# METROLOGICAL TRACEABILITY FOR INSTRUMENT TRANSFRORMERS APPLICATIONS

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**Abstract.** A critically important segment of the electrical industry is the supply of electricity using high-voltage technologies. The metrological reliability of voltage, current and electrical energy measuring devices is confirmed by timely verification of compliance of measurement errors with the requirements of standards. In export-import operations with electricity, recognition of measurement and testing results at the international level comes to the fore. Metrological traceability and measurement uncertainty assessment, which are established during the calibration of standards and measuring instruments, are important components in the recognition of measurement results. The article presents the ranges of AC voltage and current measurement values, the ranges of the corresponding measurement uncertainty and the standards used, linked in the schemes of metrological traceability chains. The construction and clarification of metrological traceability chains for high AC voltage and current measurement using instrument transformers is a relevant task that is solved in the work. The proposed chains of metrological traceability hierarchy are used in Ukraine, in particular in the State Enterprise "Ukrmetrteststandard", which is the holder of national standards of the highest accuracy. Among others, they ensure the uniformity of measurements through the calibration of secondary and working standards, as well as the verification or calibration of working instruments for measuring high alternating voltage and high alternating current by reducing the measured value to the measurement range of electricity meters. The specified chains can be used by accredited measuring laboratories that calibrate working measuring instruments for scaling high AC voltage and current, i.e., voltage transformers and current transformers, in accordance with their own scope of accreditation.

**Key words:** Transformer, AC Voltage, Alternating Current, Metrological Traceability, Calibration, Measurement Uncertainty

## 1. Introduction

A large number of Ukrainian enterprises have settlement and economic relations with electricity suppliers. The focus of such relations is always the issue of fairness in calculating the amount of payment for services provided, which directly depends on the correctness of data exchange between the components of the accounting system. In other words, the service amount provided must have reliable confirmation, and the calculation of the bill to be paid in accordance with the current tariff must clearly correspond to the quantity of electricity consumed.

Measuring instruments such as electricity meters and instrument transformers are designed to allow charging for consumed energy resources reliably. Electricity for powerful enterprises is generated by large power plants at high voltage with high current. Therefore, in the chain of conversion of information about consumed electricity, voltage transformers (VTs) are the determining means of scaling high alternating voltage, and current transformers (CTs) are used for scaling high alternating current.

The reliability of accounting for consumed electricity in interstate commercial relations is of particular importance, which requires confirmation of the metrological characteristics of measuring instruments with international recognition. In Ukraine, instrument transformers are legally regulated measuring instruments and are subject to verification. In turn, working standards for verification must have calibration certificates, which indicate information about the uncertainty of measurements and information about metrological traceability [1] to the international SI system [2].

The best level of measurement uncertainty for AC voltage and current in the country is determined by the metrological characteristics of the corresponding national standards (NS) [3]-[5]. The measurement uncertainty when using the NS should not differ significantly from the values of similar standards of other countries. Metrological traceability usually occurs during the calibration of a measuring instrument [6], [7], along with the measurement uncertainty which is also determined [8]. NSs should have published calibration and measurement capabilities (CMC) in the database on the website of the International Bureau of Weights and Measures [9]. If the NS has published CMC rows, then it provides a connection with the international SI system and allows us to establish the traceability of measurements of the corresponding physical quantity. The NS has the task of ensuring the state an appropriate level of competitiveness of national producers in the global market system.

## 2. Drawbacks

There are several problematic aspects related to calibration, and, consequently, to the traceability and uncertainty of measurements, when determining the metrological characteristics of instrument transformers and sensors. Several approaches to determining the amplitude and angular errors of these measuring instruments can be identified, for example, within the laboratory [10], where the best conditions for calibration exist, or on-site [11], where many questions arise regarding connection to installed equipment. In particular, overcoming the problem of both the grounding measuring equipment and the requirements for high-voltage insulators using non-contact voltage sensors is accompanied by an increase in measurement errors [12]. Non-traditional approaches to determining the errors of instrument transformers are also emerging, for example, by using large amount of accumulated data with great discretization [13]. At the same time, the traditional approach to CTs calibration is being improved to investigate previously unassessed factors of influence, in particular, high voltage-induced leakage current on calibration results [14].

With the development of modern digital technologies, calibration laboratories face new challenges, such as overcoming problems with the design features of digital instrument transformers [15], taking into account the influence of temperature during remote calibration [16], and correcting errors using a modern measurement information processing system [17]. The integration of digital technologies into the power supply system has enabled the application of an online monitoring method for the metrological characteristics of capacitive VTs [18]. In contrast to this approach, the application of an improved method of comparison with a standard has also enabled the calibration of instrument transformers for the purposes of assessing the quality of electricity [19]. However, in the presented works, certain questions regarding metrological traceability remain, in particular, in work [20] the aspect of taking into account the branching of the traceability direction through the use of a means of comparing two secondary voltages or currents is considered.

## 3. Goal

The purpose of this work is to highlight the features of establishing metrological traceability of high-voltage measurements in the range from 1 kV to 1.2·330/√3 kV and high-current measurements in the range up to 3 kA to ensure the link with the international SI system and recognition of measurement results at the international level. Moreover, the measured quantities are scaled down using measuring VTs and CTs to values compatible with the measurement range of electricity meters in energy accounting systems, in particular when exporting or importing electric energy.

## 4. National standards for scale transformation coefficients of alternating voltage and current

### 4.1 National standard for scale transformation coefficient of AC voltage

The NS of the scale transformation coefficient of AC voltage is intended for metrological support of high AC voltage measurements using VTs. It has been developed and operates at the State Enterprise "Ukrmetrteststandard" (UMTS, Kyiv, Ukraine) since 1999. It stores the units of the AC voltage and the scale transformation coefficient of AC voltage and provides link to the international SI system as well as accurate measurements of high AC voltage in the range from 1 to 1.2·330/√3 kV. Metrological characteristics of NS of scale transformation coefficient of alternating voltage are:

- range of rated primary voltage – from 1 to 330/√3 kV;
- range of rated secondary voltage – from 100/3 to 150 V;
- standard deviation of the measurement result when reproducing the scale transformation coefficient of alternating voltage does not exceed $1\cdot10^{-4}$;
- expanded measurement uncertainty for ratio error is from $7\cdot10^{-5}$ to $3\cdot10^{-4}$;
- expanded measurement uncertainty for phase displacement is from 0.5 to 1.5 min;
- annual instability does not exceed $1\cdot10^{-4}$.

NS of scale transformation coefficient of alternating voltage does not have capability to be transported and consists of the next parts:

- 3 measures for scale transformation coefficient of alternating voltage:

M1 consists of several inductive scale transformers of poured type up to 15 kV;

M2 is an inductive scale transformer of oil type up to 110/√3 kV;

M3 is an inductive scale transformer of oil type up to 330/√3 kV;

- a precision scale converter for low voltage;
- a precision meter of voltage difference;
- voltmeters for a voltage up to 200 V;
- a complex of devices for investigating the measures for scale transformation coefficient of alternating voltage.

The general view of DETU 08-05-99 is shown in Fig. 1.

The application of a low-voltage scale converter allows us to compare the secondary voltages of two VTs during calibration with a resolution of 0.001 V for a secondary voltage of 100 V. The process of determining the metrological characteristics (ratio error and phase displacement) of the reference VT being calibrated is implemented by applying a high voltage from the step-up power transformer to the parallel-connected primary windings. Due to the use of the method of simultaneous comparison of two secondary voltages, the transfer of the scale coefficient size is accompanied by high stability of the readings of the voltage difference meter. The metrological characteristics of the reference VT are determined when loading its secondary winding using a conductivity burden, setting the required power value. Using the step-up power transformer, the required primary voltage values are set.

*Fig. 1. The general view of the National Standard of the AC Voltage Scale Coefficient*

When calibrating a working or secondary standard, it is necessary to determine the actual values of the scaling errors of the standard transformer taking into account the actual value of the scale transformation coefficient of the NS, which is calculated by the formula:

$$\varepsilon_{VX} = \frac{K_{VX} - K_{VS}}{K_{VS}} \cdot 100\% , \quad (1)$$

where $K_{VX}$ is the AC voltage scale transformation coefficient of the working standard, determined during the calibration, $K_{VS}$ is an actual value of the AC voltage scale transformation coefficient of the NS.

Regarding the second metrological characteristic, that is, the phase shift between the primary and secondary voltages – it is determined by the formula:

$$\Delta\varphi_{VX} = \varphi_{VX} - \varphi_{VS} , \quad (2)$$

where $\varphi_{VX}$ is phase displacement of the AC voltage scale transformation of the working standard, determined during the calibration, $\varphi_{VS}$ is an actual value of the phase displacement between the primary and secondary voltages of the NS.

The combined standard uncertainty when determining the scale transformation coefficient of the reference VT is calculated by the equation:

$$u_{\varepsilon VX} = \sqrt{\left(c_{KVS} \cdot u_{KVS}\right)^2 + \left(c_{KVX} \cdot u_{KVX}\right)^2} , \quad (3)$$

where $c_{KVS}$ is a sensitivity coefficient for ratio error of reference VT under calibration due to the change of the scale transformation coefficient of the NS; $u_{KVS}$ is the type B standard uncertainty of the scale transformation coefficient of the NS; $c_{KVX}$ is a sensitivity coefficient for ratio error of reference VT under calibration due to the change of the scale transformation coefficient of the working standard; $u_{KVX}$ is the type A standard uncertainty of the scale transformation coefficient of the working standard determined as the standard deviation during calibration.

The calibration and measurement capabilities of the scale transformation coefficient of the NS of Ukraine are comparable to the characteristics of measuring systems of similar purpose of other National Metrology Institutes (NMI), some of which are presented in Table 1 [9].

Table 1 shows that the best among the listed CMCs capabilities are declared by the Canadian NRC in terms of the ratio between the maximum voltage and the corresponding measurement uncertainty. It should be noted that depending on the level of technical development of a particular country, the relevant NMI provides CMC service up to a certain value of the AC voltage. Thus, Georgia, Uruguay, South Korea, and Hungary establish metrological traceability for AC voltage measurements using VTs to a level lower than in Ukraine. The other NMIs presented in the table provide better levels of maximum voltage and measurement uncertainty.

**Table 1.** Metrological characteristics of some national standards for high AC voltage scale coefficient

| Country, NMI | Maximum voltage, kV | Expanded uncertainty, μV/V |
|---|---|---|
| Argentina, INTI | 525 | 200 |
| Australia, NMIA | 500 | 60 |
| Georgia, GEOSTM | 70 | 100 |
| Czech Republic, CMI | 400 | 100 |
| Ukraine | 220 | 300 |
| Germany, PTB | 277 | 10 |
| Uruguay, UTE | 150 | 300 |
| South Korea, KRISS | 200 | 40 |
| Hungary, BFKH | 70 | 170 |
| Canada, NRC | 500 | 20 |

### 4.2 National standard for scale transformation coefficient of AC current

The NS of the scale transformation coefficient of AC current is intended for metrological support of measurements of large current using CTs. It has been developed and operates at UMTS, Ukraine since 2007. It stores the size of the scale transformation coefficient of AC current and provides link to the international SI system as well as accurate measurements of high AC current in the range from 10 A to 1.2·10 kA. Metrological characteristics of NS of scale transformation coefficient of alternating current are:

- range of rated primary current – from 0.5 to 10000 A;
- rated secondary current – 1 and 5 A;
- standard deviation of the measurement result when reproducing the scale transformation coefficient of alternating current does not exceed $1.5 \cdot 10^{-5}$;
- expanded measurement uncertainty for ratio error is from $3.2 \cdot 10^{-5}$ to $1 \cdot 10^{-4}$;
- expanded measurement uncertainty for phase displacement is from 0.3 to 1 min;
- annual instability does not exceed $1 \cdot 10^{5}$.

NS of scale transformation coefficient of AC current does not have capability to be transported and consists of the next parts:

- 3 measures of scale transformation coefficient of AC current:

M1 consists of several input and output windings for currents up to 1 kA;

M2 is a two-stage CT which provides a transformation coefficient of 100 for currents up to 5 kA;

M3 is applied in conjunction with M1 and has several secondary windings for currents up to 10 kA;

- a comparator CA507;
- a control-regulating unit for currents from 0.5 to 3000 A;
- a measuring circuit power supply transformer up to 10 kA;
- specialized auxiliary equipment.

Calibration of reference measuring instruments is carried out using the CA507 comparator which is a part of the NS. The functioning of the scale transformation coefficient measures M1, M2, and M3 is ensured by a complex of power equipment when reproducing the size of the scale transformation coefficient of the AC current. The purpose of the power equipment is to provide electric current with a frequency of 50 Hz with the necessary parameters (range of current, THD factor, and short-term stability of the set current) in the primary current circuit of the NS and the working standard under calibration. The power equipment of the NS is divided into two autonomous complexes that perform the assigned functions of the standard in two current ranges: from 0.5 to 3000 A, and from 3000 to 10000 AThis division is due to the technical features of the elements of electrical equipment (power transformers, voltage regulators) which are used as part of power equipment to create and supply electrical circuits. The power supply of the measuring circuit is provided by two power sources: single-phase has a rated voltage of 380 V and a power capability of 76 kVA, and three-phase has a voltage of 380 V and a power capability of 24 kVA.

The general view of the NDETU EM-02-2019 is presented in Fig. 2.

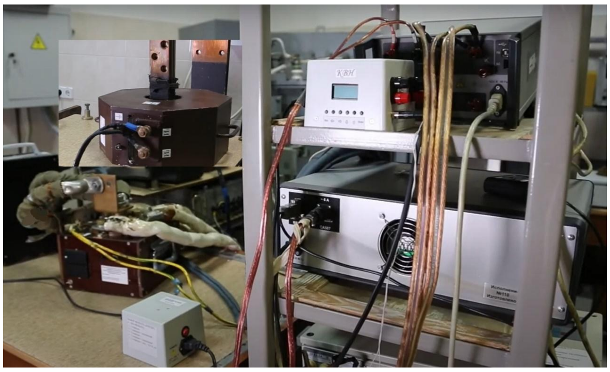

*Fig. 2. The general view of the National Standard of the AC Current Scale Coefficient*

Due to the use of the method of simultaneous comparison of two secondary currents, the dissemination of the scale transformation coefficient of AC current is accompanied by high stability of the AC comparator readings. Since this measuring instrument also contributes to the expanded uncertainty, its metrological characteristics were also evaluated [21]. The metrological characteristics of the CT under calibration are determined by loading its secondary winding using a resistance burden and setting the required power value. The required primary current is set using a step-up power transformer.

When calibrating a working or secondary standard, it is necessary to determine the actual values of the ratio errors of this reference CT coefficient taking into account the actual value of the current scale transformation coefficient of the NS. It is calculated by the formula:

$$\varepsilon_{CX} = \frac{K_{CX} - K_{CS}}{K_{CS}} \cdot 100\% , \qquad (4)$$

where $K_{CX}$ is the AC current scale transformation coefficient of the working standard, determined during the calibration, $K_{CS}$ is an actual value of the AC current scale transformation coefficient of the NS.

Regarding the second metrological characteristic, that is, the phase shift between the primary and secondary voltages – it is determined by the formula:

$$\Delta\varphi_{CX} = \varphi_{CX} - \varphi_{CS} , \qquad (5)$$

where $\varphi_{CX}$ is phase displacement of the AC current scale transformation of the working standard, determined during the calibration, $\varphi_{CS}$ is an actual value of the phase displacement between the primary and secondary currents of the NS.

The combined standard uncertainty when determining the scale transformation coefficient of the reference CT is calculated by the equation:

$$u_{\varepsilon CX} = \sqrt{(c_{KCS} \cdot u_{KCS})^2 + (c_{KCX} \cdot u_{KCX})^2}, \quad (6)$$

where $c_{KCS}$ is a sensitivity coefficient for ratio error of reference CT under calibration due to the change of the scale transformation coefficient of the NS; $u_{KCS}$ is the type B standard uncertainty of the scale transformation coefficient of the NS; $c_{KCX}$ is a sensitivity coefficient for ratio error of reference CT under calibration due to the change of the scale transformation coefficient of the working standard; $u_{KCX}$ is the type A standard uncertainty of the scale transformation coefficient of the working standard determined as the standard deviation during calibration.

Table 2 presents information on the calibration and measurement capabilities of the AC current scale transformation coefficient of the Ukrainian NS and similar characteristics of measuring systems of some other NMIs [9].

According to Table 2, among the presented CMCs, the best capabilities are declared by the Australian NMI (NMIA). It is seen that Australia, Austria, and South Korea establish metrological traceability for measurements of AC current using TC to a higher maximum value than in Ukraine. At the same time, these NMIs declare a lower measurement uncertainty. Other NMIs presented in the table provide lower levels of maximum current, although sometimes with better measurement uncertainty.

**Table 2.** Metrological characteristics of some national standards for high AC current scale coefficient

| Country, NMI | Maximum voltage, kV | Expanded uncertainty, µV/V |
|---|---|---|
| Sweden, RISE | 7500 | 60 |
| Saudi Arabia, SASO-NMCC | 4000 | 120 |
| Brazil, INMETRO | 5000 | 35 |
| Australia, NMIA | 20000 | 15 |
| New Zealand, MSL | 4000 | 500 |
| Austria, BEV | 10000 | 50 |
| Ukraine, UMTS | 10000 | 80 |
| Hungary, BFKH | 5000 | 30 |
| South Korea, KRISS | 20000 | 30 |
| Uruguay, UTE | 8000 | 150 |

## 5. Metrological traceability chains for AC voltage and current scale transformation coefficients

### 5.1 Metrological traceability for measuring AC voltage up to 500/√3 kV using voltage transformers

According to the information specified in the KCDB database of the International Bureau of Weights and Measures, the CMCs of NMIs provide for the measurement and reproduction of high AC voltage using:

- inductive and capacitive VTs;
- high AC voltage kilovoltmeters;
- high AC voltage sources;
- high AC voltage capacitors;
- high AC root-mean-square voltage measurement systems;
- high AC voltage resistive-capacitive dividers.

In the context of reducing the AC voltage to the values measured by meters in electricity metering systems, large-scale conversion instruments like VTs have greater importance. The most common in Ukraine are VTs of voltage level up to 330 kV. This range is covered by the DETU 08-05-99 standard, which is the upper link in the metrological traceability chain for measurements using VTs, and it is confirmed by international comparisons [3]. In addition, the use of the doubling method [22] in VT calibration allows us to expand the voltage range in which the calibration is performed to the operating values of secondary standards. Secondary standards up to 500/√3 kV for calibration of working standards in Ukraine are usually specially designed and thoroughly researched standard high-voltage AC VTs with the following metrological characteristics:

- rated primary voltage range is from 1 kV to 500/√3 kV;
- expanded measurement uncertainty for ratio error is from $1.5 \cdot 10^{-4}$ to $5.0 \cdot 10^{-4}$;
- expanded measurement uncertainty for phase displacement is from 1.5 to 3 min.

Working standards up to 330/√3 kV when verifying working VTs in Ukraine are standard high AC voltage VTs with the following metrological characteristics:

- rated primary voltage range is from 1 kV to 500/√3 kV;

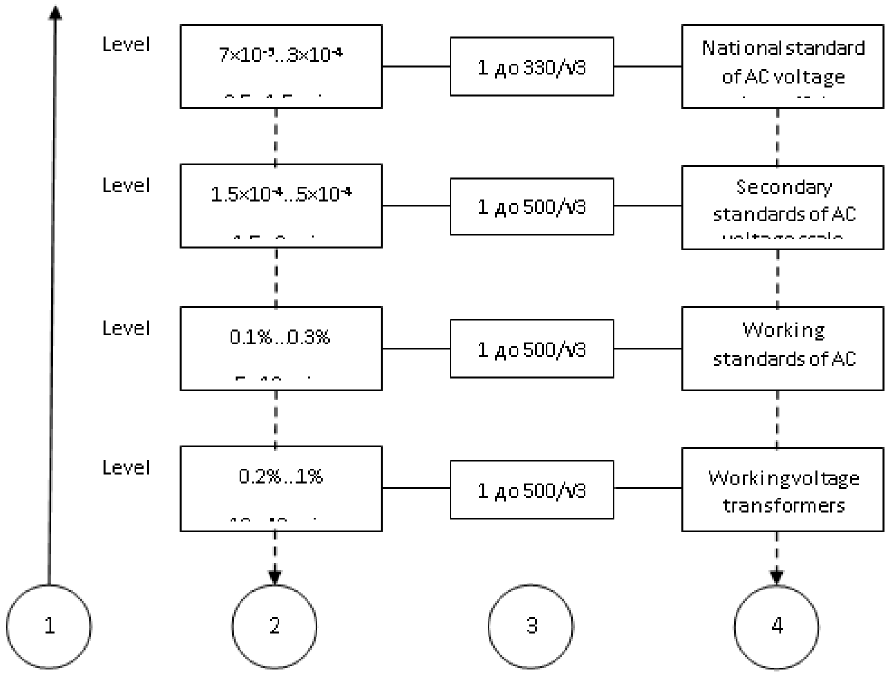


*Fig. 3. Metrological traceability chain for AC voltage scale coefficient:*
*1 – metrological traceability; 2 – measurement uncertainty; 3 – voltage level;*
*4 – calibration hierarchy*

– expanded measurement uncertainty for ratio error is from 0.1% to 0.3%;

- expanded measurement uncertainty for phase displacement is from 5 to 12 min.Fig. 3 shows the metrological traceability chain for high-precision measurement using a VT. It consists of four levels of calibration hierarchy and is based on analytical research. The DETU 08-05-99 standard is at the highest level (Level 1) of the hierarchy, the secondary standards of high AC voltage are at the second level (Level 2), the working standards of high AC voltage are at the third level (Level 3), and the working instrument VTs, which create the input measured value (AC voltage) for electricity meters are at the fourth level (Level 4). The downward branches of the chain show the measurement standards or measuring instruments (marked 4) and the corresponding metrological characteristics (marked 2) in the measurement ranges (marked 3).

**5.2 Metrological traceability for measuring AC current using current transformers**

According to the information specified in the KCDB database of the International Bureau of Weights and Measures, the CMCs of NMIs also include the measurement and reproduction of large alternating current using:

- inductive CTs;
- non-conventional or non-inductive CTs;
- optical and other high-voltage AC sensors;
- Rogovsky type AC current transducers;
- high AC current sources;
- high AC current meters.

Reduction of the AC current to the values required for the operation of meters in electricity metering systems is mainly performed by CTs. The most common in Ukraine are CTs with rated primary currents of up to 3 kA, less often up to 10 kA, and sometimes even higher. This range is mainly covered by the NDETU EM-02-2019 standard, which is the upper link in the chain of metrological traceability of measurements using CTs as confirmed by international comparisons [23]. The secondary standard up to 4 kA is intended for frequent use, i.e., unloading the NDETU EM-02-2019 standard and calibrating working standards, and is a thoroughly investigated reference CT with the following metrological characteristics:

- range of rated primary current is from 0.5 A to 4 kA;
- expanded measurement uncertainty for ratio error is from $6 \cdot 10^{-5}$ to $3 \cdot 10^{-4}$;
- expanded measurement uncertainty for phase displacement is from 0.6 to 3 min.

Working standards up to 3 kA when verifying working CTs in Ukraine are standard laboratory CTs with the following metrological characteristics:

- range of rated primary current is from 0.5 A to 3 kA;
- expanded measurement uncertainty for ratio error is from 0.02% to 0.2%;
- expanded measurement uncertainty for phase displacement is from 2 to 10 min.

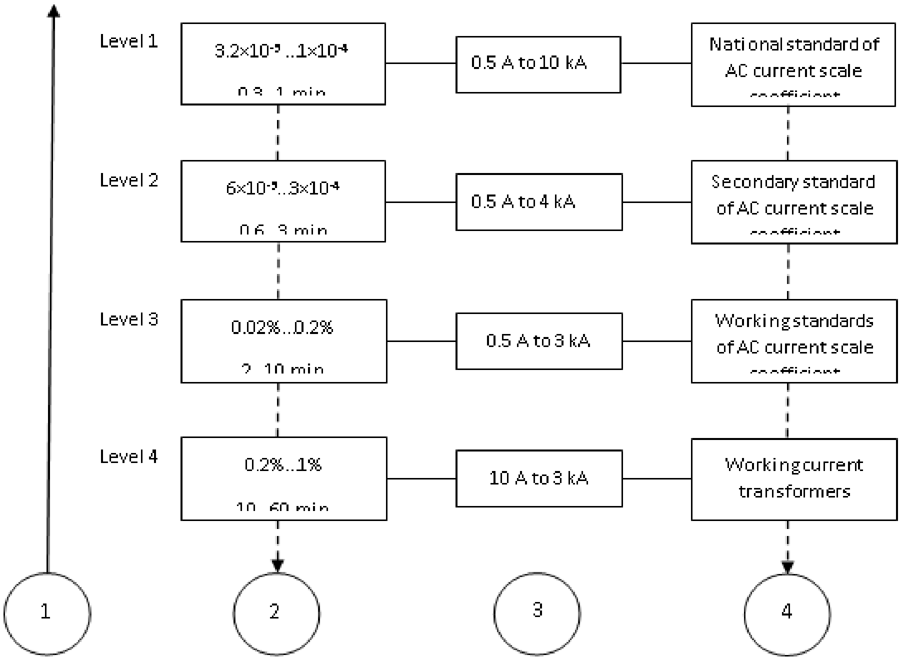


*Fig. 4. Metrological traceability chain for AC current scale coefficient:*
*1 – metrological traceability; 2 – measurement uncertainty; 3 – current range;*
*4 – calibration hierarchy*

Fig. 4 shows the metrological traceability chain for measuring a large alternating current scaled using a TC. It also consists of four levels of calibration hierarchy and is based on analytical research. The NDETU EM-02-2019 standard is at the top (Level 1) of the hierarchy, the secondary standard of high AC current is at the first intermediate position (Level 2), the working standards of high AC current are at the second intermediate position (Level 3), and the working instrument CTs, which create the input measured value (AC current) for electricity meters are at the bottom (Level 4). The downward branches of the chain show the measurement standards or measuring instruments (marked 4) and the corresponding metrological characteristics (marked 2) in the measurement ranges (marked 3).

## 5. Conclusions

Specialists of the State Enterprise “Ukrmetrteststandard” have been creating national standards (which are considered in detail in the work) for storing, reproducing and disseminating the units of scale transformation coefficients of AC voltage and current for the past 30 years. Based on the accumulated scientific and technical experience, metrological traceability chains have been built for measuring high AC voltage and large current using VTs and CTs, which allows establishing a connection of the final measurement result with the international SI system. The specified measurement uncertainties of standards and working measuring instruments are optimally selected taking into account measurement ranges as well as ongoing development of science and technology. The drawn chains in the metrological traceability hierarchy are used in the State Enterprise “Ukrmetrteststandard” for the calibration of secondary and working standards as well as working instrument VTs and CTs intended for high-scale transformation of the corresponding quantities. These chains can also be used by accredited measurement laboratories that calibrate instrument transformers in accordance with their scope of accreditation.

## Conflict of Interest

The authors state that there are no financial or other potential conflicts regarding this work.

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