Wideband AC Voltage Standards

Krzysztof Kubiczek, Marian Kampik, Michał Grzenik, Krzysztof Musioł, Anna Piaskowy
Politechnika Śląska, Wydział Elektryczny, Katedra Metrologii, Elektroniki i Automatyki, ul. Akademicka 10, 44-100 Gliwice

Abstract: This article presents a critical review and comparison of constructions and metrological properties of contemporary wideband standards for AC voltage. It focuses on selected thermal voltage converters (TVCs) used in alternating current-direct current (AC-DC) transfer voltage standards and for the most precise measurements of AC voltages up to approximately 100 MHz. These devices serve as primary AC voltage standards at National Measurement Institutes (NMIs).

Keywords: calorimetric thermal voltage converter, thermal voltage standards, quantum voltage standards, precision metrology, ac-dc transfer difference

1. Introduction

Alternating (AC) voltage or, more precisely, its root mean squared (RMS) value is one of the most frequently measured electrical quantities. Instruments used for measurement or synthesis of AC voltage must be calibrated periodically, and appropriate standards must be used for this purpose. Currently, the leading National Measurement Institutes (NMI) of highly developed countries use four basic types of AC voltage standards:

- Josephson voltage standard (JVS),
- standards using single-junction thermal converter (SJTC),
- standards using planar multi-junction thermal converter (PMJTC),
- standards using calorimetric thermal voltage converters (CTVC).

The frequency range of operation of these devices is shown in Figure 1.

In this article, we provide a comprehensive description of AC-DC transfer and thermal voltage converters used to reproduce standard AC voltage in a very wide frequency range. We also give a short description of the principle of operation of the quantum voltage standards. Finally, we present some possibilities to improve the thermal voltage converters, which are viable due to technological progress in recent years.

2. Quantum AC voltage standards

The principle of operation of quantum Josephson voltage standards (JVS) is based on the quantum Josephson phenomenon. This phenomenon occurs in the so-called Josephson junctions. A typical Josephson superconductor-isolator-superconductor (SIS) junction consists of two superconductors, separated by a thin layer of insulator [1]. The Josephson alternating current effect occurs when a junction is polarized with direct current in a weak magnetic field. Then, in addition to direct current, an alternating current begins to flow through the junction with a frequency f associated with a DC voltage that polarizes the junction U [2] based on the following equation:

$$f = \frac{2e}{h}U, \qquad (1)$$

where e and h are the charge of the electron and the Planck constant, respectively.

In fact, the current-voltage (I-U) characteristics of the Josephson junction take the shape of steps (the so-called Shapiro steps) [3]. Very high accuracy for the microwave frequency generated by modern generators, and adoption of physical constants as exact numbers in the new SI system, resulted in the design of quantum DC and AC voltage standards able to generate voltages of very low uncertainty [4]. Because the voltage obtained from a single Josephson junction is relatively low (in the order of 0.1 mV), the generation of voltages of the order of volts requires the use of matrices made of several to tens of thousands of Josephson junctions connected in series [5]. The junctions are irradiated with an alternating elec-

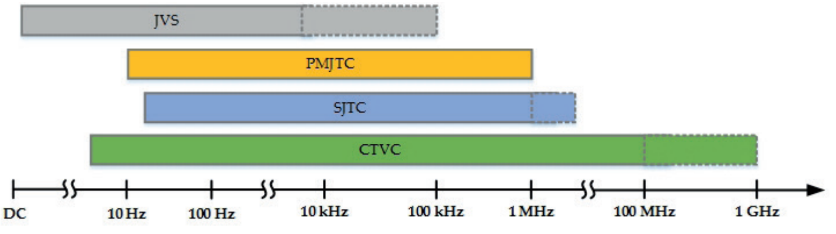

Fig. 1. Frequency bands in which standards of AC voltage are used
Rys. 1. Przedział częstotliwości stosowania wybranych wzorców napięcia przemiennego

Autor korespondujący:
Krzysztof Kubiczek, krzysztof.kubiczek@polsl.pl

Artykuł recenzowany
nadesłany 11.12.2023 r., przyjęty do druku 29.01.2024 r.

tromagnetic field generated by a microwave frequency source reaching several tens of GHz. The uncertainty of this frequency is 10^{-10} or less [6].

As given in equation (1), the quantum voltage level can be adjusted by the frequency f or the number of Josephson's junctions. Because the typical frequency required to realize a quantum voltage is at a very high level of about 60–80 GHz, and the frequency must be known with atomic-clock accuracy, frequency manipulation is very difficult [7]. Instead, researchers prefer to tweak the number of active junctions by switching the bias constant current on and off. This principle of operation is applied to the programmable Josephson voltage standard (PJVS). This standard contains binary-divided Josephson junction arrays, whose sections can be activated/deactivated by switching the constant bi-as current [8]. This standard is used for the generation of quantum DC voltage or, by sequential bias current adjustment, for generating stepwise approximated AC voltage up to a few kHz [9]. Unfortunately, due to residual parameters of the junction arrays, the switching frequency is limited. Moreover, the voltage during the transient from one volt-age step to the next one is not quantized. Thus, the uncertainty of the generated voltage in-creases above a few kHz. Furthermore, the stepwise approximation of the generated sinewave leads to the increase of harmonics in the output signal [10].

To bypass the need for a switching of the bias current, the design of the Josephson arbitrary waveform synthesizer (JAWS) was proposed [11]. The shape and the voltage of the quantum output signal are controlled by the pulse pattern generator. The generator is connected to the constant high-frequency reference signal (typically 15–20 GHz) and generates bipolar or ternary pulses according to the predefined pattern. The pulse pattern is obtained by the simple sigma-delta software conversion of the required shape and amplitude. This produces the required pulse-driven signal shape and amplitude with an extensively pure spectrum [12].

PJVS synthesized AC voltage is in the frequency range from a few Hz to several kHz. Hence, this rather limited frequency range does not qualify them as wideband AC voltage standards. Therefore, for the leading NMIs, intensive work has been underway to increase the frequency range to at least 100 kHz [13]. This includes developing and applying sub-sampling methods based on comparing high-frequency non-quantum, semiconductor-based generators with the low-frequency quantum voltage only in a specific and short space of time in many consecutive periods [7].

The quantum sources of AC voltages have been implemented as a primary standard by the National Institute of Standards and Technology (NIST) [11, 14] and Physikalisch-Technisch Bundesanstalt (PTB) [15, 16]. However, the application of quantum AC voltage standards continues to face difficulties, among other things, because of the high cost of their purchase, maintenance, and operation. This is because these standards require expensive and complex cryogenics, vacuum or liquid helium cryogenic systems, and GHz-frequency ultra-stable generators (sometimes modulated using fast deep-memory bit-pattern generators).

An interesting solution is the microwave quantum-defined source described in previous work [17]. It generates a sinusoidal voltage of approximately 17 mV at a single frequency equal to 1.005 GHz. It seems that a set of such devices, generating voltage at discrete frequencies, may be used as a source of standard high-frequency voltage. Unfortunately, its output voltage is too low to calibrate thermal voltage converters directly. More-over, the output current of the device must be sufficient to drive the heater of a TVC.

In recent years, the improvement of the JVS is focused on improving the operation of the cryocoolers, which enable significant reduction of usage of expensive liquid helium [18, 19], increasing the amplitude of the generated voltage by up to 20 V by increasing the number of Josephson junctions in the arrays (even up to 300 000) [20] and reducing the harmonics in the output signal developed from the Josephson arbitrary voltage synthesizer (JAWS) [21].

3. Thermal AC-DC transfer

Currently, the most accurate way to determine wideband sinusoidal AC voltage in the frequency range from approximately 1 kHz to 100 MHz is the substitution method, which is called AC-DC voltage transfer or – in the case of radiofrequency (RF) voltage – RF-DC voltage transfer. In this method, thermal voltage converters (TVCs) are used.

The principle of operation of the TVC is based on the definition of the RMS of alternating voltage, which is defined as [22]:

$$U_{AC} = \sqrt{\frac{1}{T}\int_0^T u^2(t)\,dt}, \tag{2}$$

where $u(t)$ and T are the instantaneous value and the AC voltage period, respectively.

The above definition is based on the Joule-Lenz law, which defines the DC power, P_{DC}, and AC power, P_{AC}, dissipated in a resistance R for DC and AC voltages, respectively, as [23]:

$$P_{DC} = \frac{U_{DC}^{\;2}}{R}, \tag{3}$$

$$P_{AC} = \frac{U_{AC}^{\;2}}{R}. \tag{4}$$

The idea of AC-DC transfer is essentially based on the substitution of an unknown AC voltage with a known DC voltage of equivalent power. For the Joule-Lenz law, if the power dissipated by these two signals is equal (in a resistor of nominally the same resistance), the unknown RMS voltage of the AC signal is equal to the known DC voltage. A simplified schematic diagram of the thermal voltage converter is shown in Figure 2.

A typical TVC consists of a resistor with small residual impedance parameters, acting as a heater, and a thermometric sensor converting the temperature rise of the heater into a direct voltage. The simplified block diagram of a system realizing the AC to DC transfer is shown in Figure 3.

In the system shown in Figure 3, at first, the stable sinusoidal voltage of unknown RMS from an AC voltage source $U_{AC}$is applied to the TVC heater. After stabilization of the temperature of the heater, the output voltage $E_{AC}$of the TVC is measured, and then the known DC voltage from the DC

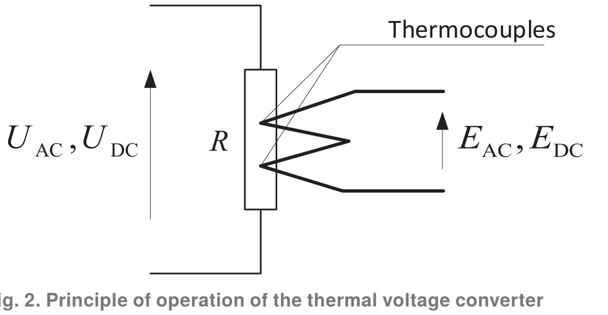

Fig. 2. Principle of operation of the thermal voltage converter
Rys. 2. Zasada działania termicznego przetwornika napięcia

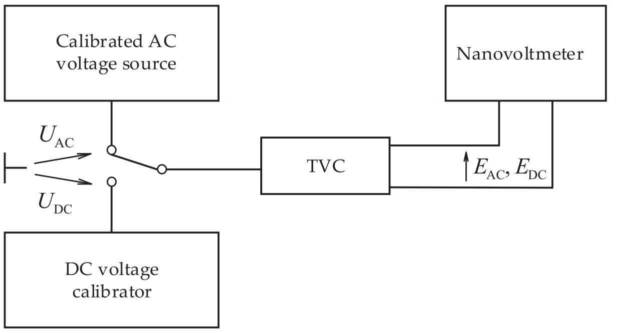

Fig. 3. Simplified measurement setup used for the AC-DC transfer
Rys. 3. Uproszczone stanowisko pomiarowe do transferu AC-DC

voltage calibrator U_{DC} is applied to the converter. This voltage is adjusted until the TVC output, E_{DC}, has a voltage equal to the previously obtained voltage, E_{AC}. If these two voltages are equal, then the RMS AC voltage is equal to the known DC voltage.

At frequencies above approximately 100 kHz, due to numerous phenomena such as skin effect, reflection associated with impedance mismatch, thermoelectric phenomena, etc., the same amount of thermal energy is released for the same resistance at different AC and DC voltage values. This difference is given by the following:

$$\delta_{AC-DC} = \left.\frac{U_{AC}}{U_{DC}}\right|_{E_{AC}=E_{DC}} - 1, \qquad (5)$$

where δ_{AC-DC} is the AC-DC transfer difference.

The AC-DC transfer difference and its uncertainty are among the most important parameters describing the TVC. The AC-DC transfer difference can be calculated from an appropriate mathematical model of a TVC or by comparison with a TVC of known δ_{AC-DC}. The first method is used to determine the AC-DC transfer difference of the most accurate TVCs used as primary standards. The δ_{AC-DC} strongly depends on the frequency.

At frequencies below approximately 100 Hz, the main cause of the AC-DC transfer difference is a nonlinear thermal phenomenon and insufficient temperature averaging in the heater and thermocouples. To define δ_{AC-DC} at these frequencies, typically, the quantum AC voltage standard [24] may be used.

In the ultra-low frequency band (up to about 10 Hz), due to the thermal constant of the heater being comparable with the input signal period, the special AC-DC transfer systems are designed [25] aiming to become a special TVC such as a double-heater TVC (i.e., DHTVC) [26]. The principle of operation of this system is the use of the input signal provided to the first heater and the signal's shifted twin (orthogonal signal) into the second heater to artificially average the dissipated power.

In the frequency band from about several Hz to about 10 kHz, the transfer difference is determined primarily by thermoelectric phenomena. In this frequency range, the methods for measuring the transfer difference using a rectangular voltage reference source shall be used, e.g., for fast reversed DC voltage or current method, FRDC [27] or a more expensive method using a quantum AC voltage standard [24].

In the frequency range from approximately 10 kHz to approximately 1 MHz, the influence of the skin effect dominates. The AC-DC transfer difference in this frequency range is determined by comparison with a converter of a known transfer difference [3, 28] or calculated based on a mathematical model of the converter, in which there are geometric dimensions and material constants of the TVC [29]. Converters with calculated δ_{AC-DC} are called calculable.

The value of the AC-DC transfer difference above approximately 1 MHz is dominated by wave phenomena (i.e., wave reflection, interference, and long-line effects) and skin effects. There is also a large influence on the residual parameters of the TVC heater. In this frequency range, the AC-DC transfer difference is determined from a mathematical model of the converter based on its geometrical dimensions and material constants or by comparison with a converter of a known δ_{AC-DC} [30].

The precision of measurement results obtained with an AC-DC transfer system when comparing two TVCs strongly depends on the stability of the DC and AC voltage sources used in the system. The AC-DC transfer procedure is lengthy. Typically, it takes approximately 1 hour to perform an AC-DC transfer at one frequency and one voltage. Moreover, during this time, the DC voltage is adjusted to keep the E_{DC} as close as possible to the E_{AC}. Hence, it is the short-term stability of the voltages of both sources that is most critical from the point of view of precision of AC-DC transfer results. Usually, a DC voltage calibrator is used as the DC voltage source. The short-term stability of the voltage generated by such calibrators depends on the voltage size but typically is below 1 μV/V and has an almost insignificant influence on the standard deviations of the results of the AC-DC transfer. For the 10 Hz – 1 MHz frequency range, the role of the AC voltage source is played by the AC voltage calibrator (typically part of a multifunction calibrator). The short-term stability of the AC voltage generated by such calibrators is typically higher than that of the DC voltage calibrators and depends on the voltage and frequency. However, it still achieves an acceptable precision for the AC-DC transfer results.

The problem of short-term stability of the AC source is visible above 1 MHz. Some AC voltage calibrators have a built-in option that enables them to generate voltages up to 30 MHz or even 50 MHz. However, the short-term stability of the voltage is substantially lower. Moreover, the output impedance of the AC voltage calibrator at these frequencies rises to 50 W. Above 30–50 MHz, it is necessary to use commercial radio-frequency signal generators. Their short-term stability is usually even worse than the short-term stability of the voltage generated with high-frequency optional modules of AC voltage calibrators. The results of a comparison of selected AC voltage generators for high-frequency AC-DC transfer performed at SUT at Istituto Nazionale di Ricerca Metrologica (INRIM) in Turin, Italy [31]. The setup at SUT used for the AC-DC transfer at higher frequencies is presented in Figure 4.

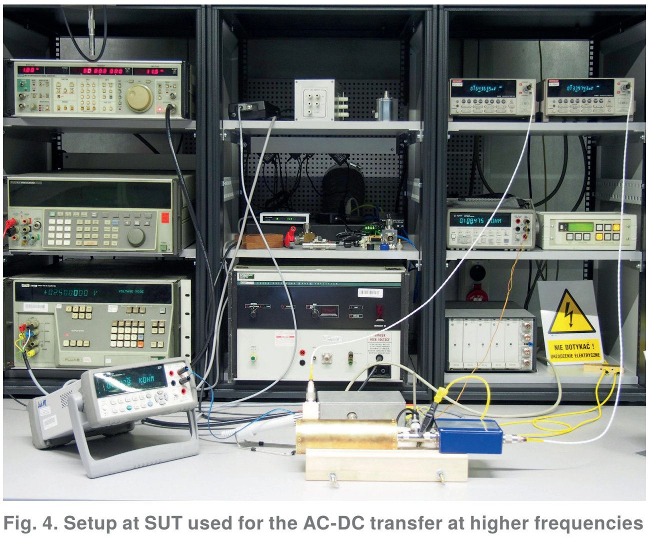

Fig. 4. Setup at SUT used for the AC-DC transfer at higher frequencies
Rys. 4. Stanowisko do wysokoczęstotliwościowego transferu AC-DC na Wydziale Elektrycznym Politechniki Śląskiej

4. Thermal voltage converters

As previously described, despite spectacular achievements in the field of quantum methods of synthesis of standard alternating voltage, modern primary AC voltage standards used in the frequency band from 10 Hz to 100 MHz are still using TVC. Such a converter consists of a resistor with small residual parameters, acting as a heater, and a thermometric sensor, converting the temperature rise of the heater into a DC voltage (more strictly an electromotive force, EMF).

4.1. Single junction thermal voltage converters

The design of the single-junction thermal voltage converter (SJTC) is presented in Figure 5.

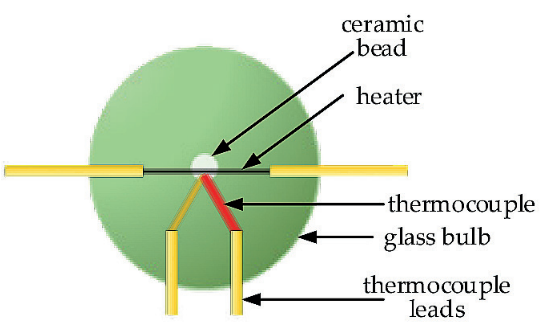

Fig. 5. Single junction thermal converter
Rys. 5. Jednozłączowy termiczny przetwornik wartości skutecznej napięcia

This device is equipped with a thermometric sensor in the form of a single thermocouple [32]. For this reason, a single-junction thermal converter is characterized by a relatively low sensitivity, defined as the increase in output voltage to the power dissipated in the heater. Its output EMF is low, in the order of a few mV, due to the dissipated power of up to several mW [33]. In addition, the use of a single thermocouple increases the DC reversal error caused by irreversible thermoelectric phenomena, which contributes to the increase of the AC-DC transfer difference component, which is independent of the current frequency [34]. The parameter characterizing this influence is the DC reversal error defined by:

$$\delta_r = 2 \cdot \left. \frac{U_{DC+} - |U_{DC-}|}{U_{DC+} + |U_{DC-}|} \right|_{E_{DC+} = E_{DC-}}, \tag{6}$$

where U_{DC+} and U_{DC-} are the DC input voltages of the same value but opposite polarity, applied sequentially to the TVC heater.

The DC reversal error of a commercially produced SJTC is in the range from about 0.005 % to 0.2 %, but selected and thoroughly manufactured devices can have a DC reversal error even below a few μV/V [35]. The advantage of the SJTC is its uncomplicated geometry, which facilitates the calculation of its transfer difference in the frequency range from approximately 10 kHz to approximately 1 MHz. Among the contemporary available SJTCs, the optimal metrological parameters possess devices of 90 Ω heater resistance and a nominal heater current of 5 mA [36]. The main advantage of the SJTC is its uncomplicated geometry, which facilitates the calculation of its transfer difference in the frequency range from approximately 10 kHz to approximately 1 MHz. The main drawback of the SJTC is its vulnerability to an overload followed by the destruction of the heater. Another disadvantage of the SJTC is its low sensitivity. At a nominal input voltage, the output EMF usually does not exceed 10 mV. To extend the low value of the input voltage of the SJTC (0.2–0.5 V), a resistor is connected in series with the heater, called a *range resistor*. In the case of primary standards, this resistor has a coaxial form, which simplifies the development of a mathematical model and calculation of the transfer difference of the range resistor-SJTC assembly in the higher frequency band (typically, 10 kHz – 1 MHz). The TVC composed of an SJTC integrated with a coaxial resistor, developed, and constructed at SUT, is presented in Figure 6. A set of coaxial resistors makes it possible to use the SJTC in AC voltage standards up to 1000 V.

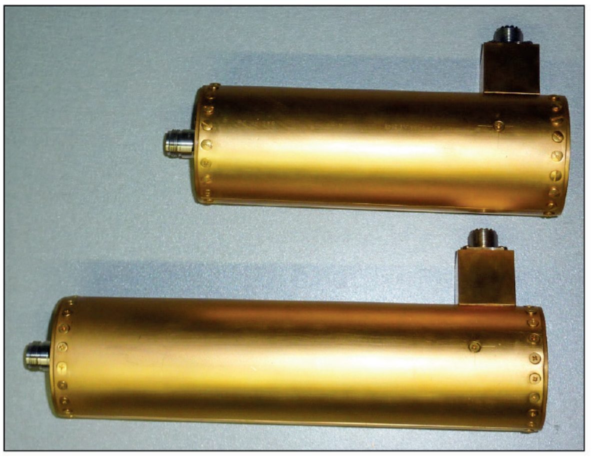

Fig. 6. Single junction thermal converter
Rys. 6. Jednozłączowy termiczny przetwornik wartości skutecznej napięcia

Due to the wave phenomena occurring in a relatively long waveguide, SJTCs are mainly used as AC voltage standards in the frequency range of up to 1 MHz. However, thoroughly constructed coaxial designs can serve as calculable AC-voltage standards up to several dozens of MHz [37–39]. Comparisons performed in 2020 confirmed good accuracy of such standards in the 1–30 MHz frequency range [40].

4.2. Planar multi-junction thermal voltage converters

The design of the planar multijunction thermal voltage converter (PMJTC) is shown in Figure 7.

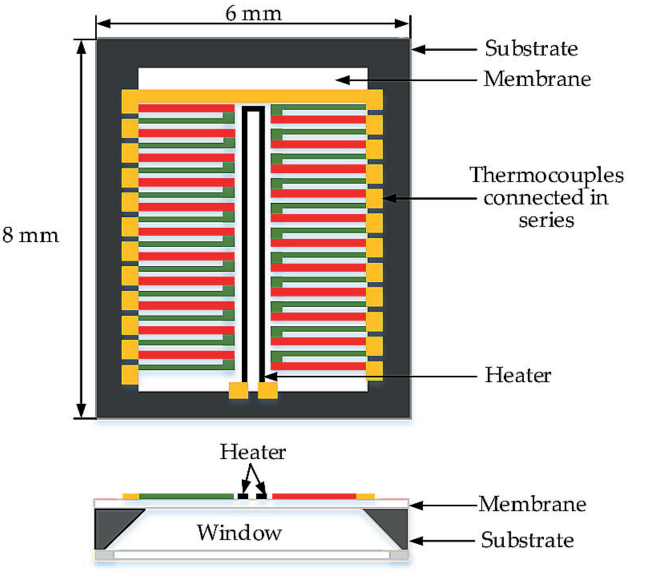

Fig. 7. Planar multijunction thermal converter
Rys. 7. Planarny, wielozłączowy termiczny przetwornik wartości skutecznej napięcia

Due to the use of several dozen thermocouples connected in series, this converter is characterized by a higher sensitivity than the sensitivity of the SJTC [41]. Its output EMF is approximately one order greater than the output EMF of the SJTC and reaches a value from several dozen to several hundreds of mV. In addition, the use of many thermocouples distributed along the entire length of the bifilar heater reduces the detrimental impact of thermoelectric reversible phenomena, so that the PMJTC DC reversal error is significantly reduced, reaching values of 1 μV/V. Planar technology enables the construction of a heater with resistance in the range from several dozen ohms to about 1 kΩ, which allows us to bring to the PMJTC input a voltage with an effective value in the range from a fraction of a volt to several volts [42]. For this reason, primary standards using PMJTC generally do not require the use of range resistors for voltages in the range from 0.5 to approximately 5 V.

In the last decade, PMJTC has often been made on silicon substrate [43]. They have very good metrological properties in the frequency range from several dozen Hz to several hundred kHz. At frequencies higher than approximately 100 kHz, their AC-DC transfer difference increases, mainly due to the adverse influence of the membrane and silicon substrate. For this reason, PMJTCs on quartz substrate [36], fused silica, and fused quartz [44] were developed. Multi-junction hybrid converters were also developed, in which thermocouples were sputtered onto a kapton film stretched on an Al_2O_3 frame, and a chromium-nickel (Ni75Cr20Al2.5Cu2.5) radiator was deposited onto an aluminum nitride (AlN) substrate [45]. Converters of this type are usually used in the frequency range up to several MHz.

Comparison of the AC-DC transfer differences of the thermal voltage converters

Figure 8 shows the frequency dependence of the AC-DC voltage transfer differences of selected TVCs, which may be used in wideband AC-DC transfer systems:

- CTVC developed at the NRC,
- JTC with a range resistor, developed at the Dutch National Metrology Institute (VSL) [3],
- SJTC with a range resistor, developed at the Institute of Measurement Science, Electronics and Control (IMEiA) at the Silesian University of Technology, Poland [46, 47],
- PMJTC with a fused silica substrate and radiator resistance of 472 Ω, developed at the National Institute of Standards and Technology, NIST, USA [45],
- PMJTC with a quartz substrate and radiator resistance of 1 kΩ, developed at the German National Metrology Institute, PTB [36],
- hybrid PMJTC with a radiator deposited on an aluminum nitride substrate, developed at the Japanese National Metrological Institute, AIST [48].

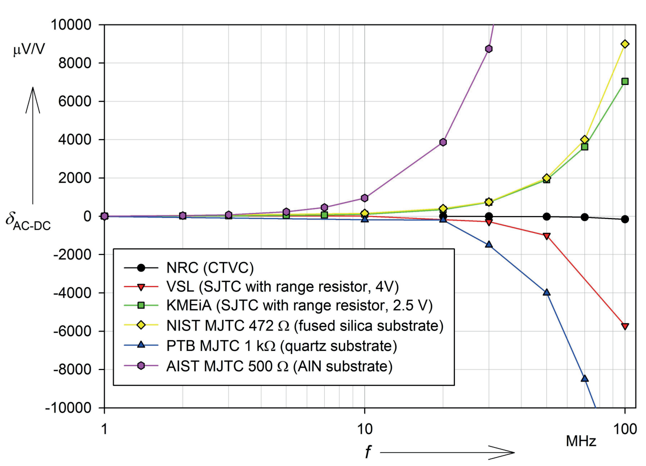

Fig. 8. Comparison of the AC-DC transfer differences for selected wideband thermal voltage converters in a frequency range 1–100 MHz
Rys. 8. Porównanie charakterystyk różnicy transferowej dla wybranych szerokopasmowych termicznych przetworników napięcia w przedziale częstotliwości od 1 do 100 MHz

A comparison of the characteristics shown in Figure 8 reveals that – compared to other converters – CTVC is characterized by an extremely small transfer difference in the frequency range 1–100 MHz.

5. Conclusion and future work

Currently, several types of TVCs are used, differing in the design of circuits and the heater, and consequently in the transfer difference. The digest whose mathematical model is the most versatile and simpliest is the SJTC. However, its sensitivity due to just a single thermocouple is the lowest of the mentioned. It has also relatively high AC-DC transfer difference and its uncertainty. The second described design was PMJTC which despite very complex mathematical model, expensive thin-film structure is nowadays the most widely used in the calibration laboratories. The most promising mentioned TVC is CTVC which combines advantages of the SJTC and PMJTC. It is expected that due to the intensive development of the generation and measurement apparatus used in the industrial laboratories and assembly lines, further investigation on new voltage standards with wider frequency range will be required. The thermoelectric element, which measures the temperature rise of the converter resistor, has a different design, which significantly affects the sensitivity of the TVC. The lowest absolute value of the AC-DC transfer difference in the frequency band up to about 100 MHz is the CTVC. Unfortunately, due to the large DC reversal error and relatively low sensitivity, this converter is not widely used. The disadvantages of CTVC can be minimized by modifying its design. In the second part of the article, the authors will present the construction of the converter and the research on improvements. The further development of TVCs ought to be focused on continuation of miniaturization of its assembly parts. This may lead to an increase in their accuracy and expanding the operational frequency range in which they can be effectively utilized. Ongoing research should consider the application of nanotechnology to deposit ultra-thin layers of thermocouples and a heater, allowing more precision temperature measurement with higher sensitivity. Simultaneously, there is a growing interest in integrating TVCs with digital signal processing systems, enabling advanced control of calibration processes.

Acknowledgments

The research was carried out within project number 2022/47/B/ST7/00047 granted by Polish National Science Centre (NCN).

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Wzorce napięcia przemiennego o szerokim paśmie częstotliwości

Streszczenie: W artykule przedstawiono porównanie konstrukcji i właściwości metrologicznych współczesnych wzorców napięcia przemiennego pracujących w szerokim zakresie częstotliwości. Wzorce te stosowane są w transferze AC-DC, będącym obecnie najdokładniejszym sposobem wyznaczania wartości skutecznej napięcia przemiennego w paśmie częstotliwości od kilkudziesięciu kHz aż do ponad 100 MHz. Urządzenia te pełnią rolę pierwotnych wzorców napięcia przemiennego w Narodowych Instytutach Metrologicznych (NMIs) w paśmie wysokich częstotliwości.

Słowa kluczowe: termiczny przetwornik napięcia, kalorymetryczny przetwornik napięcia, krajowe instytuty metrologiczne, wartość skuteczna napięcia przemiennego, transfer AC-DC

Krzysztof Kubiczek, PhD Eng.
krzysztof.kubiczek@polsl.pl
ORCID: 0000-0002-2178-6650

Graduate of the Faculty of Electrical Engineering at the Silesian University of Technology (2017). He obtained a PhD degree in Electrical Engineering in 2022. Since 2021, he has been a Research Assistant at the Department of Metrology, Electronics and Control at the Silesian University of Technology and Assistant Professor since 2023. The main areas of interest are broadband precision thermal voltage standards, precise broadband current shunts, quantum voltage standards and numerical methods in modeling of physical quantities. In 2021, he received a scholarship from the Foundation for Polish Science for 100 outstanding young scientists at the beginning of their scientific careers. Author of more than 40 scientific publications, completed 6 scientific internships, among others, at the Karlsruhe Institute of Technology, Institute for Technical Physics, Karlsruhe, Germany, Istituto Nazionale di Ricerca Metrologica, Turin, Italy and National Scientific and Technical Research Council, Santa Fe, Argentina. He actively cooperates with National Metrology Institutes, including the National Institute of Standards and Technology, NIST, USA.

Prof. Marian Kampik, DSc PhD Eng.
marian.kampik@polsl.pl
ORCID: 0000-0002-4928-3684

He received the M.Sc., Ph.D., and Habilitate Doctorate (D.Sc.) degrees, from the Silesian University of Technology, Gliwice, Poland, in 1988, 1996, and 2010, respectively, all in electrical engineering. He was a Professor with President of the Republic of Poland in 2017. He has been with the Department of Measurement Science, Electronics and Control, Faculty of Electrical Engineering, Silesian University of Technology since 1988, where he became a University Professor in 2010, the Director of the Institute in 2012 and the Dean of the Faculty of Electrical Engineering in 2020. His current research interests include ac voltage and current standards, thermal converters, digital signal synthesis and impedance measurements. He was the recipient of the Siemens Prize (team) in 2003, the Research Excellence Grant granted by the European Research Metrology Programme in 2013 and two scholarships granted by the German Academic Exchange Service in 1993–1995 and 1999. In 2020, he was the recipient of IEEE Gold Medal as most published author in the past 7 years from Poland and the top 70 most-published authors in the past 7 years.

Krzysztof Musioł, DSc PhD Eng.
krzysztof.musiol@polsl.pl
ORCID:0000-0001-5532-7463

Graduate of the Faculty of Electrical Engineering of the Silesian University of Technology (2002). He obtained a PhD degree in Electrical Engineering in 2007. Since 2024 Associate Professor (habilitation) at the Department of Metrology, Electronics and Automation of the Silesian University of Technology. The main areas of interest are precise systems for measuring impedance and alternating voltage. Leader of three research projects in the field of high-precision metrology, author of 97 scientific publications, including over 80 on electrical precision measurements. He actively cooperates with national metrology institutes in Europe, such as METAS, INRiM, CMI and GUM.

Michał Grzenik, PhD Eng.
michał.grzenik@polsl.pl
ORCID: 0000-0002-7313-3985

Graduate of the Faculty of Automatic Control, Electronics and Computer Science at the Silesian University of Technology (2010). He received the M.S. and Ph.D. degrees from the Silesian University of Technology (SUT), Gliwice, Poland, in 2010 and 2015, respectively. Since 2015, he has been with the Department of Measurement Science, Electronics and Control, Silesian University of Technology. His current research interests include ac voltage standards and thermal voltage converters.

Anna Piaskowy, PhD Eng.
anna.piaskowy@polsl.pl
ORCID:0000-0001-7577-3946

She received her M.S. degree in Power Electronics from the Silesian University of Technology, Gliwice, Poland in 2006, and her Ph.D. degree in Electrical Engineering from the same university in 2012. Since 2012, she has been an Assistant Professor at the Department of Measurement Science, Electronics and Control, Silesian University of Technology. Her research interests primarily include precise measurement setups and calibration. She is the author of over 50 scientific publications about precise measurements.