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Dissemination of reference AC/DC voltage difference between ranges of AC/DC transfer standard

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Abstract

The measurement of low voltage up to 1000 V with a frequency of up to 1 MHz is crucial in electricity and magnetism. The AC/DC voltage transfer difference (AC/DC difference) is a critical metrological characteristic of the reference thermal converter. The metrological traceability of electrical voltage measurements shall be validated by either comparison with other national standards or calibration using standards with lower measurement uncertainty. Since, in practice, the period between comparisons of national standards is not always appropriate, calibration is more suitable for establishing metrological traceability if a primary standard is not introduced. This paper shows the way how to address the issue of irregular calibration of the component (Fluke 792A instrument) of the state standard DETU 08-07-02, detailing the approach to disseminate the reference AC/DC difference. Features of the mentioned measuring instrument are outlined, and ranges of voltage comparison are analysed, including one more suitable for being a link between the AC/DC difference and other measurement ranges. The diagram for disseminating the reference AC/DC difference demonstrates the proposed approach. The applied approximation allows one to deduce relations between the output quantity (AC/DC difference) of the studied standard and the input voltage depending on frequency for each input range. Using the mathematical processing program Microsoft Excel, the approximate equations were obtained, including polynomial dependence coefficients and coefficients of determination. In addition, by extrapolating the results of comparing the AC/DC differences it is possible to observe the potential bias in the controlled quantity.

Keywords: electrical voltage; alternating current; comparison; dissemination; thermal converter; measurement; standard; calibration; uncertainty.

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1. Introduction

In Ukraine, metrological traceability of alternating (AC) voltage measurement results up to 1000 V with a frequency up to 1 MHz is provided by the state standard DETU 08-07-02. There are two alternatives to establish a link with the internationally recognized measurement units approved by the International Bureau of Weights and Measures (BIPM) [1]: 1) calibration of reference measuring instruments using the corresponding primary standards registered in the Key Comparison Database (KCDB); 2) comparison of the results of the DETU 08-07-02 standard against similar results obtained with the reference systems of national metrological institutes (NMIs). These two approaches allow confirming calibration and measurement capabilities (CMCs), validating the relation of the reproducible AC voltage unit with both the quantum constants and the calculable value of the difference between AC voltage and direct (DC) one (AC/DC difference) – a quantity fixed by the NMI capabilities in the KCDB for comparing AC and DC voltages – the primary calculable thermal voltage converter. In addition, during comparisons, the degree of equivalence of the DETU 08-07-02 standard with foreign analogues [2] is determined, recording the dispersion of the reproduced value across all compared systems of measurement standards. Therefore, the usual way to establish the metrological traceability is to apply one or another aforementioned method.

2. The scope of the studied problem

Four types of AC/DC voltage transfer standards can be distinguished based on the study background [3–6]:

1) single-junction thermoelectric converters – SJTC;

2) multi-junction thermoelectric converters – MJTC;

3) planar-type multi-junction thermoelectric converters – PMJTC;

4) semiconductor root-mean-square (RMS) voltage sensors – RMS-sensors.

According to [7] – a report on the determination of the AC/DC difference of thermal converters – many European, and not only, secondary standards are traceable to the primary standard of German NMI – PTB – whose scientists determine primary reference characteristic of PMJTC by calculation and experiment [8, 9]. Particularly, calculating the AC/DC differences of the primary thermal converter by the model, the German NMI specialists considered three crucial uncertainty components [10]:

1) the impedance change of the heater depending on the frequency change (δ_{u1});

2) capacitance between the copper connecting conductors, the chip with gold contacts and thermocouples, the conductance before the N-type contact, conductive dielectric losses, skin effect, and the quartz part losses (δ_{u2});

3) standing wave voltage in the N-type connector and tee (δ_t).

Therefore, the full expression of the AC/DC difference (δ_u) model of the primary reference thermal converter is as follows [10]:

$$\delta_u = \delta_{u1} + \delta_{u2} + \delta_t. \quad (1)$$

A comparative analysis of reference voltage converter types [11] showed the relative advantage of PMJTC thermal converters over other types. For instance, an absent power supply for internal components and a simple design allow for uncertainty decrease and constructing a schematic model of the reference AC/DC difference, unlike Fluke 792A voltage converter. For comparison, the Canadian NMI determined the AC/DC difference for the PMJTC with a measurement uncertainty of 0.4 μV/V at a frequency of 1 kHz, while the same characteristic for the Fluke 792A instrument was 1.2 μV/V.

Regarding metrological traceability, the calibration of the reference Fluke 792A transfer standard (also known as AC/DC transfer standard) [6], which is a component of the national standard DETU 08-07-02, using the primary thermal voltage converter is accompanied by legal and logistical problems associated with many legislative inconsistencies and customs procedures. With all these issues, it is impossible to keep a definite schedule of calibration sequences for each precision measuring instrument from as part of the DETU 08-07-02 standard.

This challenge to ensuring and maintaining metrological traceability in Ukraine can be resolved by introducing a specific system for step-by-step propagation of the disseminated AC/DC difference across ranges of a precision AC/DC transfer standard. Additionally, the input carrier of the disseminated quantity shall be the high-tech planar thermal voltage converter PMJTC [8] (Germany), which is used to study the DETU 08-07-02 standard [12] as it has excellent stability characteristics.

3. A brief overview of the Fluke 792A multi-range voltage converter

The procedure, described in [13], for comparing characteristics of the two AC/DC converters (Fluke 792A and PMJTC) is the beginning of disseminating the target quantity from the PMJTC to the Fluke 792A. Following the common definition, the AC/DC difference of a thermal converter is calculated by the formula:

$$\delta_{AC-DC} = \left.\frac{U_{AC} - U_{DC}}{U_{DC}}\right|_{E_{AC}=E_{DC}}, \quad (2)$$

where U_{AC} is the input AC voltage, and U_{DC} is the DC voltage value of the Fluke 792A; E_{AC} and E_{DC} are the output thermoelectromotive force (thermo-EMF) of the studied device.

The procedure deals with the measurement range of 2.2 of the Fluke 792A instrument at six selected frequencies (10 and 45 Hz, 1, 10, and 100 kHz, and 1 MHz). The long-term metrological performance of the AC/DC transfer standard, outlined in [12], is primarily studied at 1.5 V. Nonetheless, it is stated that a certain amount of accumulated data comparing the AC/DC differences of the PMJTC thermal converter and the Fluke 792A voltage converter for an observed voltage of 1 V is also collected.

It should be noted that a decrease in the input voltage of a thermal converter is accompanied by both a negative effect of dropped sensitivity (as the output thermo-EMF decreases from approximately 88 mV to 39 mV) and a positive one of reducing thermal drift due to less heating of the thermal converter heater. Nonetheless, if to compare the AC/DC differences of the converters at 0.6 V (the output thermo-EMF is about 14 mV), then one can compare the characteristics of the converters for this observation point and for two adjacent measurement ranges (2.2 V and 700 mV). The voltage of 1.5 V is quite acceptable for comparing the AC/DC differences of the studied instruments for other two adjacent measurement ranges of 2.2 V and 7 V.

In Fig. 1, the diagram of both the RMS sensor and the input circuits of the Fluke 792A instrument can be seen with some simplification.

Following the technical description of the Fluke 792A standard [6], both resistors and capacitors are components of the input circuit. The input resistance depends on the level of voltage to be measured. It should be noted that the minimum resistance is 420 Ω for the input voltage up to 2.2 V, while the maximum resistance for the three low voltage ranges (22, 220, and 700 mV) is 10 MΩ. The three voltage comparison ranges, not exceeding 700 mV, have shunt capacitances,

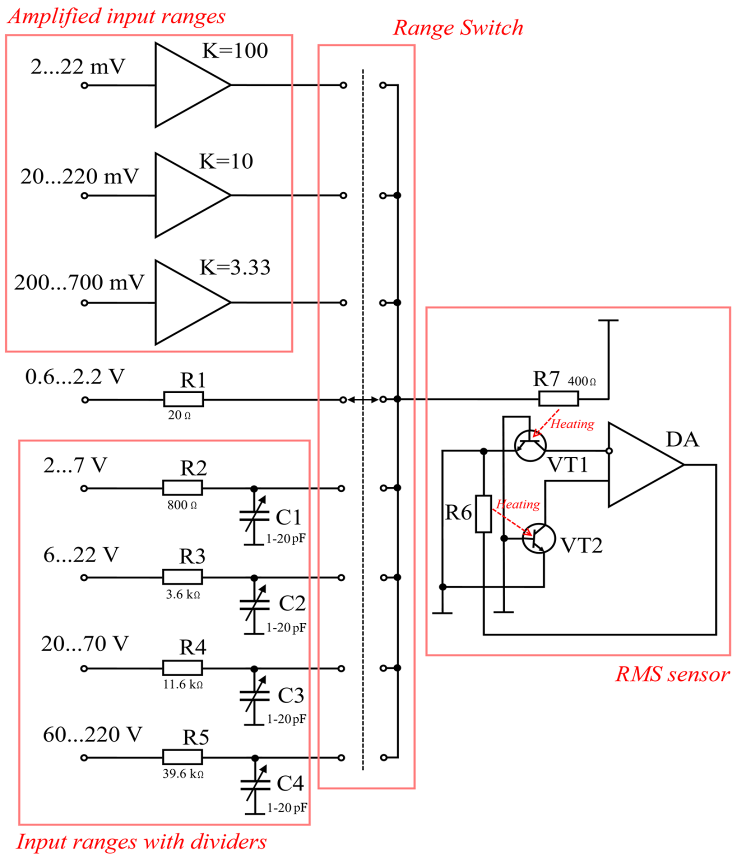

Fig. 1. The Fluke 792A voltage converter input circuit and RMS sensor schematic diagram

not exceeding 40 pF, while the other six ranges have a slightly smaller input reactance component – 20 pF or less.

Regarding Fig. 1, capacitors C1...C4 are adjustable for setting better characteristics (input resistors and capacitors for the lower comparison ranges are not included, as the corresponding low input voltage amplification circuits [6] include them). The mechanical switch (Range Switch) allows one to select the desired voltage comparison range and commutate the RMS sensor, patented [14] by the developer, Fluke Corporation, and the input circuit.

Fig. 1, on the right, shows a simplified diagram of an RMS sensor based on the automatic balance principle, considering the output voltages of two transistors VT1 and VT2, using a differential amplifier (DA). The current, entering the RMS sensor circuit from the input circuit, heats the resistor R7, placed near the base of the transistor VT1 and affects the circuit equilibrium as the consequence when the current in the collector changes [15]. The DA provides a corresponding current in the resistor R6, and its heat increases the VT2 current, which results in restoring the equilibrium of the DA. The voltage sensor, developed by Fluke Corporation, is sensitive to the following specified uncertainty. First, the metrological characteristic has an additional uncertainty from reactive components. Second, a low signal-to-noise ratio at small input values is another disadvantage. The maximum output signal is approximately 2 V.

When using the precision Fluke 792A voltage converter, the influence of factors that can become additional sources of measurement uncertainty shall be considered. Such factors include: DC voltage polarity reversal, connecting cables, thermo-EMF of the Seebeck effect, stray ground bus currents, electromagnetic interference, etc.

It should be reiterated that the fundamental difference between the measurement ranges above 2.2 V (7, 22, 70, 220, and 1000 V) and those below 2.2 V (700, 220, and 22 mV) is the integration of dividers for the upper voltages and the presence of voltage amplifiers for the lower ones. However, the 2.2 V measurement range stands alone, having neither a divider nor a voltage amplifier, making it the best dissemination link to receive the AC/DC difference value from the reference input carrier.

4. Principle of disseminating the reference AC/DC difference from the reference thermal converter to the multi-range voltage converter

Collecting the comparison data with the input carrier – the PMJTC thermal converter – of the disseminated quantity at observation voltages of 0.6, 1, and 1.5 V for three measurement ranges creates conditions for achieving greater reliability of the obtained results and their verification. The general diagram for disseminating the reference characteristic across the ranges of Fluke 792A is shown in Fig. 2.

Fig. 2 shows the route of initial information (i.e., the value of the AC/DC difference) from entering the system for disseminating the specified characteristic from the PMJTC thermal converter, which is characterized by ultra-high stability during its service life [8]. The values of 0.6 and 1.5 V serve as the baseline for comparing the main measuring range of 2.2 V and the two adjacent ones (the lower one is 700 mV and the upper one is 7 V) with each other and with the PMJTC thermal converter. Given that Fluke 792A instrument was previously calibrated at 0.6, 1, and 2 V, and the upper limit of the PMJTC thermal converter operating voltage is 1.5 V, it is necessary to apply the principle of interpolation within the available information.

Since the three voltage comparison ranges of the device under consideration (700 mV, 2.2 and 7 V) are direct links for obtaining the reference value of the disseminated quantity, and are directly used when comparing two converters (PMJTC and Fluke 792A), they obtain the reference value of the AC/DC difference with lower uncertainty than the links shown in Fig. 2.

The two-way arrows in Fig. 2 symbolize the equal status of these links, which receive the reference value without approximation. The one-way arrows show the direction of propagation of the disseminated quantity from the PMJTC, and the lower status of each subsequent link, which is accompanied by increasing measurement uncertainty.

For additional verification of the obtained results, it is advisable to use the accumulated data array of AC/DC differences of the PMJTC thermal converter and the Fluke 792A voltage converter at a voltage of 1 V. For that, the approximation of the functional relation $\delta = F(U; f)$ between the input quantities, voltage U and frequency f, and the output quantity (δ) of the Fluke 792A AC/DC transfer standard, was applied, according to the calibration certificate of this measuring instrument.

The next step is to compare the AC/DC differences of two compared converters obtained experimentally,

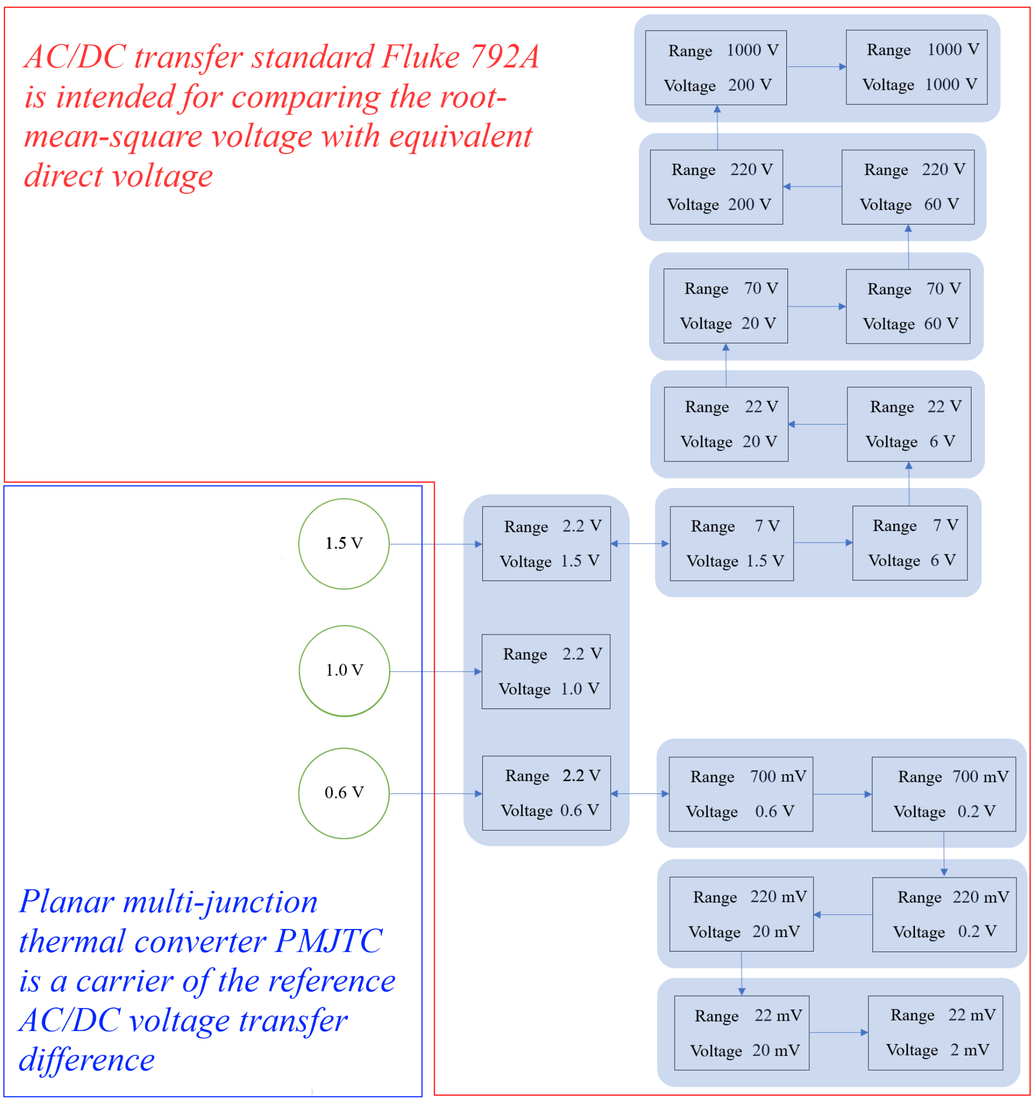

Fig. 2. Scheme of disseminating the reference AC/DC difference across the Fluke 792A ranges

considering the value obtained at the previous step as the reference (the direction of the arrow symbolises the direction of propagation of the reference value of the quantity). This principle shall be applied both to disseminating the reference value down to the 22 mV range and to disseminating it up to the 1000 V range. Finally, the disseminated quantity goes across measuring ranges through the approximated functional relation $\delta = F(U; f)$ – second-order polynomial trend lines (more details about the approximation are provided in the next section) generated by Microsoft Excel – for the highest and lowest measuring ranges of the studied voltage converter. Using an approximate functional relation, the bias, for example, at the 1000 V point, shall be estimated using the observed corresponding bias at the 200 V reference point. Similar considerations shall be applied to the lower comparison range. This method of extrapolating the obtained results beyond the selected observation points allows establishing metrological traceability over the entire range of reproduction of the AC voltage unit from 2 mV to 1000 V.

It should be emphasized that the proposed approach to disseminating the reference AC/DC difference and building a basis for establishing the metrological traceability of AC voltage measurement results accordingly, is developed considering the method described by the specialists from the North-American NMI (NIST) [16], combined with the methods of approximation, interpolation, and extrapolation of the obtained results beyond the selected observation points.

5. Approximation of voltage dependence of reference AC/DC difference of multi-range voltage converter

Following operation instructions [6] of the Fluke 792A instrument, its metrological characteristics can be estimated by calculation based on previously obtained experimental data, i.e., the developer proposes to interpolate the AC/DC difference of the instrument within the available information. To derive the functional relation, it is recommended to apply the following logic:

- to use the AC/DC differences of this device and measurement uncertainties for frequencies above 100 Hz in all voltage comparison ranges from the calibration certificate, but within 2% deviation from the frequency and voltage of the observation point;
- to apply the values from the calibration certificate for interpolation within 2% deviation from the frequency of the observation point and the propagation of measurement uncertainty for frequencies up to 100 Hz in voltage comparison ranges of not less than 2.2 V using a functional relation $\delta = A/f^2 + B$ (A and B are the coefficients calculated according to [6]);
- to apply the values given in the calibration certificate for interpolation within 2% deviation from the voltage of the observation point and the propagation of measurement uncertainty for frequencies up to 100 Hz in voltage comparison ranges of not less than 2.2 V using a functional relation $\delta = C \cdot U^2 + D$ (C and D are the coefficients calculated according to [6]);
- not to use the interpolation technique for comparison ranges up to 2.2 V, as this approach does not work for input circuits that require power for amplifying elements.

It should be noted that the guideline [6] does not provide any recommendations for ranges below 2.2 V, but rather states that there is no typical systematic dependence. However, it confirms the high stability of the AC/DC difference of Fluke 792A at the observation point, even for measuring ranges below 2.2 V. Moreover, there are no relevant recommendations for deriving dependencies for regions other than 2% from the observation point. Therefore, it is advisable to search for individual functional relations for the specified measuring subranges of the instrument under consideration, which serves as the basis for the national subsystem for establishing metrological traceability of AC voltage measurements in the frequency range up to 1 MHz. To address the issue, one needs to process the available data on the AC/DC difference of the Fluke 792A voltage converter (as a result of multiple calibrations in a competent laboratory) using Microsoft Excel software.

The available data set for processing is conveniently presented as an array shown in Table 1.

Table 1

Typical listing of data on the AC/DC difference of Fluke 792A voltage converter

Compared voltage	AC/DC difference depending on frequency							
	f_1	f_2	…	f_i	$f_{(i+1)}$	…	$f_{(n-1)}$	f_n
U_1	δ_{11}	δ_{12}	…	δ_{1i}	$\delta_{1(i+1)}$	…	$\delta_{1(n-1)}$	δ_{1n}
U_2	δ_{21}	δ_{22}	…	δ_{2i}	$\delta_{2(i+1)}$	…	$\delta_{2(n-1)}$	δ_{2n}
…	…	…	…	…	…	…	…	…
U_j	δ_{j1}	δ_{j2}	…	δ_{ji}	$\delta_{j\,(i+1)}$	…	$\delta_{j\,(n-1)}$	δ_{jn}
U_{j+1}	$\delta_{(j+1)1}$	$\delta_{(j+1)2}$	…	$\delta_{(j+1)i}$	$\delta_{(j+1)(i+1)}$	…	$\delta_{(j+1)(n-1)}$	$\delta_{(j+1)n}$
…	…	…	…	…	…	…	…	…
U_{k-1}	$\delta_{(k-1)1}$	$\delta_{(k-1)2}$	…	$\delta_{(k-1)i}$	$\delta_{(k-1)(i+1)}$	…	$\delta_{(k-1)(n-1)}$	$\delta_{(k-1)n}$
U_k	δ_{k1}	δ_{k2}	…	δ_{ki}	$\delta_{k(i+1)}$	…	$\delta_{k(n-1)}$	δ_{kn}

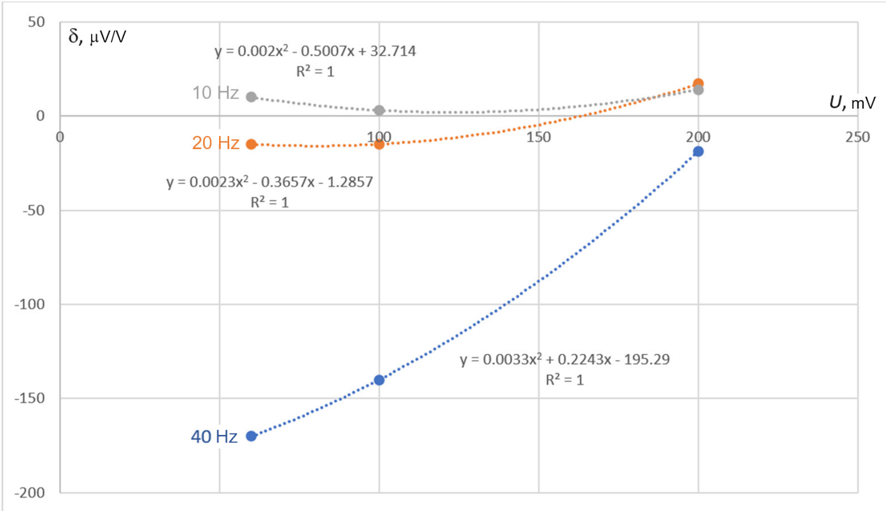

Fig. 3. Restored functional relationships between the Fluke 792A AC/DC difference and voltage

Table 1 shows that each unique value of the metrological characteristic of the Fluke 792A has two parameters: an input voltage and a frequency. The points fixed according to Table 1 for establishing metrological traceability are suitable for study, considering their presence in several calibration certificates, the unique difference between the characteristics of adjacent measuring ranges, and the voltage concurrence on two adjacent ranges.

By entering the available data into a table of the Table 1 type and by subsequently displaying the observation points $\delta_{ji}(U_j; f_i)$ in a graphical form, an array of graphical information is constructed. By approximating the empirically obtained values at the selected points for different frequencies, approximate functional relations $\delta = F(U; f)$ are established, which form an analytical basis for the dissemination of the target quantity across the ranges of the AC/DC transfer standard, and thus, establishing the metrological traceability of AC voltage measurements.

The result of analytical processing is the restored series of functional relations between the disseminated quantity and the Fluke 792A voltage at the selected frequency. In Fig. 3, an example of approximation for frequencies of 10, 20, and 40 Hz in a comparison range of 220 mV is shown.

In Fig. 3, one can notice that each functional relation is expressed with a second-order polynomial expression calculated using Microsoft Excel. The indicated determination coefficients represent the scatter of the output quantity, which is expected from the available data. The obtained functional relations are characterized mainly by almost unity factors of determination, except for the 22 mV range, where the worst indicator reached $R^2 = 0.96$. However, increasing the approximation order to 3, to get a better coefficient of determination, allows one to obtain $R^2 = 1$ for the voltage range and frequencies under consideration.

It should be noted that the contribution of the uncertainty source due to the approximated dependences with determination coefficients of 1 reaches negligible values. However, when disseminating the reference value of the AC/DC voltage difference between the Fluke 792A ranges, one shall account for the measurement uncertainty that arises at each stage of comparing the readings of the device under consideration when applying the specified voltage alternately to two measuring circuits of adjacent ranges. In this case, the uncertainty arising at the previous step shall be combined with the standard deviation of the comparison result. In this paper, the initial measurement uncertainty is that assigned to the value of the reference AC/DC voltage difference of the PMJTC reference thermal converter.

Conclusion

The presented approach to propagate the disseminated AC/DC voltage transfer difference of the studied Fluke 792A, which represents the state standard DETU 08-07-02, allows one to overcome the problem of establishing metrological traceability of measurement results in transferring from alternating voltage to direct voltage, which is the basis for the consistency of low-voltage measurements up to 1000 V in the frequency range up to 1 MHz. The approximated functional relations between the disseminated reference value and the voltage of the studied instrument, depending on the frequency, form the basis for extrapolating the target quantity beyond the available data set obtained as a result of calibration in a competent higher-level laboratory.

Поширення еталонної AC/DC різниці напруги між діапазонами еталона AC/DC переходу

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Анотація

Вимірювання низької напруги до 1000 В частотою до 1 МГц є важливим предметом електрики та магнетизму. Різниця переходу від напруги змінного струму до напруги постійного струму (AC/DC різниця напруги) є критично важливою метрологічною характеристикою еталонного термоперетворювача. Метрологічна простежуваність вимірювань електричної напруги повинна бути обґрунтована звіреннями з національними еталонами або калібруванням із застосуванням еталонів з меншою невизначеністю. Оскільки на практиці не завжди дотримуються інтервалу між звіряннями національних еталонів, калібрування є більш надійним способом забезпечення метрологічної простежуваності вимірювань у разі відсутності первинного еталона. Стаття пропонує підхід до подолання проблеми недотримання чіткого інтервалу між калібруваннями приладу Fluke 792A зі складу національного еталона ДЕТУ 08-07-02 та деталізує спосіб поширення еталонного значення AC/DC різниці напруги від термоперетворювача з меншою невизначеністю. Розглянуті технічні особливості згаданого засобу вимірювання та виділений діапазон вхідної напруги, що є з’єднувальною ланкою між вхідним носієм еталонної AC/DC різниці напруги та іншими діапазонами вимірювання. Схема поширення еталонного значення AC/DC різниці напруги описує запропонований підхід. Застосований у дослідженні метод апроксимування дозволяє відновлювати функційні зв’язки між вихідною величиною (AC/DC різницею напруги) досліджуваного еталона і вхідною величиною (вхідною напругою) залежно від частоти для кожного вхідного діапазону. Шляхом застосування програми математичної обробки Microsoft Excel отримані апроксимовані рівняння включно з оцінками коефіцієнтів поліноміальної залежності та коефіцієнтів детермінації. Крім того, екстраполювання результатів звірення AC/DC різниць напруги суміжних діапазонів досліджуваного приладу поза межі наявних даних дає можливість спостерігати за потенційним зміщенням контрольованої величини.

Ключові слова: електрична напруга; поширення значення; змінний струм; звірення; термоперетворювач; вимірювання; еталон; калібрування; невизначеність.

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