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A fast-reversed DC voltage/current source to measure frequency-independent AC-DC transfer difference of thermal voltage converters

Abstract

The paper presents a fast-reversed DC voltage/current source (FRDC) used for determination of the frequency-independent AC-DC transfer difference of thermal voltage converters. It contains also results of experiments and measurements.

Keywords: AC voltage standards, thermal converters, AC-DC transfer difference.

1. Introduction

Despite spectacular progress in the development of quantum AC voltage standards [1, 3, 8] the thermal RMS-DC voltage converters (TVC) are still being used in frequency range from 10 Hz to 1 MHz [6, 10]. A thermal converter is made from a heater and thermometric sensor, converting a temperature rise of the heater to DC voltage.

The principle of operation of a TVC can be simply described as follows:

1. An unknown AC voltage U_{AC} is applied to the heater of the thermal converter. After a temperature of the heater settles, the output voltage of thermal converter E_{AC} is measured,
2. A precisely known DC voltage U_{DC} from a DC calibrator is applied to the heater. Its voltage is set so that after the temperature settles the TVC output voltage E_{DC} is equal to $E_{AC.}$
3. RMS value of the applied alternating voltage U_{AC} is calculated from the following formula:

$$U_{AC} = U_{DC}\left(1+\delta_u\right), \quad (1)$$

where δ_u is the AC-DC transfer difference of the thermal converter.

A typical frequency characteristic of the AC-DC transfer difference is shown in Fig.1.

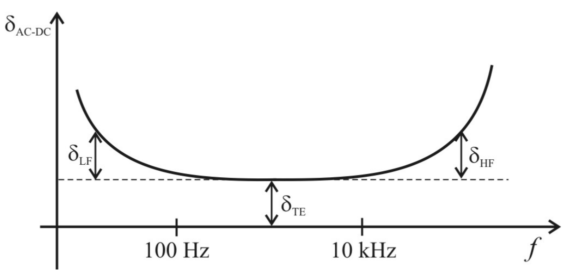


Fig. 1. Typical frequency dependence of the AC-DC transfer difference of a thermal converter

For frequencies from 100 Hz to approximately 1 kHz, the AC-DC transfer difference of the TVC is determined by reversible thermoelectric Thomson and Peltier effects. These effects and their influence on properties of alternating voltage standards are, among other, described in [7].

The insufficient precision of mathematical and simulation methods of evaluation of the frequency- independent AC-DC transfer difference component δ_{TE} is the main cause of developing experimental methods. If a quantum AC voltage standard or a TVC with known δ_{TE} is available, then this parameter can be measured by performing AC-DC thermal transfer. In the Physikalisch-Technische Bundesanstalt (PTB, Germany) and the Japanese Institute of Metrology (AIST), the Fast-Reversed DC (FRDC) voltage/current method of δ_{TE} measurement was developed [9]. In this method a fast-reversing DC voltage/current is applied to the heater of the TVC. The period of these changes is usually much shorter than the thermal time constant of the TVC. This method is called thermal FRDC-DC Transfer. The fundamental difference between AC-DC and FRDC-DC transfer methods is the shape of the voltage signal applied to the heater: the first uses a sine wave while the second uses a square wave.

The paper presents an FRDC source built in the Institute of Measurement Science, Electronics and Control of the Silesian University of Technology. It is a modified version of the FRDC source described in [9]. The source is used to determine the frequency-independent component AC-DC transfer difference of primary standards of AC voltage maintained in the Laboratory of AC-DC Standards of the Institute of Measurement Science, Electronics and Control, Silesian University of Technology.

2. Signals generated by the FRDC source

The FRDC source output signal can be in one of the three states: DC+, DC- or FRDC. Two first of these states are direct voltage signals of opposite polarity. The FRDC state is when the signal polarity is switched between DC+ and DC- with a frequency f_{SW} (Fig. 2). When the FRDC source generates a DC voltage or current, a combination of Thomson and Peltier effects affects the temperature distribution along the TVC heater. The temperature increase caused by these effects changes the sign after the change of polarity of the heater current, which in effect, causes the change in the temperature distribution. For high switching frequency f_{SW} in the FRDC mode, the first order Thomson and Peltier effects are averaged out and influence of the second order Thomson effect decreases. Influence of thermoelectric effects on the transfer difference can be evaluated by comparison of the TVC output voltages during the DC and the FRDC mode.

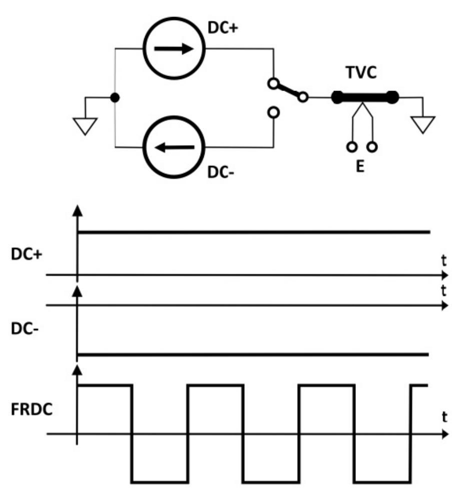


Fig. 2. Simplified schematic diagram of the FRDC source and its output signals

For signals shown in Fig. 2 a strong influence of finite rising and falling times of the FRDC output signal can be observed. In theory, to achieve equality between the RMS value of direct voltage in the DC mode and the RMS value of alternating voltage in the FRDC mode, the switching frequency should be infinitely high. Because this condition cannot be achieved in a real instrument, signals generated by the FRDC source have to be modified. A simplified schematic of the source and modified signals is depicted in Fig. 3. Modification of the signals involves an additional OFF state. Due to this modification the effect of finite switching times is almost completely eliminated.

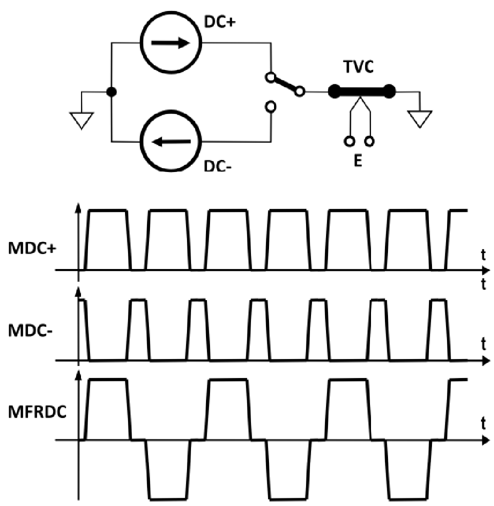


Fig. 3. Simplified schematic diagram of the modified FRDC source and its output signals

Measurements taken with the modified FRDC source show a small linear increase of the FRDC-DC transfer difference related to an increase of the switching frequency f_{SW}. This effect implies a small energy loss with each switching cycle and is caused by an analog switch, used during generation of the FRDC signal. When the switch changes its state from conducting to high impedance state, a small charge, in order of few pC, is trapped in a channel of a switching MOSFET transistor. Amount of this charge depends on the value of the current flowing through the transistor during conducting state. When the transistor is turned on for the next time, then the trapped charge is released as an additional surge current. This phenomenon is known as "memory effect" of the transistor. This issue can be addressed by switching the transistor off in the state when no current is conducted through it. This method was implemented at the cost of complexity of the FRDC source circuitry.

The modified FRDC source consists of two, completely independent, sources: source A and source B. Each of the sources can be used as voltage or current source with positive or negative polarity. Each of the sources A and B is full time active and full time under load. The main load is the heater of the TVC. When the source is not loaded with the heater of the TVC, then its output is loaded with a built-in programmable resistance, matched to the resistance of the TVC heater. This solution keeps constant power dissipation in the both sources and built-in resistors in every phase of the measurement cycle and provides stable thermal conditions.

The A and B sources generate four types of signals (Fig. 4):

- MFRDC(A+B-), when source A generates positive and source B generates negative part of the signal,
- MDC(A+B+), when both sources A and B generate positive part of the signal alternately,
- MDC(A-B-), when both sources A and B generate negative part of the signal alternately,
- MDRDC(A+B-), when source A generates negative and source B generates positive part of the signal.

In Fig. 4, the output current from source A is depicted with the solid line, while the output current from source B is drawn with the dotted line. During generation of one of the types of the output signal, sources A and B do not change the polarity of generated signals. Because the phases of signals are reversed, it is possible to connect them in any configuration. The final form of the signal input to the TVC is selected by a source output switch which switches the signal alternately from source A and B. Switching is performed only in the moments when source A and B output signal is zero, which prevents the memory effect to occur.

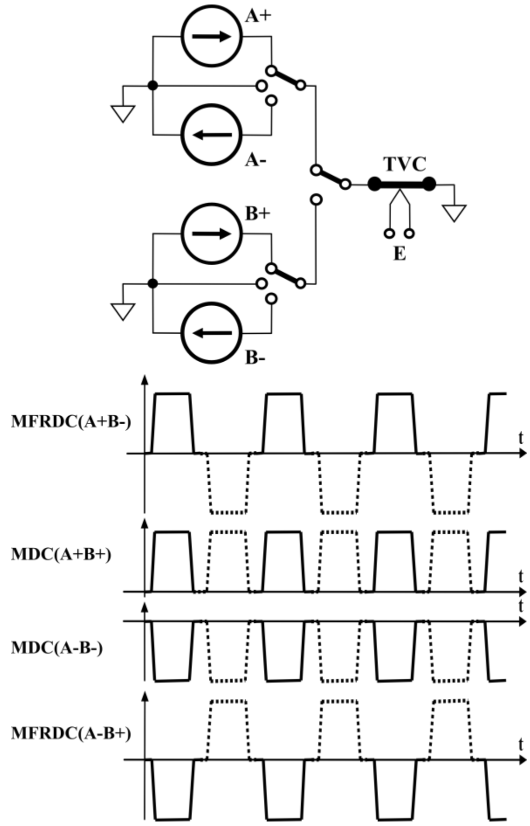


Fig. 4. Simplified schematic diagram of the FRDC source and its modified output signals

3. Design of the FRDC signal source

A simplified block diagram of the developed FRDC source is shown in Fig. 5. The main components are: power supply block, control unit and two identical, digitally controlled, bipolar DC voltage and current sources A, B.

The power supply block contains three separate, magnetically and electrostatically shielded toroidal transformers. The complex shielding reduces the influence of magnetic or capacitive coupling between primary and secondary windings of the transformer and between transformers as well. The transformers are connected to the mains through a common power supply noise reduction filter. Each of the transformer powers one of three, multi-voltage, independent power supplies, placed in aluminium boxes. These boxes act simultaneously as heatsinks for voltage regulators and provide electrostatic shielding.

The control unit was placed in a separate aluminium shielding box. A fast, 32-bit ARM family microcontroller unit (MCU) was used. Operation of the MCU unit is supported by a complex-programmable logic device (CPLD), responsible for time-critical switching and synchronisation. The main purpose of the control unit is generation of control signal sequences for sources. It was realized with the use of MCU internal counters-timers.

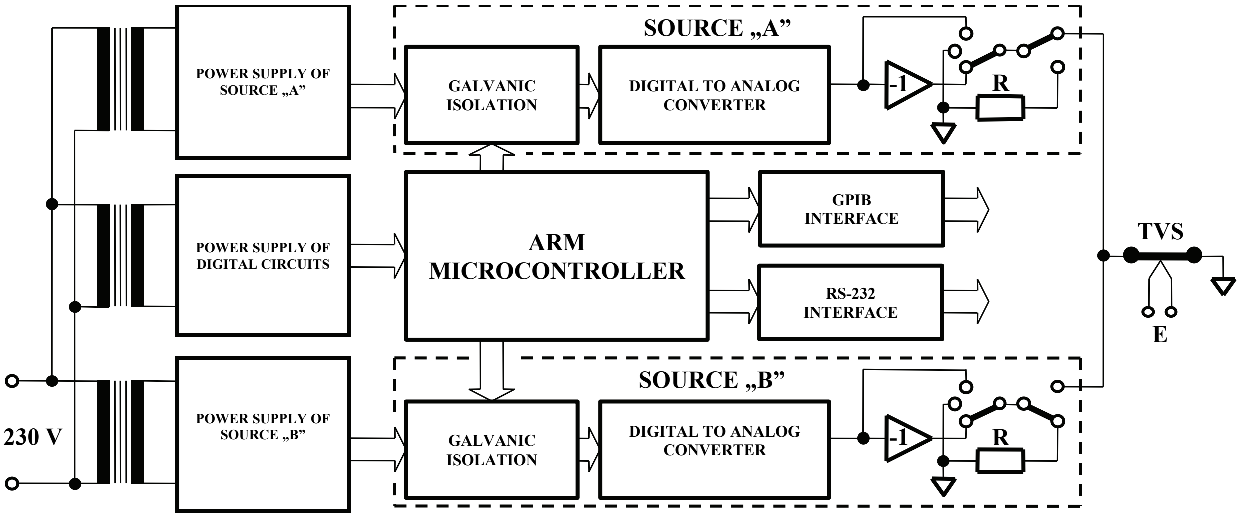


Fig. 5. Block diagram of the FRDC voltage source

The MCU is also responsible for communication with personal computer (PC) and miscellaneous other tasks such selection of the operation mode, setting the values of output voltage or current signals and setting the sources built-in resistances. The measurement algorithm is executed by the PC.

The electronics for both sources A and B were placed in two separate aluminium boxes. The thermal mass of these boxes reduces thermal feedback between the both sources and short-term ambient temperature fluctuations. To minimise possible electrical coupling, galvanic isolation on all digital lines between the sources and the control unit was used.

Both sources are equipped with high precision digitally programmable current limiters on their outputs, which provide protection for both measurement device and device under test. High complexity of electronics and high component density forced the usage of 6-layer printed circuit boards (PCB). High quality modern components were used in development of the FRDC source.

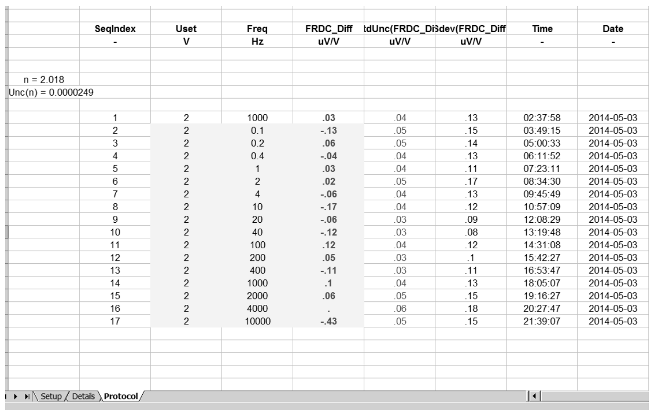
4. The measurement procedure with FRDC source

Measurement of the transfer difference $\delta_{\mathrm{FRDC\text{-}DC}}$ with the usage of the FRDC source is made in an automated measurement system, located in the electromagnetically-shielded chamber located in the Laboratory of AC-DC Standards. Temperature inside the chamber is (23,0±0,2)ºC and relative humidity is (40±10)%. The input of the TVC under test is connected to the FRDC output using N connector. The output of the TVC is connected to the input of the Agilent 34420A nanovoltmeter using a shielded cable with Teflon isolation and UHF-Twin/Lemo connectors. A nanovoltmeter is controlled through a GPIB interface, while the FRDC source is controlled via an RS-232 interface. In the final setup, the Agilent 82357A USB/GPIB converter for Agilent 34420A and the USB/RS-232 converter for FRDC source were used. The both converters were connected to the USB hub which was connected with the PC with a galvanic isolator and USB/USB cable.

The final measurement protocol is shown in Fig. 6. The measurement results are copied to a separate file and processed using Excel VBA macro, which calculates the frequency-independent AC-DC transfer difference component δ_{TE} and time constant τ_{TE} associated with thermoelectric effects. This calculation is performed using the least squares method by evaluating equation [9],

$$\delta_{\mathrm{FRDC\text{-}DC}} \approx 2\delta_{\mathrm{TE}}\tau_{\mathrm{TE}} f_{\mathrm{SW}} \tanh\left(\frac{1}{2\tau_{\mathrm{TE}} f_{\mathrm{SW}}}\right). \qquad (2)$$

Eq. (2) allows determination of the relation between $\delta_{\mathrm{FRDC\text{-}DC}}$ and switching frequency f_{SW}. It is used also to find the frequency-independent AC-DC transfer difference component δ_{TE} for the tested TVC and the time constant τ_{TE}.



	SeqIndex	Uset	Freq	FRDC_Diff	tdUnc(FRDC_Di	Sdev(FRDC_Diff	Time	Date
	-	V	Hz	uV/V	uV/V	uV/V	-	-
n = 2.018								
Unc(n) = 0.0000249								
	1	2	1000	.03	.04	.13	02:37:58	2014-05-03
	2	2	0.1	-.13	.05	.15	03:49:15	2014-05-03
	3	2	0.2	.06	.05	.14	05:00:33	2014-05-03
	4	2	0.4	-.04	.04	.13	06:11:52	2014-05-03
	5	2	1	.03	.04	.11	07:23:11	2014-05-03
	6	2	2	.02	.05	.17	08:34:30	2014-05-03
	7	2	4	-.06	.04	.13	09:45:49	2014-05-03
	8	2	10	-.17	.04	.12	10:57:09	2014-05-03
	9	2	20	-.06	.03	.09	12:08:29	2014-05-03
	10	2	40	-.12	.03	.08	13:19:48	2014-05-03
	11	2	100	.12	.04	.12	14:31:08	2014-05-03
	12	2	200	.05	.03	.1	15:42:27	2014-05-03
	13	2	400	-.11	.03	.11	16:53:47	2014-05-03
	14	2	1000	.1	.04	.13	18:05:07	2014-05-03
	15	2	2000	.06	.05	.15	19:16:27	2014-05-03
	16	2	4000	.	.06	.18	20:27:47	2014-05-03
	17	2	10000	-.43	.05	.15	21:39:07	2014-05-03

Setup / Details / Protocol

Fig. 6. Screenshot of the final protocol of measurement

The uncertainty of δ_{TE} measurement depends, among others, on power dissipated in the TVC heater and its rated power. The value of this uncertainty was estimated as lower than 1 µV/V, for the rated TVC heater power.

5. Validation of measurement results

Validation of the δ_{TE} measurement with the FRDC source may be, in general, performed in two ways:

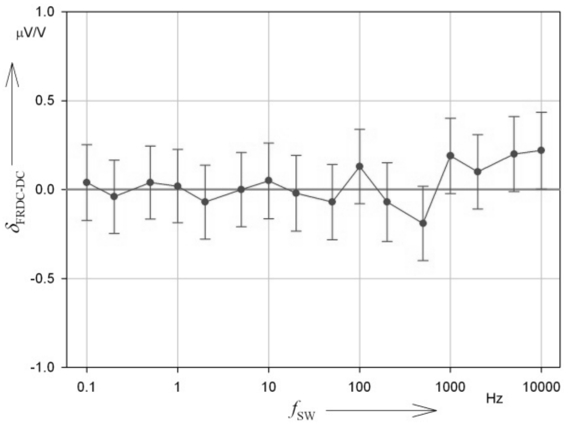
1. By checking whether $\delta_{\mathrm{FRDC\text{-}DC}}$ results obtained with use of the described FRDC source are consistent with the results obtained with FRDC source of a different design,
2. By checking whether δ_{TE} parameter obtained with use of the FRDC source is equal to the frequency-independent AC-DC transfer difference component $\delta_{\mathrm{AC\text{-}DC}}$.

Ad. 1.

The $\delta_{\mathrm{FRDC\text{-}DC}}$ of a TVC (VS-3C-b) with input voltage rating of 3 V, consisting of a PTB/IPHT planar multijunction thermal converter (PMJTC) with heater resistance of 200 Ω and a built-in range resistor (Alpha Metal Foil MP 200 Ω) was measured with the use of the PTB/AIST FRDC source held in the Swiss Institute of Metrology (METAS, Bern) and with the FRDC described in this paper. Comparison of the results is shown in Fig. 7.

The results shown in Figs. 7a and 7b are similar. A slight decrease of $\delta_{FRDC\text{-}DC}$ visible in Fig. 7b is the effect of different period of OFF state (2,5 µs compared to 10 µs used in the PTB/AIST source).

a)



b)

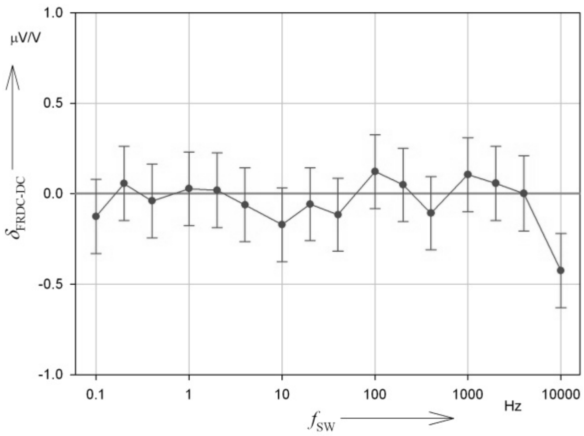


Fig. 7. Measurement results $\delta_{FRDC\text{-}DC}$ of the standard VS-3V-b at a voltage of 2 V: *a)* using the FRDC source maintained at the Swiss Metrology Institute METAS, *b)* using the designed FRDC source

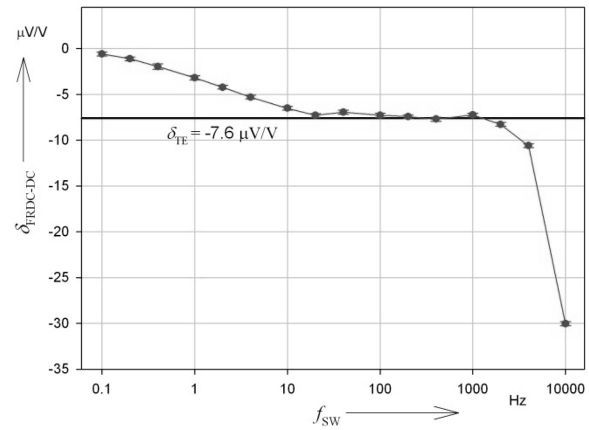
Ad. 2.

Confirmation whether δ_{TE} parameter obtained with use of the FRDC source is equal to the frequency-independent AC-DC transfer difference component $\delta_{AC\text{-}DC}$ can be performed by more than one method. One of them is a comparison between δ_{TE} value resulting from $\delta_{FRDC\text{-}DC}$ measurement of a specific TVC with the FRDC source with the value of transfer difference $\delta_{AC\text{-}DC}$ of the same TC, but measured in relation to a standard with known transfer difference.

To achieve this, another TVC was constructed, containing a single junction thermal converter (SJTC) of Standard S7 type. This SJTC was selected because its AC-DC transfer difference $\delta_{AC\text{-}DC}$ was relatively worse than $\delta_{AC\text{-}DC}$ of the other TVCs used in the laboratory. First the frequency characteristics of the $\delta_{FRDC\text{-}DC}$ was measured with use of the FRDC source and the value of δ_{TE} was calculated. Next its transfer difference $\delta_{AC\text{-}DC}$ was measured using a standard TVC of 1.5 V rated input voltage (VS-1.5V-c). The VS-1.5V-c TVC was calibrated at Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig. This calibration was traceable to German national AC voltage standard.

The result of δ_{TE} measurement using the FRDC method is shown in Fig. 8a. Fig. 8b presents the results of δ_{TE} measured against the TVC calibrated at PTB. The results shown in Figs. 8a and 8b show good consistency within 100 – 1000 Hz range.

a)



b)

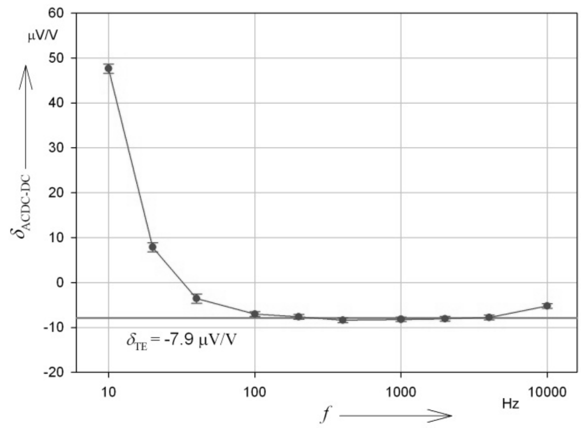


Fig. 8. Measurement results δ_{TE}: a) the method using FRDC, b) with the thermal AC-DC transfer

6. Summary

The apparently simple process of switching direct voltage or current standards with different polarisation, which is the basic concept of FRDC source, leads to generation of multiple undesired effects, affecting the RMS value of switched voltages and currents, which in turn impacts the value of the measured transfer difference. Finite switching times and memory effect in electronic switches have the strongest influence. Minimization of the influence of these effects leads to complexity of the FRDC source. The level of complexity of this source is increased due to the need of shielding many elements and usage of galvanic isolation. Despite of its complexity, the built FRDC source with the proper measurement procedure enables measurements of the frequency-independent component of the AC-DC transfer difference with a sufficient accuracy. This conclusion has been confirmed by the conducted tests and their validation. The results obtained for the same TVC with FRDC source maintained at METAS and described in the paper show good consistency. Similarly the results obtained from the FRDC measurements show good agreement with the results through the AC-DC comparison with the TVC calibrated at PTB. The obtained results confirm the usefulness of the built FRDC source for determination of a frequency-independent component of the AC-DC transfer difference.

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