Chapter

# Methodological Aspects of Using Comparators for Metrological Traceability of Instrument Transformers

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## Abstract

Instrument transformers are widely used in accounting the electricity as well as in protecting the energy generation systems. The accuracy of both voltage and current transformers is a critical parameter in terms of ensuring the reliability of functioning whether high-voltage or low-voltage networks. Two approaches are predominant in characterizing the voltage transformers with high primary rated voltage, these are applying either reference capacitor or reference transformer. Both methods require a device that enables the comparison of either two currents or two voltages. The errors of current transformers are determined by using the means of comparing two secondary currents, one of which is an output of reference transformer and the other is an output of a device under test. The calibration of such comparators may be a very sophisticated procedure. As metrological traceability depends on the measuring instruments and working standards used in calibration, the application of the proposed specific combinations of measuring instruments allows identifying the metrological traceability routes when calibrating the comparators.

**Keywords:** instrument transformer, current, voltage, calibration, measurement uncertainty, metrological traceability

## 1. Introduction

The current transformers (CT) are used in both high-voltage and low-voltage networks when the task arises to scale high currents to a value acceptable for measurement by ammeters, electricity meters, and other current-related devices. As for voltage transformers (VT), they are mainly used to scale alternating voltages above 1000 V down to values of 100, 120, 200, 230 V [1]. When it comes to the accuracy of settlement between energy supplier and consumer, the main elements of the measuring circuit are instrument transformers (IT) and meters. This means that the correctness of the accounting of consumed energy resources directly depends on the magnitude of errors of ITs.

The trend of development of modern smart grids and the use of renewable energy sources pushes the technical progress in the field of electrical measurements in the direction of expanding the use of digital low-power current and voltage converters [2–4]. However, today the vast majority of substations in the world continue to operate by using traditional electromagnetic ITs. For this reason, the metrological characterization of ITs does not lose its relevance [5, 6].

Among the varieties of nonconventional approaches to the characterization of ITs, there are those based on the use of a personal computer [7, 8] or with applying the special digitizers [9, 10]. A new approach (by using synchrophasor data) was proposed as an alternative to existing ones to determine the metrological characteristics of transformers [11]. No less important task is the calibration of ITs on-site [12, 13]. However, traditional methods for determining the amplitude and angular errors of ITs are currently used by the vast majority of accredited calibration laboratories because, among the requirements in accreditation, there is the validation of methods and measurement traceability [14]. The conventional methods presented in this chapter are used in the practice of calibration laboratories in the branch of determining the errors of both earthed and unearthed VTs, and CTs.

The reference measuring systems, which may differ both in the reference measuring instrument and in the auxiliary measuring means, are used when calibrating the VT. Consequently, the metrological traceability of the measurement result obtained using the same transformer can reach national standards of different physical quantities. Thus, the measurement method determines the direction (or directions for indirect measurements) of metrological traceability.

A device for comparing (comparator or bridge) the voltage or current of both transformer under test and working standard is almost always used when determining the amplitude component (ratio error) and the angular component (phase displacement) of the error of IT. As for the working standard, the traceability is established quite simply to the primary standard of the National Metrology Institute, but the comparison device is calibrated with an indirect determination of its characteristics. To create a procedure for verifying the correctness of the readout of the comparison device, the metrologist must analyze the sources of uncertainty of such means [15–17]. Several methods for calibrating comparison devices have been developed [18–23], and all they have certain features. This chapter proposes methods for characterizing comparators of almost identical alternating currents or voltages to establish the metrological traceability when using such instruments for the calibration of CTs or VTs.

## 2. Traditional approaches to characterization of voltage transformers

### 2.1 The usage of reference voltage transformer

A typical measuring system for calibration of VT using the method of a reference transformer [24] is shown in **Figure 1**.

It could be seen in **Figure 1**, the means of comparing two voltages with a range of values from 20 to 150% (possibly 200%) of the rated secondary voltage of VT with an operating frequency of 50 and/or 60 Hz. Such a comparator can measure the voltage ratio error in the range from 0 to 30%, the voltage phase displacement in the range from 0 to 0.1 rad. Also, the comparator should perform the function of measuring the secondary voltage with a relative uncertainty of ±3%, its frequency with an absolute uncertainty of ±0.05 Hz (below the authors will briefly describe the main differences in the construction of the devices for comparing currents and voltages in the context of the formation of primary measurement information).
A reference high-voltage measure of the voltage transformation ratio is a reference VT with a primary voltage range from 20 to 150% of the rated primary voltage of the VT under test.

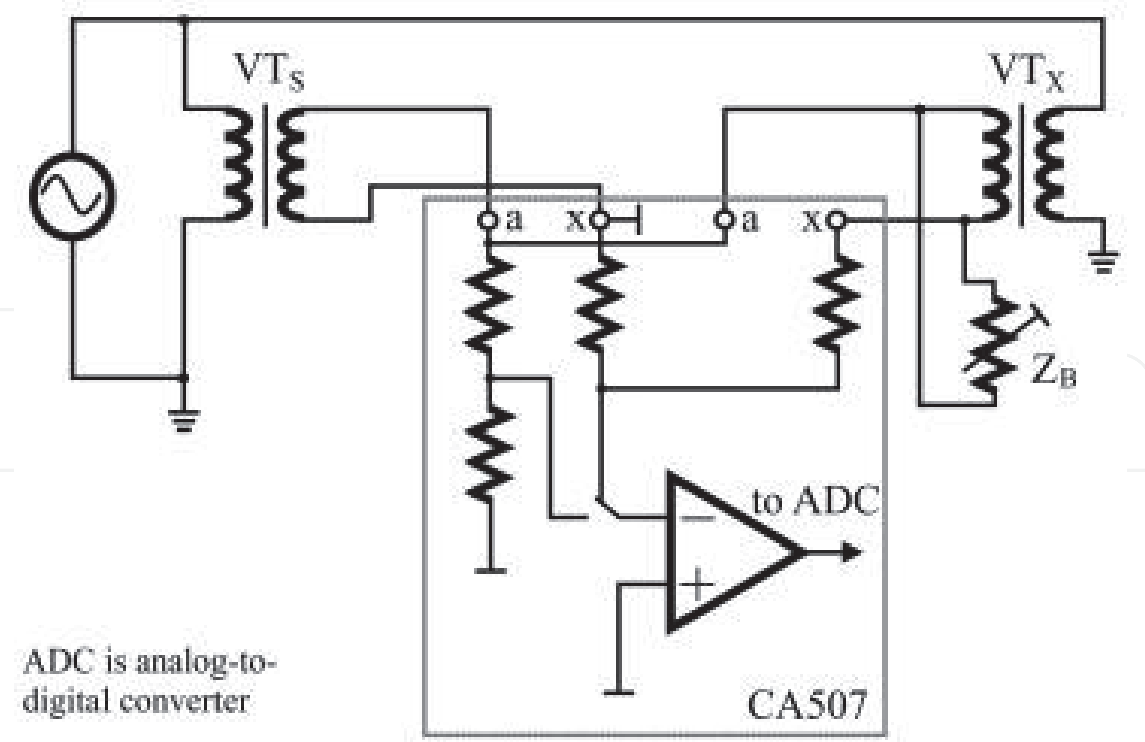


**Figure 1.**
*Measuring system for calibration of VT using the method of a reference transformer.*

The VT calibration by the reference transformer is performed with a connection to the comparator using conductors with a resistance of not more than 0.015 Ohm for accuracy class 0.05 and 0.1 or 0.06 Ohm for accuracy class 0.2 and less accurate.

When a message about an incorrect connection appears, the operator needs to change the direction of current flow in the winding of the calibrated VT by swapping the wires at the terminals of the secondary winding. Determination of errors is performed when loading the calibrated VT using the $Z_B$ instrument with a power equal to the rated and quarter of the rated value. Using a high-voltage source, the voltages are set following the requirements of the IEC standard or at the request of the customer. The voltage and frequency can usually be observed on the display of a comparator.

In the case of commensurability of the error of the reference VT and comparator readout, it may make sense to carry out corrective calculations by the formulas:

$$\varepsilon_{VX} = \varepsilon_{VM} + \varepsilon_{VS}; \Delta\varphi_{VX} = \Delta\varphi_{VM} + \Delta\varphi_{VS}. \tag{1}$$

where $\varepsilon_{VM}$ is a comparator readout concerning ratio error, $\Delta\varphi_{VM}$ is a comparator readout concerning phase displacement, $\varepsilon_{VS}$ is a ratio error of the reference transformer assigned by the calibration certificate, and $\Delta\varphi_{VS}$ is a phase displacement of the reference transformer assigned by the calibration certificate.

For VTs with significant errors, the result read from the display of the comparator can be considered to be the final measurement result.

### 2.2 The usage of the reference voltage divider

A typical measuring system for VT calibration by the method of reference voltage divider [25] is depicted in **Figure 2**.

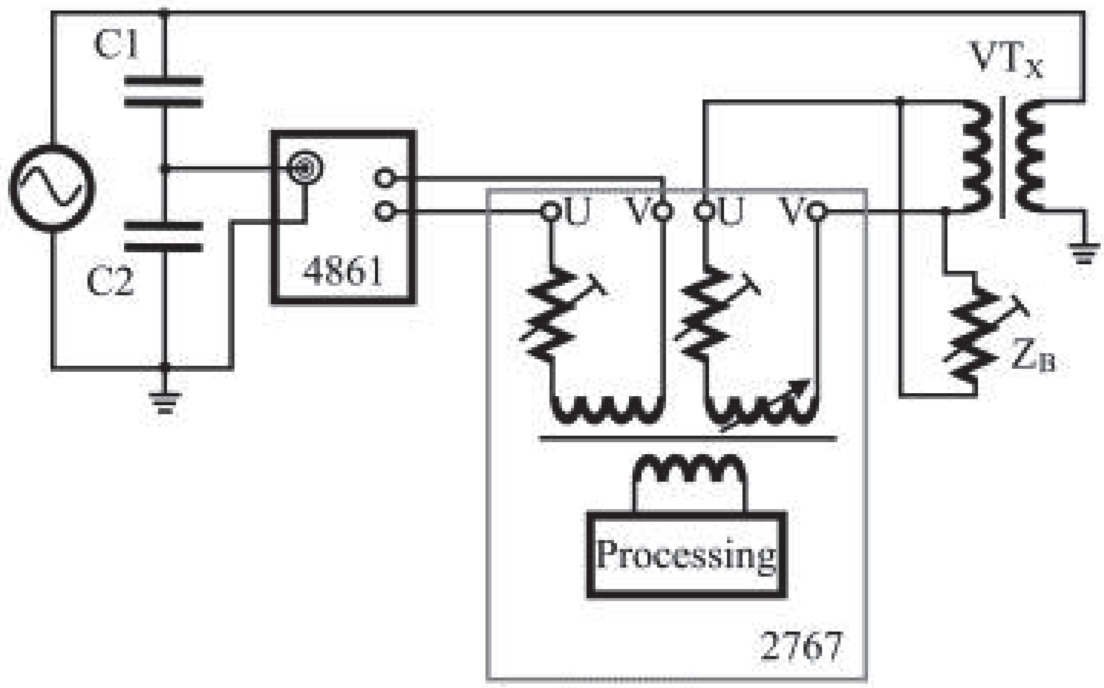


**Figure 2.**
*Measuring system for VT calibration by the method of a reference voltage divider.*

The requirements for the reference divider correspond with the requirements for the reference VT specified in the previous section. In this case, the rated scaling factor of the high-voltage standard may not match with the rated scaling factor of the transformer under test.

**Figure 2** shows a reference voltage divider consisting of two capacitors C1 and C2. The requirements for conductors should be as described in the previous method. The load device $Z_B$ of the calibrated VT must be set to a value equal to the rated output or a quarter of its value. The high-voltage source should allow setting the voltage required for characterizing the VT.

A comparison device (2767 in **Figure 2** or a specialized volt-phase meter) usually allows controlling the actual voltage and frequency.

In the absence of automatic equilibration as in the design of the 2767 bridge, the value $\varepsilon_{VM}$ can be calculated using the formula:

$$\varepsilon_V = 100 \cdot (K_{VX} \cdot U_{X2} – K_{VS} \cdot U_{S2}) / K_{VS} \cdot U_{S2}, \tag{2}$$

where $U_{X2}$ and $U_{S2}$ are the secondary voltages measured by the first and the second channels of the volt-phase meter; $K_{VX}$ and $K_{VS}$ are the rated transformation ratios of both the VT under test and the working standard.

## 2.3 Comparison of design features of comparators of two alternating voltages

In the practice of modern metrological service regarding the calibration of VT, there are two main options for comparing the secondary voltages of the transformer under test and the working standard. The first of them, as noted when considering the method of a reference transformer, requires the use of a standard with an identical transformation ratio. The reference measure should have a large number of primary voltages, which allows providing the full range of primary voltages of the VTs in operation. In this case, it is advisable to use a two-voltage comparator without the possibility of adjusting the output signal of the voltage difference

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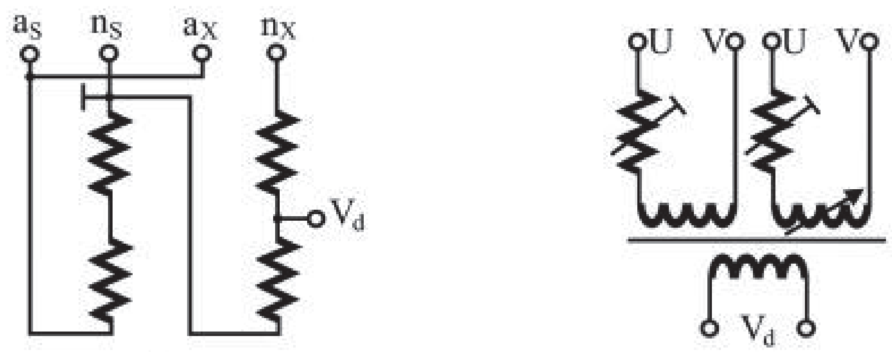


3.1 3.2

**Figure 3.**
*Input sensor elements of devices for comparing two secondary voltages of VTs.*

sensor. **Figure 3** has a position 3.1 with the schematic of the resistive input sensor of the voltage difference of two VTs.

The voltage divider between the terminals $a_S$ and $n_S$ for connecting the secondary winding of the reference VT is required for measuring the actual voltage relative to which the deviation is determined. The voltage divider between the $n_S$ and $n_X$ terminals is used for obtaining information about the potential difference between two sinusoidal signals. Subsequently, both measured signals are transmitted to the phasor measuring analog-to-digital converter (ADC) that allows decomposing the signal into orthogonal components. Further, the processor calculates two values for the ratio error and the phase displacement.

The second option involves the use of a measure with a much smaller number of ratios and the mandatory possibility of balancing (or other methods of comparing significantly different values) of the input voltages in the design of the device for comparing these values. As can be seen from position 3.2 of **Figure 3**, the 2767 measuring bridge has special adjustable active and reactive elements that allow balancing two voltages in a wide range of their ratio (from 0.5 to 10 times). It should be noted that the uncertainty of measurement by this bridge increases as well as the correctness of the readings of such instrument deteriorates with increasing ratio matching factor of voltages of comparable VTs.

It should also be noted that the world market of measuring equipment is saturated with different types of means for comparing two secondary voltages of VTs from different more or less known manufacturers. Some manufacturers use their peculiarities of the input-measuring circuits with or without the possibility of balancing the secondary voltages of the VTs. For example, the AITTS-98 comparator compares two slightly different voltages by using two inductive sensor elements without the ability to adjust the voltage ratio [16].

### 2.4 The usage of the reference capacitor

The methods for determining the errors of VTs also include the use of two capacitors and a precision transformer bridge built on the principle of current comparison [26]. It is known that the magnetic flux is reduced to the minimum possible value in the transformer core of the current comparator when balancing bridges of similar design [27, 28]. If there is some residual magnetic flux, the proportional signal is generated in the measuring circuit. One of the variants of the bridge measuring scheme with a close inductive coupling is shown in **Figure 4**.

The diagram shows the first stage of determining the errors of the VTs, which determines the basic current ratio of high-voltage and low-voltage capacitors. Currents are generated in two parallel circuits of both reference and unknown

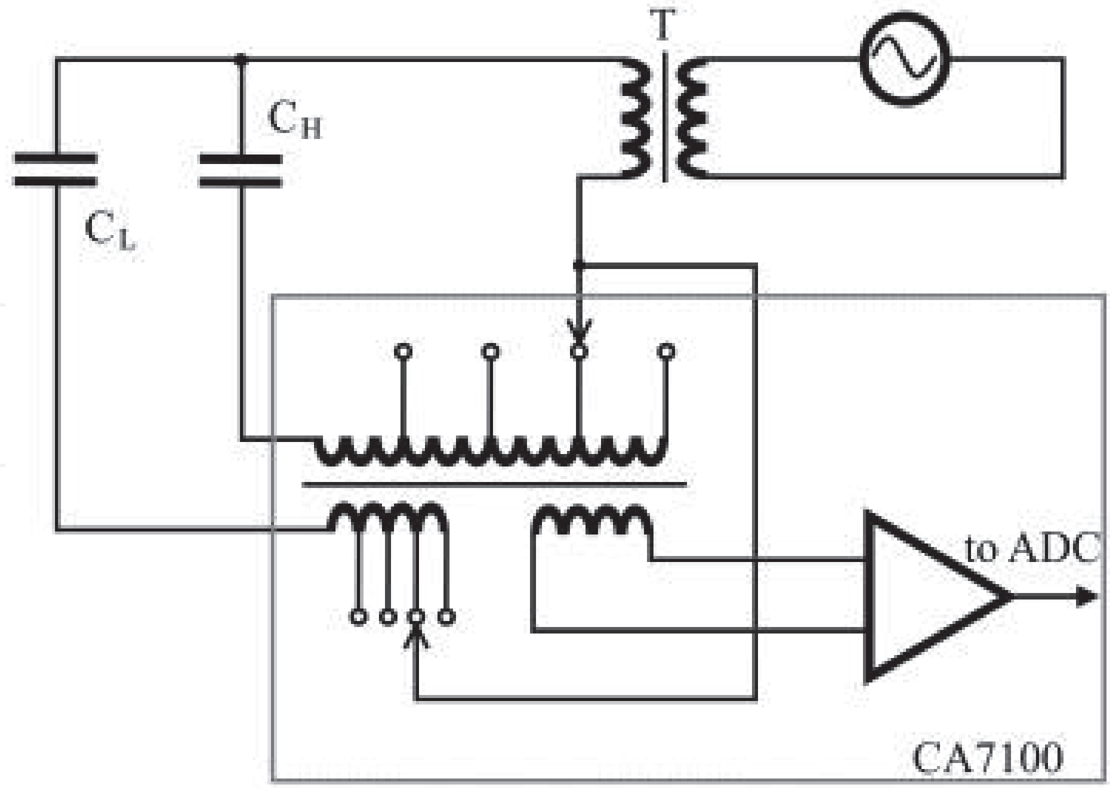


**Figure 4.**
*Measuring diagram of an automatic transformer bridge with two capacitors.*

capacitors. The ratio of the turns of the current comparator is automatically adjusted so that the minimum magnetic flux flows through the core. In this case, the ratio of the turns of the current comparator, which minimizes the difference of magnetic fluxes, with some accuracy (which depends on the number of adjustable turns that is a discretization of feasible ratios) will be equal to the ratio of currents flowing in the arms of the bridge with capacitors $C_L$ and $C_H$. The residual imbalance signal should be amplified, and its additional contribution to the determined current ratio should be calculated by the processor. A typical measuring system for VT calibration by the method of reference capacitor is shown in **Figure 5**.

The principle of balancing the bridge circuit is used as the basis for the measurement by the method of the reference capacitor. Therefore, the most metrologically significant element is a high-voltage transformer bridge, which is a current comparator with a range of compared currents from 0.1 μA to 50 mA. Such a bridge should provide a measurement of both the voltage scaling factor from 0.1 to 10,000 and phase displacement in the range from 0 to 0.1 rad at a frequency of 50 or 60 Hz. The measurement of VT secondary voltage with a relative uncertainty of $\pm$3% and a frequency with an absolute uncertainty of $\pm$0.05 Hz should also be included in the functions of the instrument.

The necessary elements of such a measuring system are two capacitors. Low-voltage electrical capacitor is designed for 10 times voltage of the secondary winding of the VT to be calibrated. $C_L$ is a shielded, highly linear, and highly stable three-electrode electrical capacitor based on film technology and ceramics, with a capacitance in the range from 1000 to 5000 pF depending on the sensitivity of the high-voltage bridge. The tangent of the dielectric loss angle in the operating voltage range should not exceed $10^{-4}$.

The high-voltage electrical capacitor must be intended to operate with voltages up to 120% of the VT-rated primary voltage. $C_H$ is a shielded, highly linear, and highly stable three-electrode electric capacitor, made of coaxial electrodes placed in

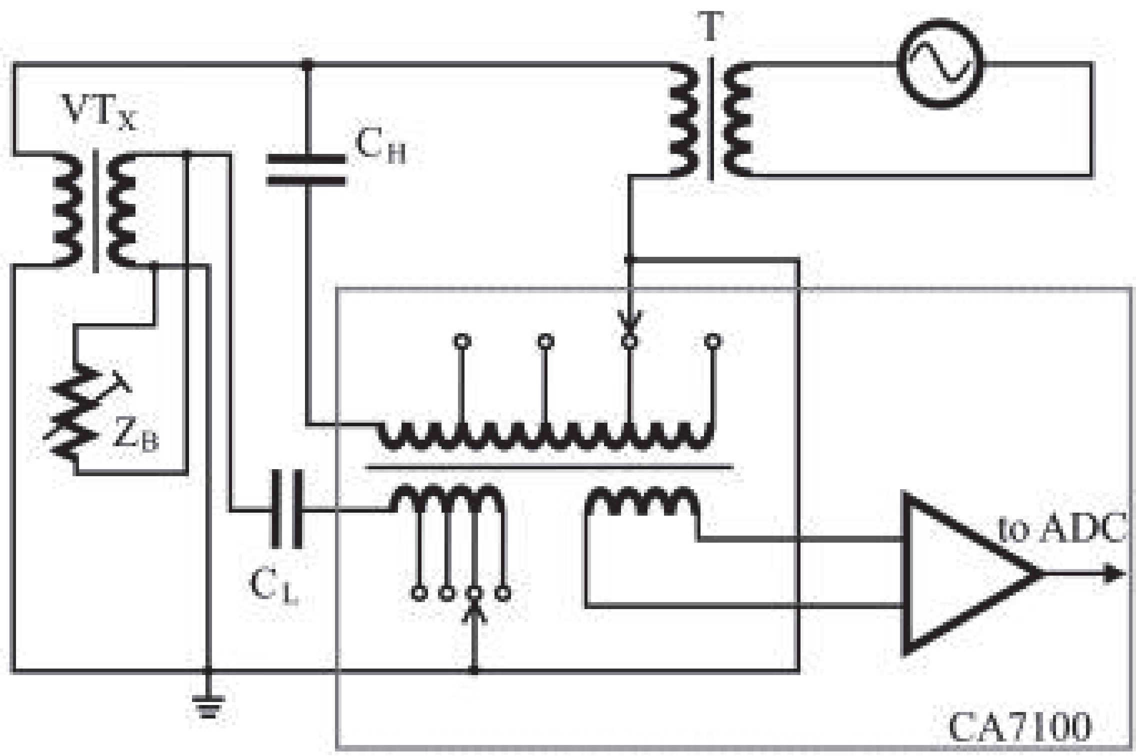


**Figure 5.**
*The second-stage diagram for VT calibration by the method of a reference capacitor.*

a case with a gas-insulated dielectric, with a capacitance in the range from 40 to 150 pF depending on the sensitivity of the high-voltage bridge. The tangent of the dielectric loss angle should also not exceed $10^{-4}$. When using the method of a reference capacitor, the VT errors are determined from the measurement results obtained during two stages.

At the first stage, it is necessary to determine both the ratio of the currents flowing through two capacitors ($K_{L/H} = I_L/I_H$) and the phase shift angle between these currents ($\varphi_{L/H}$). The voltage across the capacitors should be set at the level of about 1000 V, the bridge should be equilibrated automatically following the command of an operator, and the software must calculate and display certain characteristics.

The measuring circuit at the second stage corresponds to **Figure 5** and differs from the first stage by the presence of a calibrated VT and its load. In this case, the potential input of the low-voltage capacitor is not connected with the similar input of the high-voltage capacitor, but with the secondary winding of the VT under test.

Before turning on the high-voltage source, the burden should be set to the rated or a quarter of the rated value. The high voltage should be set according to the selected calibration points by the reading of the measuring bridge or alternative measuring instrument. At each of the values of the set voltages, the bridge must be balanced as well as both the new ratios ($K_{H/L} = K_{VT} \cdot I_H/I_L$) of the currents flowing through the $C_L$ and $C_H$ capacitors and the new phase shift angles ($\varphi_2 = \varphi_{H/L} + \varphi_{VT}$) must be determined. The ratio error of the VT under test ($\varepsilon_V$) and the phase displacement of voltage ($\Delta\varphi_V$) for each voltage and load set during calibration should be calculated by the following formulas:

$$\varepsilon_V = 100 \cdot \left(1 - K_{L/H} \cdot K_{H/L}/K_{VTr}\right); \Delta\varphi_V = \varphi_{L/H} + \varphi_2, \qquad (3)$$

where $K_{VTr}$ is a rated transformation ratio of the VT under test.

## 3. Metrological characterization of current transformers

### 3.1 Traditional approaches to characterization of current transformers

Traditionally, the errors of CTs are determined by comparing their secondary current with the secondary current of the reference transformer [29]. A typical measuring system is shown in **Figure 6**.

The current source must allow regulating the current in the primary circuit in the range from 1 to 150% of the rated primary current of the CT under test with a deviation of not more than 10%. The primary current flows through the primary windings of both the working standard and the CT under the test and causes a magnetic flux in the cores of both transformers.

As a result, currents proportional to the primary current, which is the same at each time point, occur in both secondary windings. The burden ZB causes a change in the actual metrological characteristics of the calibrated CT and should allow changing the load in the range from a quarter to the rated power at a power factor of 0.8 with an uncertainty of impedance, which does not exceed ±4%. In some cases, it is sensible to use the actual load (or its equivalent) with which the CT operates. The current comparison device must allow the measurements with intrinsic uncertainty in the range from ±0.03 to ±0.001% when measuring the current ratio error and from ±3.0′ to ±0.1′ when measuring the phase displacement depending on the difference between the currents of the working standard and the CT under test.

The amplitude ($\varepsilon_I$) and angular ($\Delta\varphi_I$) errors of the CT should be determined by the differential method following **Figure 6** at the primary current and load by customer order. The connection of devices in the measuring circuit according to **Figure 6** is carried out following the requirements of the operating manual of the current comparison device used. For the CT being tested, the relative current ratio error in percent and the absolute phase displacement in minutes are taken equal to the values at the comparator display.

A variant of implementation of the measurement setup may also be the use of a means for comparing the primary and secondary currents of the CT under test. A feature of such a comparator is the presence of an integrated reference transformer with a variable transformation ratio and high precision. An example of the scheme is shown in **Figure 7**.

The device used for comparing two currents consists of two units (transformer-electronic and electronic-computing) and contains the reference transformer inside. Due to the presence of the integrated standard, such device allows implementing two options for comparison—using the built-in standard or using the external

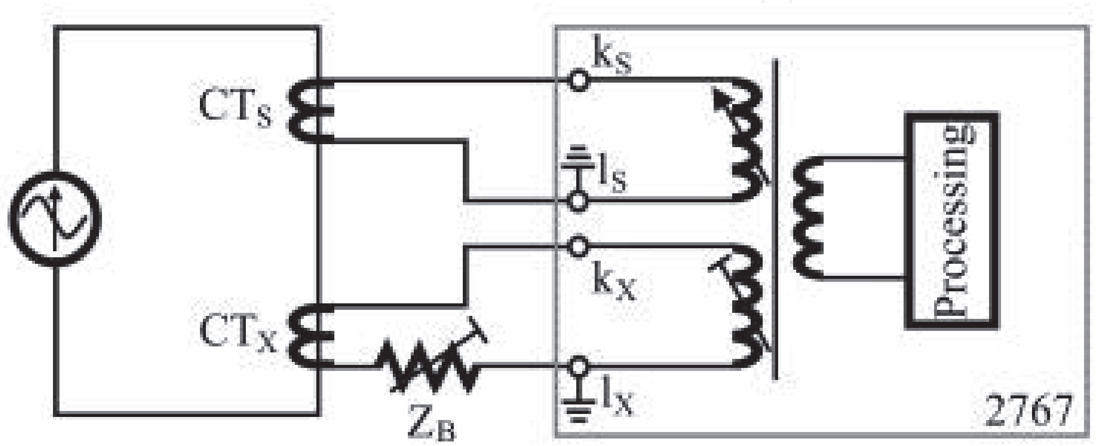


**Figure 6.**
*Measuring system for calibration of CT by means of comparison with a reference transformer.*

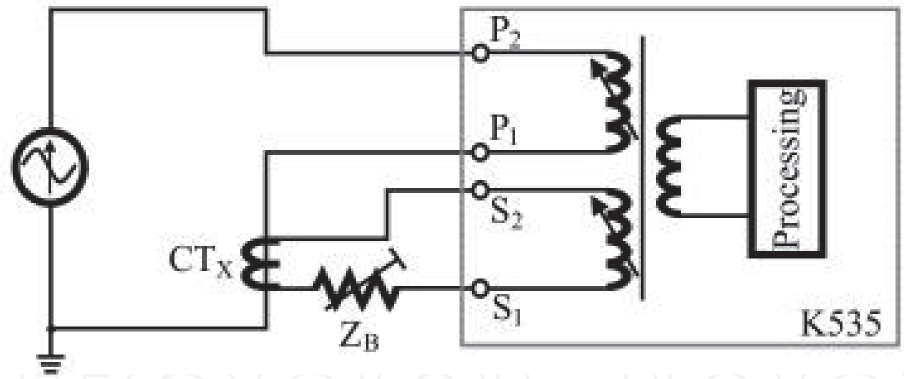


**Figure 7.**
*Measurement setup for calibration of CT with comparing primary and secondary currents.*


**Figure 8.**
*Input sensor elements of means for comparing two secondary currents of the CTs.*

reference CT. For the transformer under test, this scheme compares the magnetic fluxes generated by both the scaled primary current and the secondary current equaled with the help of reference inductive converters of the transformer-electronic unit. The signal generated by the secondary winding of the magnetic flux comparator is proportional to the difference between the almost equal currents. The second option for using the K535 device requires the presence of two CTs with the same transformation ratios and, therefore, is similar to that described above.

In the general case, the input-measuring circuits of the comparison means create a load effect that can distort the measurement result. Apart from the input inductive current difference sensors, the resistive measuring elements are also used, namely shunts. The resistive and inductive sensors create voltage drops in addition to the load $Z_B$, and the effect of some comparators on the calibration result was investigated previously [30]. The examples of mentioned sensors are shown in **Figure 8**.

Similar to voltage difference sensors, manufacturers of precision instruments have implemented options of both comparison type and bridge type with the possibility of balancing two currents. Two options presented in **Figures 6** and **7** involve bringing counter-directed magnetic fluxes to almost equal values by selecting the desired number of turns. Item 8.1 of **Figure 8** presents an inductive measuring sensor of the relative difference of currents, which is implemented in the design of the 2767 measuring bridge. By adjusting the number of turns of the input windings, the developer has created the ability to vary the ratio matching factor in the range from 0.5 to 500. The difference flux remaining in the magnetic circuit creates an output information signal proportional to the difference in currents of the working standard and the transformer under test. The comparators CA507 and

HGQA-C are designed for comparing two almost identical currents, which requires the use of a working standard with a transformation ratio equal to the same characteristic of the calibrated CT. Particularly, item 8.2 of **Figure 8** presents a sensor of the relative difference of currents in the design of the CA507 comparator. The left-measuring shunt generates information about the current of the working standard, and the right shunt is intended to measure the absolute phasor difference of two currents. These two measured quantities are decomposed into orthogonal components by using a vector measuring ADC.

### 3.2 Metrological characterization by measuring current transformer parameters at low voltage

For the needs of operative and mobile determination of CT errors, an instrument for testing the CTs has recently been developed, namely a CT analyzer, which does not require a reference transformer [12, 31, 32]. It is especially convenient when determining the errors of the CTs with big currents located on-site because of the small weight and dimensional indicators. According to the theory of transformer characterization, the equivalent current transformation scheme with some simplifications can be represented as in **Figure 9**.

Each transformer winding has active resistance and reactance, which is shown in **Figure 9** as $R_P$ and $X_P$ for the primary winding and $R_S$ and $X_S$ for the secondary winding. According to the equivalent schematic, the current of the primary circuit is branched and part of it flows through the excitation branch consisting of the active Re and reactive Xe components. Excitation current through this branch is proportional to induced electromotive force E. The CT analyzer must be able to generate both direct and alternating voltages for determining both the active and reactive components of the CT windings and the excitation current [12, 32].

The use of the low-voltage reciprocity principle allows facilitating the measurement procedure in determining the errors when the internal characteristics of the CT are measured. Excitation characteristics, 10% error curve, and composite error are considered in the processing algorithm of the measuring information [12].

Following the user's guide of CT analyzer CT1, the processor of this device calculates some characteristics based on the equations obtained when considering the equivalent circuit. The results are influenced by the electrical resistance of the secondary winding, ambient temperature, etc. The calculated values of the REs are based on an excitation table. The excitation table allows us to find the phase between current and voltage, and the corresponding excitation current due to the given excitation voltage [33].

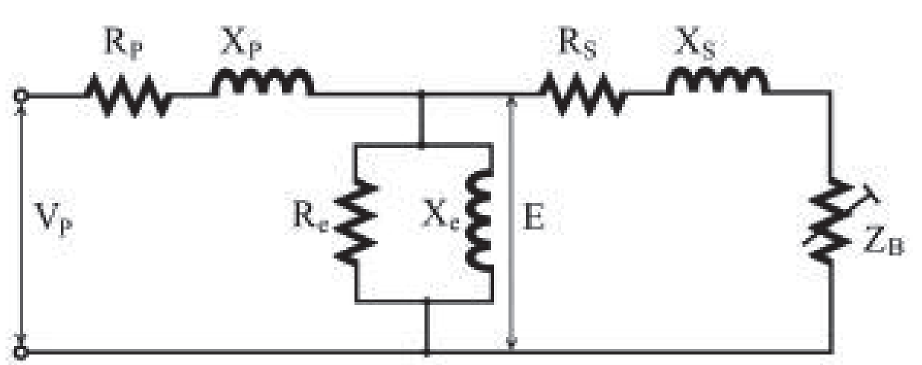


**Figure 9.**
*Equivalent simplified schematic of the CT.*

## 4. Characterization of comparators of two alternating voltages

### 4.1 Checking the correctness of comparator readings for measuring the ratio error of voltage transformers

The following procedure allows checking the correctness of the readings of the means for comparing two alternating voltages when calibrating the VTs in the range of secondary voltage from 5 to 240 V. When performing the calibration of such comparator, it is necessary to perform the operations of determining the deviation of the amplitude error of the voltage ($\varepsilon_V$) as well as determining the deviation of the phase error of the voltage ($\Delta\varphi_V$).

The measurement setup for calibration of the comparator for determining the ratio errors of VT is shown in **Figure 10**.

The main element of the presented scheme is the P4834 resistance decade box, which allows generating the required voltage ratio error. The P4834 must have terminals for connecting with the intermediate decades, which can be used as a branching point (if this condition is not met, another resistance decade box may be needed). The source of alternating current (AC) generates the required voltage between the first and the last terminals of the P4834. In the measuring scheme, a source of stable-alternating voltage should be used for minimizing the fluctuations of its output voltage to minimize the scattering of the observation results of the two measured signals. The deviation of the voltage amplitude error can be determined by using two precision digital multimeters in the AC voltage measurement mode (voltmeter), such as Agilent 3458A or Fluke 8845A. The right voltmeter is designed to measure the voltage difference between the terminals of the input secondary voltages of both the working standard and the VT under test.

The left voltmeter is required for measuring the voltage at the terminals of the input secondary voltage of the reference VT. The observed voltage difference must be divided by the voltage at the terminals of the input secondary voltage of the reference VT. The resistors R1 and R2 form a divider inside the CA507 comparator, which is designed for measuring the voltage of the working standard. The resistors R3 and R4 also form a divider inside the CA507 comparator, which is designed for measuring the difference between two secondary voltages.

Calibration of the comparator is performed for the input voltage of 50 and 100 V and generated errors are listed in **Table 1**. Since the measurement procedure is the same for each of the specified points, the following description of calibration operations is given for one abstract value of the input voltage and voltage ratio error $\varepsilon_V$.

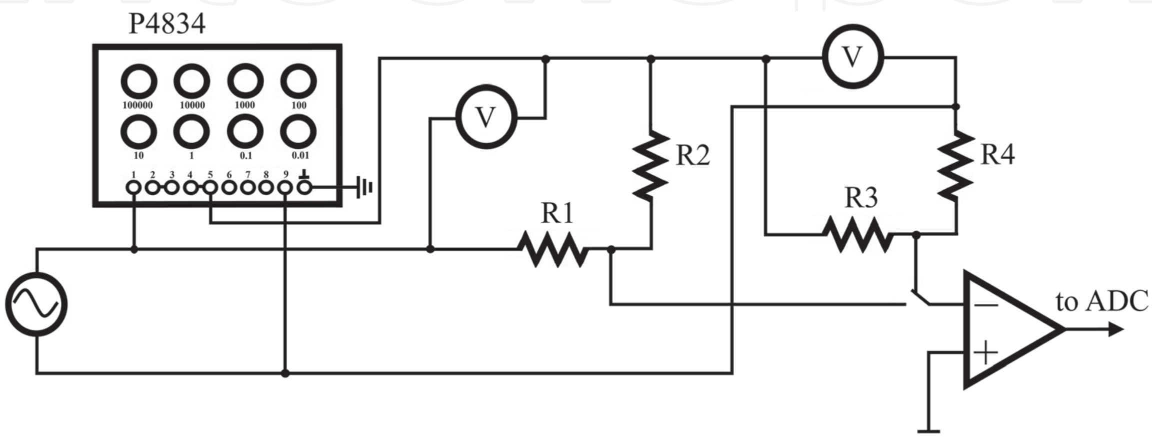


**Figure 10.**
*Measurement setup for calibration of the comparator of two almost identical voltages in measuring the ratio error.*

| Voltage ratio error (%) | Voltage phase displacement (min) | Resistance of P4830 decade box (Ω) | | Capacitance of P5025 decade box (μF) |
|---|---|---|---|---|
| | | For ratio error | For phase displ. | |
| 0.05 | — | 10,005 | — | — |
| 0.1 | 5 | 10,010 | 21,880 | 100 |
| 0.5 | 15 | 10,050 | 7295 | 100 |
| 2.0 | 50 | 10,200 | 21,880 | 10 |
| 5.0 | 100 | 10,500 | 10,939 | 10 |

**Table 1.**
*Values of P4830 and P5025 decade boxes for generating the VT errors.*

The values measured using voltmeters (the voltage $U_S$ at input terminals for reference VT and voltage $U_\Delta$ of a difference between two input voltages) should be committed to memory simultaneously following the command of the operator. The obtained values are stored in the memory of a personal computer and then exported to the electronic protocol. The observations should be repeated the required number of times $n$ obtaining a series of unit values of $U_{Si}$, $U_{\Delta i}$, and $\varepsilon_{Vi}$ ($i = 1, \ldots, n$). The least significant digit $\Delta_L$ of the comparator should be considered in evaluating the measurement uncertainty.

The average deviation of the voltage ratio error in units (%) of this metrological characteristic is calculated by the formula:

$$\overline{\Delta_U} = \sum_{i=1}^{n} \left(\varepsilon_{Vi} - 100 \cdot U_{\Delta i}/U_{Si}\right) \Big/ n \tag{4}$$

The combined standard uncertainty for this characteristic can be calculated by the formula:

$$u_\Sigma = \sqrt{\frac{10^4 \cdot \sum_{i=1}^{n} \left(\frac{U_{\Delta i}}{U_{Si}} - \frac{\overline{U_\Delta}}{\overline{U_S}}\right)^2}{n \cdot (n-1)} + \frac{\sum_{i=1}^{n} \left(\varepsilon_{Vi} - \overline{\varepsilon_V}\right)^2}{n \cdot (n-1)} + \frac{\Delta_L^2}{12} + \frac{10^4 \cdot u_\Delta^2}{U_S^2} + \frac{10^4 \cdot u_S^2 \cdot U_\Delta^2}{U_S^4}} \tag{5}$$

where $u_\Delta$ and $u_S$ are the standard uncertainties associated with measuring the corresponding voltages $U_\Delta$ and $U_S$.

### 4.2 Checking the correctness of comparator readings for measuring the phase displacement of voltage transformers

When checking the accuracy of measuring the difference between the phase errors of two VTs, the metrologist should use the scheme shown in **Figure 11**.

The resistance P4834 and capacitance P5025 decade boxes are two important elements that allow generating the required phase shift between two input voltage phasors. The P4834 decade box has a much higher value of electrical resistance than the equivalent resistance created by the P5025 capacitance box. Since the actual phase shift angles, obtained during the calibration of VTs, rarely exceed 100 min, the calculation of reproducible quantity can be carried out by a more convenient formula based on the equality of small angle and its tangent. The alternating voltage source generates the required value at the separated terminals of the P4834 and P5025 decade boxes connected in series. The deviation of the angular voltage error

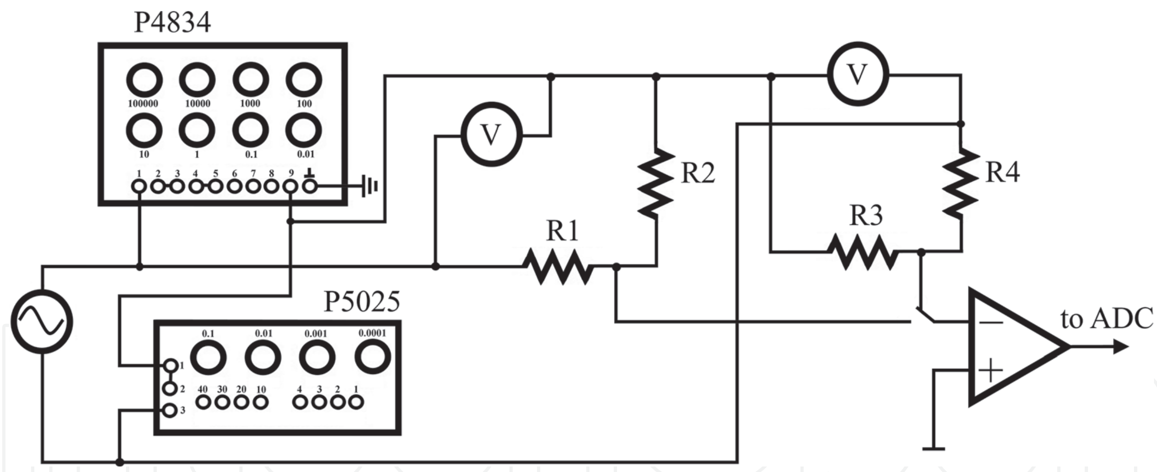


**Figure 11.**
*Measurement setup for calibrating the comparator of two almost identical voltages in measuring the phase displacement.*

displayed by the comparator can also be determined by using two precision voltmeters. In **Figure 11**, the right voltmeter is intended for measuring the imaginary component of the voltage present at the comparator terminals for the VT under test. The left voltmeter measures the voltage at the terminals for the reference VT. The obtained value of the imaginary component of the voltage should be divided by the voltage of the reference VT. As for the resistors R1–R4, their function has already been discussed in the previous section.

The calibration of the comparator by phase shift angle should be performed for the values of generated error which are listed in **Table 1**. The following description of calibration operations is given for one abstract value of input voltage and corresponding phase displacement $\Delta\varphi_V$.

The values measured using voltmeters should be committed to memory simultaneously following the command of the operator. The observations should be repeated the required number of times $n$ obtaining a series of unit values of $U_{Si}$, $U_{\Delta i}$, and $\Delta\varphi_{Vi}$ ($i$ = 1, …, $n$). The average deviation of the voltage phase displacement in units (min) of this metrological characteristic is calculated by the formula:

$$\overline{\Delta_{U\varphi}} = \sum\nolimits_{i=1}^{n} \left(\Delta\varphi_{Vi} - 3437.747 \cdot U_{\Delta i}/U_{Si}\right) \Big/ n \tag{6}$$

The combined standard uncertainty for this characteristic can be calculated by the formula:

$$u_\Sigma = \sqrt{3437.747^2 \cdot \left[\frac{\sum_{i=1}^{n}\left(\frac{U_{\Delta i}}{U_{Si}} - \frac{\overline{U_\Delta}}{U_S}\right)^2}{n\cdot(n-1)} + \frac{u_\Delta^2}{U_S^2} + \frac{u_S^2 \cdot U_\Delta^2}{U_S^4}\right] + \frac{\sum_{i=1}^{n}\left(\Delta\varphi_{Vi} - \overline{\Delta\varphi_V}\right)^2}{n\cdot(n-1)} + \frac{\Delta_L^2}{12}}. \tag{7}$$

## 5. Checking the correctness of comparator readings for measuring the errors of current transformers

The process of metrological characterization of the CT can be parted into two stages. The peculiarities of the first stage for determining the small CT errors are outlined in [34].

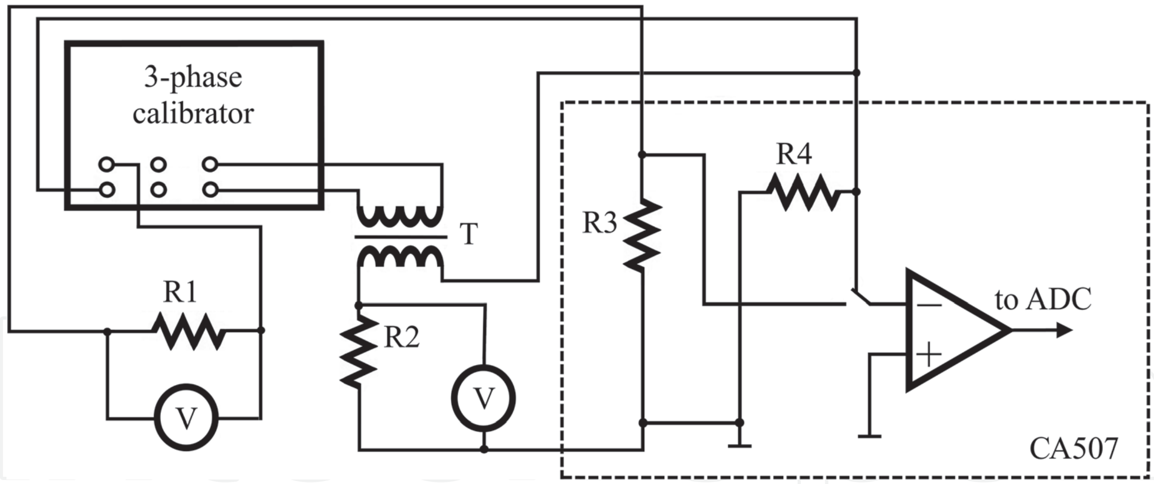


**Figure 12.**
*Measurement setup of comparator calibration when simulating CT errors greater than 0.1%.*

| Current ratio error (%) | Secondary current $I2$ of working standard (A) | Current of 3-phase calibrator | |
|---|---|---|---|
| | | In phase 1 | In phase 3 |
| 0.2 | 1; 5; 6 | $I2$ | $1.002 \cdot I2$ |
| 0.5 | | $I2$ | $1.005 \cdot I2$ |
| 1.0 | | $I2$ | $1.01 \cdot I2$ |
| 2.0 | | $I2$ | $1.02 \cdot I2$ |
| 5.0 | | $I2$ | $1.05 \cdot I2$ |

**Table 2.**
*Currents generated for calibrating comparator when ratio error is larger than 0.1%.*

The second stage of metrological characterization of the comparator for larger values of CT errors can be performed by using the scheme of **Figure 12**.

In the second stage, the three-phase calibrator is a source of generated current ratio error ($\varepsilon_I$). The readout deviation of the amplitude error of the current is determined using a voltmeter that measures the voltage $U_S$ at the output terminals of the reference resistance R1, which is in the secondary current circuit of the working standard. The second voltmeter is intended for measuring the voltage $U_X$ at the output terminals of the reference resistance R2 placed in the secondary current circuit of the CT under test. A transformer T with a current ratio of 5A/5A is used for galvanic isolation.

The measuring shunts R3 and R4 in the comparator structure are designed to measure the current of the working standard and the vector difference between the currents of the standard and the transformer under test.

The calibration of the comparator for current ratio error larger than 0.1% is performed for the input currents and generated errors that are specified in **Table 2**. The average deviation of the current ratio error in units (%) of this metrological characteristic is calculated by the formula:

$$\overline{\Delta_I} = \sum_{i=1}^{n} \left[ \varepsilon_{Ii} - 100 \cdot \left( K_R \cdot \frac{U_{Xi}}{U_{Si}} - 1 \right) \right] \Big/ n. \tag{8}$$

where $K_R$ is the relative difference factor, which is determined in characterizing the difference current-to-voltage converter consisting of R1 and R2 when the same current is flowing through both devices; $U_{Si}$ is one observation of left voltmeter readout; $U_{Xi}$ is one observation of right voltmeter readout; $\varepsilon_{Ii}$ is one observation of comparator readout.

The combined standard uncertainty for this characteristic can be calculated by the formula:

$$u_{\Sigma} = \sqrt{\frac{10^4 \cdot K_R^2 \cdot \sum_{i=1}^{n}\left(\frac{U_{Xi}}{U_{Si}} - \frac{\overline{U_X}}{U_S}\right)^2}{n \cdot (n-1)} + \frac{\sum_{i=1}^{n}(\varepsilon_{Ii} - \overline{\varepsilon_I})^2}{n \cdot (n-1)} + \frac{\Delta_L^2}{12} + \frac{10^4 \cdot K_R^2 \cdot u_X^2}{U_S^2} + \frac{10^4 \cdot K_R^2 \cdot u_S^2 \cdot U_X^2}{U_S^4}} \tag{9}$$

where $u_X$ and $u_S$ are the standard uncertainties associated with measuring the corresponding voltages $U_X$ and $U_S$.

## 6. Investigation of the metrological performance of high-voltage transformer bridge for determining the voltage transformer errors

The method of cyclic permutations is used to conduct experimental studies of the metrological characteristics of the AC transformer bridge [35]. This method allows for determining the deviations of the transformer bridge with high accuracy. Moreover, not the values of capacitance but their ratios are reproduced, and for dielectric loss tangents, their difference is reproduced. To apply this method, a group of capacitors in the amount of $(m + n)$ is used, which is shown in **Figure 13**.

The presented schematic has some simplifications and does not contain all the elements of a special impedance box for characterizing the AC bridge. With the help of a group of switches, which are not depicted, the necessary ratios between the total capacitances of n-Section and m-Section are formed. To determine the deviation of the ratio of currents $m/n$, the metrologist has to perform $(m + n)$ sequential measurements using $(m + n)$ capacitors. In each measurement, $n$ capacitors are connected in parallel to the $C_0$ input of the AC bridge, and $m$ capacitances are connected to the $C_X$ input. In each subsequent measurement, one of the capacitors from the $C_0$ input is switched to the $C_X$ input, and one of the capacitors from the $C_X$ input is switched to the $C_0$ input.

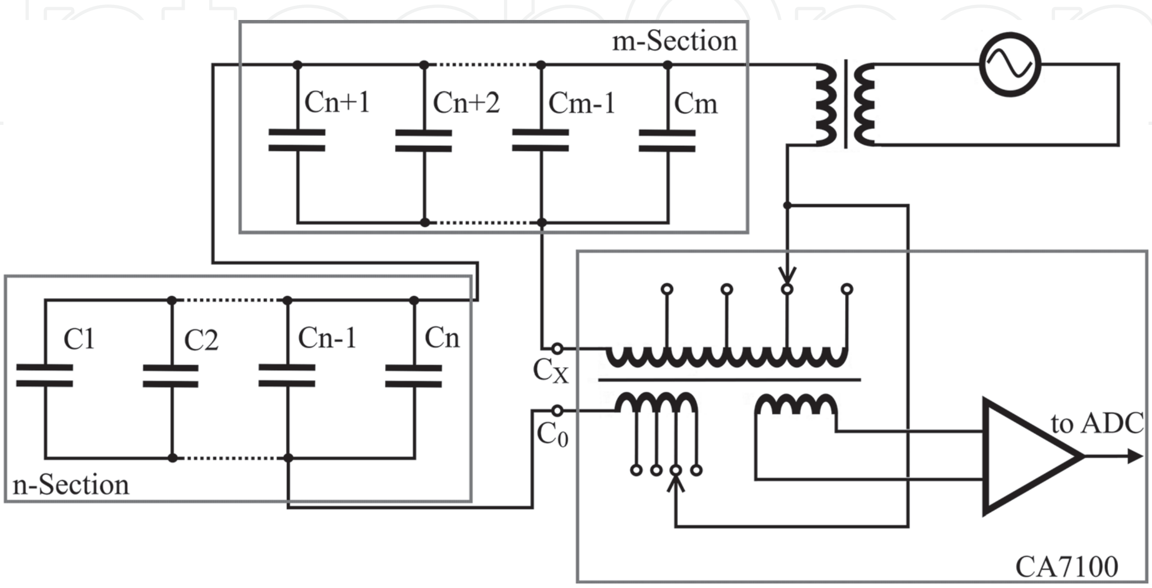


**Figure 13.**
*Measurement setup for characterization of transformer bridge.*

During $(m + n)$ measurements, each of the capacitors is connected $m$ times to the input $C_X$ and $n$ times to the input $C_0$. Processing the measurement results, the metrologist has to determine the relative deviation in measuring the capacitance by the formula

$$\delta_{Cm/n} = \sum_{i=1}^{m+n} \frac{C_{Xi}/C_0 - m/n}{m/n} \Big/ (m+n) \tag{10}$$

and the absolute deviation in measuring the dielectric loss tangent by the formula

$$\Delta tg\delta_{m/n} = \sum_{i=1}^{m+n} \Delta tg\delta_i \Big/ (m+n) \tag{11}$$

where $\Delta tg\delta_i$ is the absolute deviation in measuring the dielectric loss tangent at $i$th stage of the measurement cycle.

## 7. Routes of metrological traceability in instrument transformer calibration

**Figure 14** shows a diagram of the route of traceability of the measurement result obtained by VT calibrated by the method of reference transformer. As for the reference VT (RVT), it should be calibrated most often using the national standard (NSVSC) of the high-alternating voltage scaling coefficient [36]. This traceability route connects the VT under test with mentioned national standard through the chain of calibrations when both the voltage ratio error $\varepsilon_V$ and phase displacement $\Delta\varphi_V$ are determined (boundary branches for the ratio error and phase displacement in **Figure 14**).

The comparator (VTC) of two almost identical voltages, calibrated by the procedure described in this chapter, provides traceability to the national standard of the electric voltage. This becomes clear when considering **Figures 10** and **11**, where two voltmeters are the working standards (two middle branches in **Figure 14**).

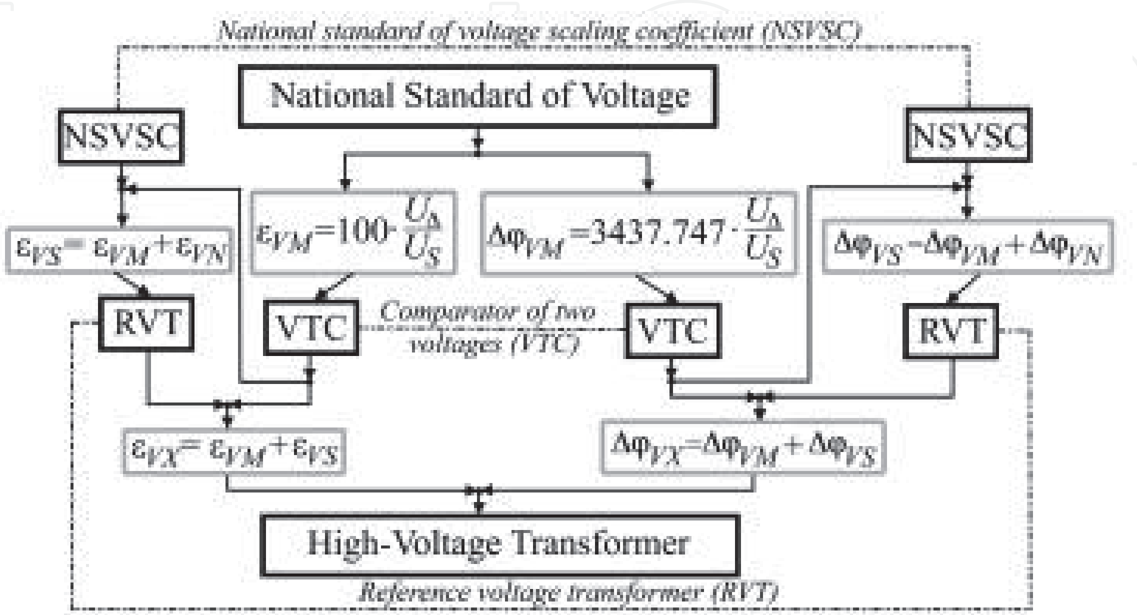


**Figure 14.**
*Traceability routes for the measurement result with VT tested using the reference transformer.*

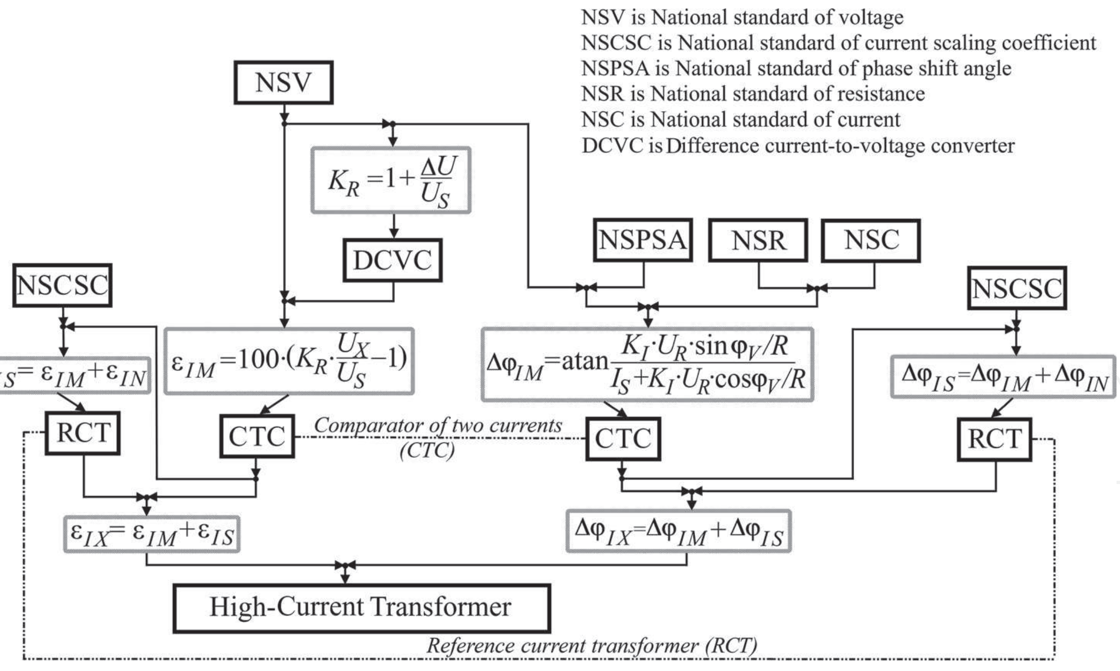


**Figure 15.**
*Traceability routes for the measurement result with CT calibrated by the conventional method.*

Regarding CTs, this chapter describes the method used by all National Metrology Institutes in the world when calibrating CTs with primary current up to 10 kA. As in the method of reference VT, a working standard and a comparator are used (see **Figure 6**).

**Figure 15** shows a diagram of the traceability route of the measurement result obtained by using the calibrated CT. As for the reference CT (RCT), it should be calibrated most often using the national standard (NSCSC) of the scaling coefficient of high-alternating current [36]. This traceability route connects the CT under test with the last-mentioned national standard through the chain of calibrations when the current ratio error ($\varepsilon_I$) and phase displacement ($\Delta\varphi_I$) are determined (boundary branches for the ratio error and phase displacement in **Figure 15**).

The comparator (CTC) of two almost identical currents, calibrated by the procedure described in this chapter, provides traceability to several national standards. Considering measurement setup for determining the low CT errors [34], it is seen that the phase meter measures the phase shift angle $\varphi_V$ between two voltages that is traceable to the corresponding national standard (NSPSA) of the phase shift angle. The readout $U_R$ of the voltmeter should be compared with the value of the national standard (NSV) of voltage as well as the reference resistance $R$ with the value of the national standard (NSR) of resistance, and the readout $I_S$ of the ammeter should be compared with the value of the national standard (NSC) of electric current. The current branching factor $K_I$ depends only on the ratio between voltmeter input impedance and reference resistance, which should be characterized at power frequency [37].

When considering **Figure 12**, one can see two voltmeters and a differential current-to-voltage converter (DCVC) consisting of the resistors R1 and R2. An electric current of the same magnitude flows in the circuit of both R1 and R2 when calibrating the last instrument, causing the next formation of the expression for determining the relative resistance difference $\Delta R/R = K_R - 1 = \Delta U/U_S$. Thus, the task of calibrating such an instrument is reduced to determine the relative voltage difference that occurs at the output terminals of the reference resistances.

Given the aforesaid, it is obvious that the metrological traceability reaches the national standard NSV when applying the comparator by the approach described.

## 8. Conclusion

Often high-voltage electrical networks provide the transfer of energy resources outside the state and the accounting chain must contain instrument transformers that are trusted. The materials presented in this chapter help to ensure the necessary trust through the application of the procedures with clearly defined routes of metrological traceability.

The method for calibrating the voltage transformer using the reference transformer gives traceability up to the national standard of the high-alternating voltage scaling coefficient. The application of comparator, characterized by the proposed method, sets a connection with the national standard of the electric voltage for both the voltage ratio error and the phase displacement.

The method for calibrating the current transformer using a reference transformer gives traceability to the national standard of the alternating current scaling coefficient. The application of comparator, characterized by the proposed method, sets connection with the national standard of the electric voltage for the current ratio error. When measuring the small phase displacement precisely, the traceability is provided up to several national standards, namely, the standard of the phase shift angle, the standard of electric voltage, the standard of electric resistance, and the standard of electric current.



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