Measurement system for investigation and calibration of digital sources of low-frequency AC voltage

Abstract. The paper presents an automated measuring system for investigation and calibration of digital sources of low-frequency (1 mHz - 1 kHz) sinusoidal AC voltage. In frequency range from 10 Hz to 1 kHz the system allows the calibration of these sources with four methods: thermal, integrating sampling, step and peak-to-peak with uncertainty attaining approximately 1 μV/V. In frequency range from 1 mHz to 10 Hz it is possible to calibrate sources with three methods: integrating sampling, step and peak-to-peak with uncertainty 1 μV/V or better.

Streszczenie. W pracy przedstawiono zautomatyzowany system pomiarowy, przeznaczony do badań i wzorcowania cyfrowych źródeł napięcia przemiennego o małej częstotliwości. W paśmie częstotliwości od 10 Hz do 1 kHz system umożliwia wzorcowanie tych źródeł czterema metodami z niepewnością rzędu 1 μV/V. (System pomiarowy do badań i wzorcowania cyfrowych źródeł napięcia przemiennego o małej częstotliwości).

Keywords: AC voltage standard, thermal converter, calibration, digital signal synthesis.

Introduction

Digital sources of low-frequency AC voltage (DSS) play an important role in modern metrology. They are used in impedance measurements [1], investigation and calibration of thermal voltage converters (TVC) [2], quantum AC voltage standards [3] and standards of AC power [4]. Digital sources of AC voltage are particularly useful at frequencies below 10 Hz, where the AC-DC transfer difference of the TVC is too high. In many cases they can replace the expensive quantum AC voltage standards based on Josephson effect [5].

DSS digitally synthesizes a sinusoidal signal with very stable RMS voltage from approximately 0.5 V to approximately 10 V in frequency range from approximately 0.01 Hz to approximately 1 kHz. The shape of the signal generated by the source is close to a sine wave. Description of the exemplary sources can be found, among others, in [6,7].

To be used as an AC voltage standard, the DSS output RMS voltage must be determined with appropriate accuracy. The process is usually called the "DSS calibration" and is usually performed prior to using the DSS as an AC voltage standard.

The paper presents an automated measuring system for investigation and calibration of the DSS. In frequency range from 10 Hz to 1 kHz the system allows the calibration of the DSS with four methods: thermal, integrating sampling, step and peak-to-peak with uncertainty attaining approximately 1 μV/V. These four methods are described in the next section.

Methods of DSS calibration

Methods of the DSS calibration can be divided into dynamic and static [7]. The dynamic methods of calibration can be divided into thermal and sampling. The static methods of calibration can be divided into step and peak-to-peak.

In the thermal method of DSS calibration a standard thermal voltage converter (TVC) is used. Its AC-DC difference $\delta_i$ must be known with appropriate uncertainty at voltage and frequency at which the DSS is calibrated [7]. In theory, the thermal calibration is performed in two steps. At first, the measured AC voltage $U_{AC}$ is applied to the input (heater) of the TVC and the corresponding TVC output electromotive force (EMF) $E_{AC}$ is measured with a high-resolution DC nanovoltmeter. In the second step, the known DC voltage $U_{DC}$ is applied to the input of the TVC and its value is adjusted until the corresponding output EMF $E_{DC}$ equals $E_{AC}$. Finally, the AC voltage $U_{AC}$ is calculated from the equation:

$$U_{AC} = U_{DC} \left(1 + \delta_i \right)$$

However, due to TVC properties, ambient temperature drift and various instabilities it is usually impossible to fulfill the condition $E_{AC} = E_{DC}$. In practice, $E_{AC} \neq E_{DC}$ with relative difference between them in the order of 10... 50 μV/V. Therefore the thermal calibration procedure is much more complicated and time-consuming.

The parameter that affects the accuracy of the thermal DSS calibration is the reversal error of the TVC. It is caused by the presence of reversible thermoelectric phenomena in the TVC heater and leads. This error is especially critical for single-junction thermal converters (SJTC) of older design [7]. Effect of the reversal error is minimized by substitution of two DC voltages of equal value but opposite polarity ($U_{DC-}$ and $U_{DC+}$) and the calculation of the arithmetic mean of the corresponding output TVC voltages ($E_{DC+}$ and $E_{DC-}$).

Despite the impact of the above-mentioned phenomena, it is possible to determine the $U_{AC}$ with a resolution of 1 μV/V [9]. To minimize the detrimental effect of various drifts, instead of the two-step procedure the following single sequence of voltages is applied to the input of the TVC: $U_{AC1}$, $U_{DC+}$, $U_{AC2}$, $U_{DC-}$, $U_{AC3}$ and the $U_{AC}$ is calculated from:

$$U_{AC} = U_{DC} \left(1 + \frac{E_{AC} - E_{DC}}{nE_{DC}} \right) \left(1 + \delta_i \right),$$

where: $E_{AC}$ is the average of the output EMFs corresponding to $U_{AC1}$, $U_{AC2}$, $U_{AC3}$; $E_{DC}$ is the average of the output EMFs corresponding to $U_{DC+}$, $U_{DC-}$, and $n$ is the exponent of the transfer function of the TVC.

The exponent of the transfer function of the TVC is equal to 2.0 for planar multijunction thermal converters (PMJTC), whereas for SJTC its value depend on voltage and is in the range from 1.6 to 2.0.

The advantage of the thermal method is its very wide bandwidth. This allows the measurement of the power of harmonics, which are present in the signal produced by the source. Unfortunately, for frequencies less than about 10 Hz temperature of the TVC heater is insufficiently averaged. This effect is critical, especially for a TVC with thermal time constant less then typical of 1... 3 seconds and leads to increase of the impact of non-linear phenomena of heat transfer from the TVC heater to the ambient. Below approximately 10 Hz the impact of these phenomena on the TVC AC-DC transfer difference is so large that it is
impossible to calibrate the DSS at 1 µV/V level of uncertainty.

In the integrating sampling method of DSS calibration a high accuracy sampling voltmeter (usually an Agilent 3458A) is used. The method was originally developed by R. Swerlein from Hewlett-Packard for HP/Agilent 3458A multimeter [10], but at present it is known in a few different variants [11,12,13]. The Agilent 3458A multimeter is equipped with integrating analog-to-digital converter (ADC). The ADC has high resolution (approximately 28 bits) and can be configured as an accurate sampler. In the sampling method, the sampler takes N samples of the signal, spaced T_s seconds apart. The T_s parameter is often called the sampling time or sample interval. Each sample U_n taken by the voltmeter sampler is an integral of the signal u(t):

\[ U_n = \frac{1}{\tau_{AN}} \int_{t_n}^{t_n + \tau_{AM}} u(t) dt, \]

where \( \tau_{AN} \) is the nominal integration (aperture) time set by the user or by the control program; \( \tau_{AM} \) is the actual (real) integration time; \( t_n \) is the time moment at which the integration starts.

The computer controlling the sampling voltmeter sets the number \( N_p \) of samples, the sampling frequency \( f_s \) and the number of averaged periods \( N_f \) to fulfill the following condition:

\[ N_p f_s = N_f f_i, \]

where \( f_i \) is the frequency of the signal generated by the DSS.

The RMS value of the signal generated by the DSS is calculated from [11]:

\[ U_{\text{RMS}} = \frac{1}{S_a(x / f_i \tau_{AN})} \sqrt{\frac{1}{N_p} \sum_{i=1}^{N_p} U_i^2}, \]

where \( S_a(x) = \sin(x)/x \).

In the peak-to-peak calibration method [4] only two DC voltages \( U_{\text{max}} \) and \( U_{\text{min}} \) are measured with a high-accuracy digital voltmeter (for example Agilent 3458A) [4]. These two DC voltages correspond to the maximum and minimum voltages of the sinusoidal signal generated by the DSS. The RMS value \( U_{\text{RMS}} \) of the signal can be calculated from [7]:

\[ U_{\text{RMS}} = \frac{1}{\sqrt{2}} \sqrt{3U_{\text{max}}^2 + 2U_{\text{max}}U_{\text{min}} + 3U_{\text{min}}^2}. \]

Measuring system requirements

It was assumed that the measuring system has to meet the following requirements:

1) should measure the rms voltage in the range from approximately 0.7 V to approximately 7 V in the frequency range from 10 Hz to 1 kHz or greater,

2) should allow DSS calibration using four methods: thermal, integrating sampling, step and peak-to-peak,

3) the measurement results should be presented in such a way as to permit intercomparison of results obtained by different calibration methods,

4) the software of the computer controlling the calibration system shall be capable of storing large amounts of data in a form suitable for further analysis,
meter. To reduce these errors the digital synchronizing signal of frequency $f_{\text{SYNC}} = 10 \text{ MHz}$, derived from the DSS internal oscillator, is applied to the external reference input (Ref In) of the Agilent 53131A. This replaces the internal time base of the Agilent 53131A with external signal with frequency $f_{\text{SYNC}}$. The A53131A measures the actual integration time $t_{\text{AM}}$ of the multimeter ADC prior to running the sampling calibration. To perform this measurement the "Ext Out" signal from Agilent 3458A is applied to the input of the 1. channel of the Agilent 53131A. To increase the resolution of the measurement the integration time is set to its maximum value ($t_{\text{AM}} = 1 \text{ s}$). Results of several consecutive $t_{\text{AM}}$ measurements are shown in Fig. 2.

Fig. 2. Dispersion of results of measurement of the integration time $t_{\text{AM}}$ of the Agilent 3458A multimeter

Relation between $f_o$ and $f_{\text{SYNC}}$ is known with very high accuracy [7]. Because $t_{\text{AM}}$ is measured in relation to $f_{\text{SYNC}}$, it is possible to use the measured value of $t_{\text{AM}}$ to correct the frequency error of the Agilent 3458A sampler. In practice, it is made by insertion of the corrected frequency $f_{\text{UNCAL}}$ in the set of the input parameters of the sampling algorithm. This set is used by the controlling program to calculate the sampling parameters. The frequency $f_{\text{UNCAL}}$ is calculated from:

$$f_{\text{UNCAL}} = f_{\text{SET}} \frac{t_{\text{AM}}}{t_{\text{AN}}}$$

where $f_{\text{SET}}$ is the nominal output frequency of the signal generated by the DSS, set by the user.

In practice, the relative difference between $f_{\text{SET}}$ and $f_o$ is below $10^{-8}$ Hz/Hz. The maximal absolute error of the determination of the period $T_o = 1/f_o$ of the signal generated by the DSS equals approximately 5 ns. Standard combined uncertainty of the sampling method of calibration, calculated for $U_{\text{AC}} = 4 \text{ V}$ and $T_{\text{meas}} = 90 \text{ s}$ is shown in Fig. 3.

Fig. 3. Relation between combined standard uncertainty of the integrating sampling method and frequency $f_o$ of the signal generated by the calibrated DSS for $T_{\text{meas}} = 90 \text{ s}$

Conclusion

The described measurement system allows investigation and calibration of digital sources of low-frequency AC voltage with four methods: thermal, integrating sampling, step and peak-to-peak. Standard combined uncertainty of the thermal method is equal to approximately 1.5 $\mu$V/V. Standard combined uncertainty of the integrating sampling method at 4 V is lower than 1 $\mu$V/V below 30 Hz. Uncertainties of step- and peak-to-peak calibration methods depend on the harmonic spectrum of the signal generated by the calibrated source. For the DSS described in [7] relative differences between results obtained at 4 V with sampling calibration methods and both static calibration methods are in the order of 0.1 $\mu$V in frequency range from 0.001 to 100 Hz.

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Author: dr hab. inż. Marian Kampik, Politechnika Śląska, Instytut Metrologii, Elektroniki i Automatyki, ul. Akademicka 10, 44-100 Gliwice, E-mail: marian.kampik@polsl.pl