is calculated by a well-known formula:

$$\delta_{AC/DC} = \frac{Q_{AC} - Q_{DC}}{Q_{DC}} \Big|_{E_{AC} = E_{DC}} \quad (1)$$

where  $Q_{AC}$ ,  $Q_{DC}$  are average values of input AC or DC quantity;  $E_{AC}$ ,  $E_{DC}$  are values of the output thermo-EMF of thermal converter at applied input AC or DC quantity.

Significant progress in achieving the lowest level of measurement uncertainty has been made following the development of a thin-film set of thermocouples, called planar multi-junction thermal converters (PMJTC), connected in series whose output signal reaches almost 100 mV [5]. The PMJTCs provide long-term stability, high sensitivity, and high dynamic range. For thermal converters in which thermocouples are used, as is the case with the PMJTC, the output thermo-EMF has a quadratic dependence on the input voltage or current.

Unlike widely used in the national standards of the vast majority of countries of the multi-junction thermal converters, the AC/DC transfer standard Fluke 792A is based on an RMS sensor which has almost linear dependence of the output signal:

$$U_{out} = K \cdot U_{in} \quad (2)$$

where  $K$  is a characteristic coefficient of a thermal converter based on the RMS sensor;  $U_{in}$  is an input AC voltage or an equivalent DC voltage.

In operation, the current, which can be estimated by a single-element thermal converter, reaches 20 A (in more modern systems up to 100 A) with the addition of resistive shunts [4]. The standard measurement uncertainties are in the range from 0.2  $\mu$ A/A at 25 mA and 1 kHz to 50  $\mu$ A/A at 20 A and 100 kHz. The reference shunts are characterized by a stable resistance and a low-temperature coefficient. Modern current shunts allow both DC and AC measurements and provide a wide frequency range. When using a precision thermal converter, the influence of the factors that may become additional sources of a measurement uncertainty must be taken into account. These factors include DC reversal of polarity, connecting cables, thermo-EMF due to the Seebeck effect, stray currents of the ground bus, electromagnetic interference, etc.

## III. COMPLEX OF MEASURING INSTRUMENTS FOR CREATED STANDARD

The general view of the created standard of the AC unit is shown on Fig. 1.



Fig. 1. The general view of the created standard of AC unit.

A rational approach to creating national standard of alternating current unit pushes to take into account the significant experience of operating another national standard of AC voltage unit (DETU 08-07-02) which includes precision thermal comparator Fluke 792A and other devices for measurement of electrical quantities [6]. Consideration should be given to using these instruments as part of the standard being created since precision A40 shunts are easily and reliably combined with Fluke 792A thermal comparator. In such a configuration, these devices are a high-precision reference for determining the AC/DC transfer difference of the current thermoelectric converters.

The comparative analysis of the long-term stability of thermal converters in the complement of national standards in many countries gave additional grounds for the use of the thermal comparator Fluke 792A as a reference for the dissemination of AC voltage unit [7]. SE “Ukrmetrtestestandard” has a positive experience in the operation of the precision measuring equipment such as precision AC/DC transfer standard Fluke 792A, multifunction calibrator Fluke 5720A, and precision multimeter Agilent 3458A. It is technically feasible and economically appropriate to use such technical means as part of the created state standard of the AC unit. The AC/DC transfer standard Fluke 792A and the A40 precision shunts have a long history of being used as the high-precision standards in many countries [8].

The disadvantages of this standard include, however, somewhat greater measurement uncertainties of in disseminating a unit of ampere than when using a multi-

junction thermal converter. Nevertheless, this characteristic can be improved by introducing one multi-junction thermal converter with the AC/DC transfer difference defined by the calculation and measurement.

The implementation of the State Standard requires at least 11 precision A40 shunts for a range of rated current which will allow providing metrological support in the current range from 0.001 to 20 A and in the frequency range from 10 Hz to 100 kHz. To ensure high metrological accuracy of the indirect measurement of DC by Ohm’s law, a stable measure of DC voltage is required. This device disseminates the unit size of a DC voltage from the State Standard of a DC unit to the precision direct voltage meters that measure the output signals of both a current thermal converter and a standard resistance measure.

The functional diagram of an implementation of the method of comparing AC with DC using a precision thermal comparator and shunts is shown in Fig. 2.

The unit of ampere for an alternating current is reproduced in at least three stages. In the first stage, an alternating current of the desired frequency flows in the current circuit. The output alternating voltage from the A40 precision shunt is applied to the input of the Fluke 792A reference thermal comparator. According to the readout of the P3003 direct voltage meter, the output signal of thermal comparator is determined and recorded (the measured value must be as constant as possible during the entire reproduction cycle). The second and third stages differ only in the direction of flow of a direct current in the circuit of a current reproduced.

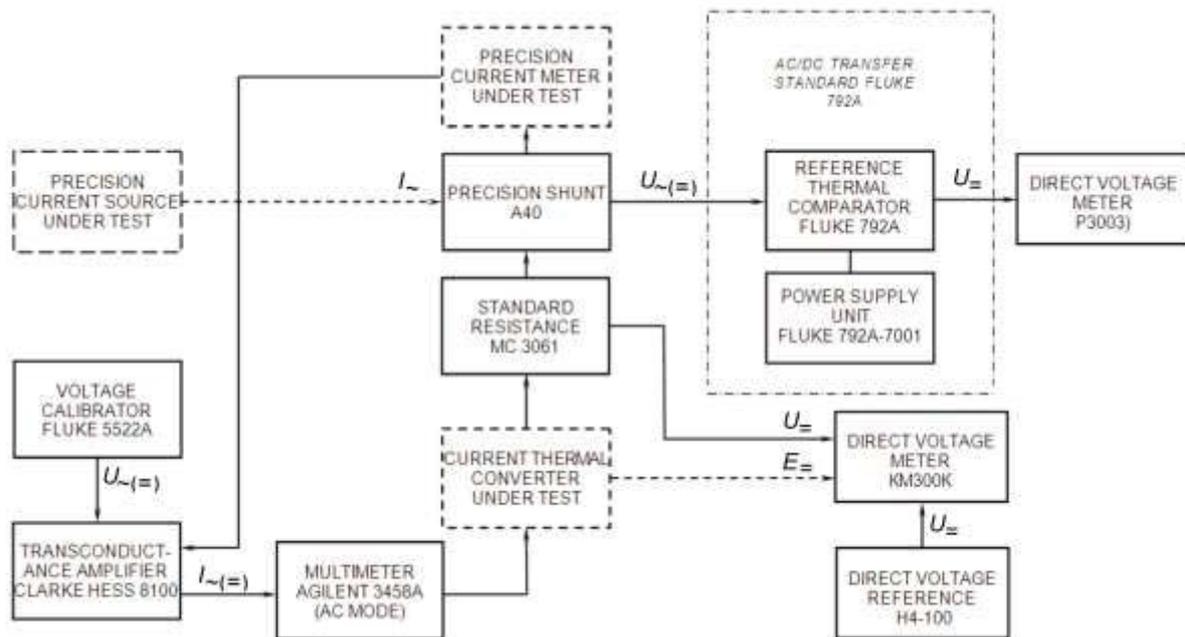


Fig. 2. Functional diagram of created State Standard of AC unit.

The magnitude of this current should be set so that the output signal of thermal comparator Fluke 792A reaches the value of the first stage. Further, the size of ampere unit is determined by Ohm's law for a direct current according to the readout of KM300K direct voltage meter and the actual resistance value of MC3061 measure. Since the AC/DC transfer differences of both the precision shunt A40 and the thermal comparator Fluke 792A are well defined, it is easy to calculate the value of corresponding alternating current.

#### IV. MEASUREMENT UNCERTAINTY ANALYSIS

For the analysis of contributions of the influent quantities at reproducing a unit of ampere, it is necessary to obtain a mathematical (measurement) model. During the flow of alternating current through a precision shunt with an electrical resistance (impedance), a complex voltage drop occurs on this resistance. When a direct current flow through a precision shunt with an active electrical resistance, a voltage drop on this resistance differs slightly (depending on AC/DC transfer difference of the A40 precision shunt) comparing with previous stage. One should take into account the AC/DC transfer difference of the thermal comparator Fluke 792A, actual resistance of MC3061 measure, correction to readout of KM300K meter to obtain an accurate value of a current.

Having analyzed the scheme in Fig. 2 and the sequence of the AC reproduction process, given expressions (1) and (2), one can obtain a mathematical model:

$$I_{AC} = (1 + \delta_{TC}) \cdot (1 + \delta_{SH}) \cdot \frac{U_{ac} \cdot (U_+ + U_-)}{R_M \cdot (U_{dc+} + U_{dc-})} \quad (3)$$

where  $\delta_{TC}$  and  $\delta_{SH}$  are the AC/DC transfer difference of thermal comparator Fluke 792A and precision shunt A40;  $U_+$  and  $U_-$  are the readout of DC voltage meter of standard resistance output depending on the direction of DC flow;  $R_M$  is the true value of the resistance of the standard measure;  $U_{dc+}$ ,  $U_{dc-}$  and  $U_{ac}$  are the readout of DC voltage meter of thermal comparator Fluke 792A output depending on DC flow direction and AC frequency.

The presented expression is a mathematical model for reproducing an alternating current in amperes, not AC/DC transfer in relative units. In this expression, there is a mathematical link of the reproduced current with the readings of direct voltage meters, which is not in expression (1). This circumstance makes it easy to evaluate a contribution of these input quantities to a combined measurement uncertainty. The sensitivity coefficients for these quantities are easily calculated by differentiating the expression (3).

From the obtained expression (3), it can be seen that alternating current is based on the values of electrical resistance and the readout of the DC voltage meter. The AC/DC transfer difference of both the reference thermal comparator Fluke 792A and the shunt A40 should also be taken into account when reproducing the AC unit.

Table 1 shows the uncertainty budget for the reproduction of 20 A at a frequency of 50 kHz.

Table 1. The uncertainty budget for reproduction of alternating current.

Source of uncertainty	Type	Distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution, A	Degrees of freedom
Resistance of standard measure	B	normal	$4.0 \cdot 10^{-9} \Omega$	$-2 \cdot 10^4 \text{ V} \cdot \Omega^{-2}$	$8.0 \cdot 10^{-5}$	30
DC voltage meter of standard resistance output	B	uniform	$2.5 \cdot 10^{-7} \text{ V}$	$1 \cdot 10^3 \Omega^{-1}$	$2.5 \cdot 10^{-4}$	$\infty$
DC voltage meter of thermal comparator Fluke 792A output	B	uniform	$1.4 \cdot 10^{-6} \text{ V}$	$50 \Omega^{-1}$	$7.0 \cdot 10^{-5}$	$\infty$
AC/DC transfer difference of thermal comparator Fluke 792A	B	normal	$6.0 \cdot 10^{-6}$	20 A	$1.2 \cdot 10^{-4}$	30
AC/DC transfer difference of precision shunt A40	B	normal	$3.2 \cdot 10^{-5}$	20 A	$6.4 \cdot 10^{-4}$	30
AC repeatability of thermal comparator Fluke 792A output meter	A	normal	$1.5 \cdot 10^{-6} \text{ V}$	$50 \Omega$	$7.5 \cdot 10^{-5}$	10
DC repeatability of thermal comparator Fluke 792A output meter	A	normal	$1.4 \cdot 10^{-6} \text{ V}$	$50 \Omega$	$7.0 \cdot 10^{-5}$	10
DC repeatability of standard resistance output meter	A	normal	$1.4 \cdot 10^{-7} \text{ V}$	$1 \cdot 10^3 \Omega^{-1}$	$1.4 \cdot 10^{-4}$	10
Root square sum of Type A standard uncertainties					$1.74 \cdot 10^{-4}$	21
Root square sum of Type B standard uncertainties					$7.06 \cdot 10^{-4}$	44
Combined standard uncertainty					$7.27 \cdot 10^{-4}$	50
Expanded uncertainty ( $k = 2$ )					$14.5 \cdot 10^{-4} \text{ A}$	

The Type B standard uncertainties were obtained from calibration certificates, and Type A uncertainties were estimated by multiple measurements with DC voltage meters.

According to GUM 1995 [9], to determine the sensitivity coefficients of the input quantities according to the mathematical model (3), one must take the first partial derivatives for each input quantity.

To estimate the contribution of AC/DC transfer difference  $\delta_{TC}$  of AC/DC transfer standard Fluke 792A, the expression presented below should be considered:

$$\frac{\partial I_{AC}}{\partial \delta_{TC}} = \frac{U_+ + U_-}{R_M} \cdot \frac{(1 + \delta_{SH}) \cdot U_{ac}}{U_{dc+} + U_{dc-}} \quad (4)$$

The  $\delta_{SH}$  contribution differs little from expression (4) and is estimated as follows:

$$\frac{\partial I_{AC}}{\partial \delta_{SH}} = \frac{U_+ + U_-}{R_M} \cdot \frac{(1 + \delta_{TC}) \cdot U_{ac}}{U_{dc+} + U_{dc-}} \quad (5)$$

The expressions for the calculation of the sensitivity coefficients for estimating the input contribution of  $U_+$  and  $U_-$  are the same and are determined as follows:

$$\frac{\partial I_{AC}}{\partial U_+} = \frac{\partial I_{AC}}{\partial U_-} = \frac{(1 + \delta_{TC}) \cdot (1 + \delta_{SH})}{R_M} \cdot \frac{U_{ac}}{U_{dc+} + U_{dc-}} \quad (6)$$

The expressions for the calculation of the sensitivity coefficients for estimating the input contribution of  $U_{dc+}$  and  $U_{dc-}$  are the same and are determined by:

$$\frac{\partial I_{AC}}{\partial U_{dc+}} = -\frac{U_{ac} \cdot (1 + \delta_{TC}) \cdot (1 + \delta_{SH}) \cdot (U_+ + U_-)}{R_M \cdot (U_{dc+} + U_{dc-})^2} \quad (7)$$

To determine the contribution of  $U_{ac}$ , the expression is as follows:

$$\frac{\partial I_{AC}}{\partial U_{ac}} = \frac{(1 + \delta_{TC}) \cdot (1 + \delta_{SH})}{U_{dc+} + U_{dc-}} \cdot \frac{U_+ + U_-}{R_M} \quad (8)$$

To determine the contribution of  $R_M$ , the expression is:

$$\frac{\partial I_{AC}}{\partial R_M} = -\frac{(1 + \delta_{TC}) \cdot (1 + \delta_{SH}) \cdot (U_+ + U_-)}{U_{dc+} + U_{dc-}} \cdot \frac{1}{R_M^2} \quad (9)$$

The expressions obtained allow us to calculate the Type A combined measurement uncertainty for indirect measurement characterized by the scattering of the readouts of precision DC voltage meters in three stages. The calculation of Type B combined measurement uncertainty, which is due to the uncertainty of the measurements in the calibration of each device used in three steps, must be performed using the above formulas as well.

## V. CONCLUSION

The main element of the national system of the metrological support of the production and operation of measuring instruments of alternating current was created in SE "Ukrmetrtestestandard".

The proposed functional diagram allowed us to derive a mathematical model of AC reproduction. Based on the proposed mathematical model, the analytical expressions were obtained to calculate the sensitivity coefficients of each input quantity.

The measurement results obtained at one of the worst point of 20 A at frequency of 50 kHz allowed to estimate the expanded measurement uncertainty of 73  $\mu$ A/A.

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