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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.
Słowa kluczowe: wzorzec napięcia przemiennego, termiczny przetwornik wartości skutecznej, wzorcowanie, cyfrowa synteza sygnału.

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 δ_t 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:

$$U_{AC} = U_{DC}(1+\delta_t)\big|_{E_{AC}=E_{DC}} . \tag{1}$$

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, $E_{AC} \cong E_{DC}$ 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:

$$U_{AC} = U_{DC}\left(1+\frac{\overline{E}_{AC}-\overline{E}_{DC}}{n\overline{E}_{DC}}\right)(1+\delta_t), \tag{2}$$

where: $\overline{E}_{AC}$ is the average of the output EMFs corresponding to U_{AC1} , U_{AC2} , U_{AC3}; $\overline{E}_{DC}$ 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 increaseof 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 $u(t)$:

$$U_n = \frac{1}{\tau_{AN}} \int_{t_n}^{t_n+\tau_{AM}} u(t)dt \,, \qquad (3)$$

where τ_{AN} is the nominal integration (aperture) time set by the user or by the control program; τ_{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_T to fulfill the following condition:

$$N_p f_o = N_T f_s \,, \qquad (4)$$

where f_o is the frequency of the signal generated by the DSS.

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

$$U_{samp} = \frac{1}{\mathrm{Sa}(\pi f_o \tau_{AN})} \sqrt{\frac{1}{N_p} \sum_{i=1}^{N_p} U_i^2} \,. \qquad (5)$$

where $\mathrm{Sa}(x) = \sin x / x$.

In the step calibration, the DC voltage U_i of each of the N steps generated by the source during one period of the output signal is measured with a high-accuracy digital voltmeter (for example Agilent 3458A) and the RMS value U_{step} is calculated from the equation [14]:

$$U_{step} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} U_i^2} \,. \qquad (6)$$

In the peak-to-peak calibration method [4] only two DC voltages U_{max} and U_{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_{peak} of the signal can be calculated from [7]:

$$U_{peak} = \frac{1}{2\sqrt{2}} \sqrt{3U_{max}^2 + 2U_{max}U_{min} + 3U_{min}^2} \,. \qquad (7)$$

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,
5) the software of the computer controlling the calibration system should be easily modifiable,
6) the calibrated DSS should provide a digital synchronizing signal of frequency f_{SYNC} = 10 MHz, derived from the DSS internal oscillator,
7) the relationship between f_{SYNC} and frequency f_{OUT} of the sinusoidal signal generated by the DSS is known.

Description of the calibration system

Schematic of the measurement system for investigation and calibration of the DSS is shown in Fig.1.

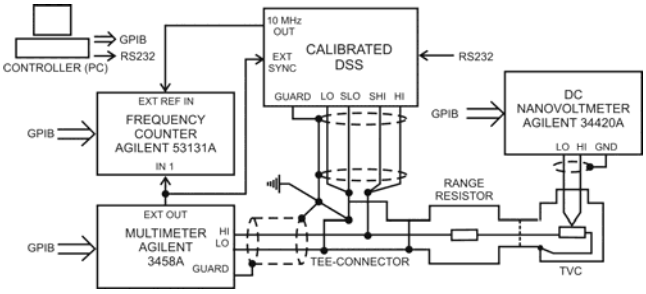

Fig.1. Schematic of the measurement system for investigation and calibration of the DSS

All the digital measuring instruments shown in Fig.1, except the calibrated DSS, are controlled with GPIB bus. In order to reduce the common-mode noise the calibrated DSS is controlled with custom-made fiber-optic isolated RS232 interface. The software of the PC computer controlling the calibration system was written in Visual Basic for Applications (VBA) for Microsoft Office Excel. The output voltage of the DSS is applied through a 20 cm four-wire shielded cable to a custom Tee-N-type-connector, which connects together inputs of the Agilent 3458A multimeter and the TVC range resistor. The TVC used was PTB/IPHT PMJTC of 90 Ω nominal heater resistance. The coaxial input of the TVC range resistor is connected to the Tee-connector directly, while the multimeter is connected to the Tee-connector by means of a two-wire shielded cable, approximately 30 cm long. The Agilent 3458A multimeter is used as sampler and DC voltmeter of high accuracy. The Agilent 34420A measures the output EMF of the TVC. For frequencies less than 20 Hz it is possible to use a passive notch filter, which reduces the ripples in the TVC output voltage, arising from insufficient temperature averaging in the TVC heater [15]. The frequency counter-timer Agilent 53131A, shown in Fig.1, reduces the systematic error, introduced by the time base of the sampler of Agilent 3458A multimeter. The time base of the multimeter uses an internal quartz oscillator (XO) with a nominal frequency of 20 MHz. The error of the frequency generated by the XO has uniform distribution of the relative width of ±0.01%. When the Agilent 3458A multimeter is configured to measure frequency or period then the XO frequency error is minimized by the inclusion of correction coefficient stored in the calibration constant memory of the multimeter. The XO is also used to clock the sampler of the multimeter, but the frequency error of the XO is not corrected. Therefore in the algorithm developed by R. Swerlein the effect of the XO frequency error is removed by measuring frequency f_o of the signal generated by the DSS and discalibrating the result of this measurement. A similar method is used in the system shown in Fig.1, but the frequency f_o is measured with the external frequency counter-timer Agilent 53131A. Unfortunately even using the external frequency meter does not reduce the time- and temperature drifts of the frequency generated by the XO and systematic error of the frequency meter. To reduce these errors the digital synchronizing signal of frequency f_{SYNC} = 10 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_{SYNC}. The A53131A measures the actual integration time τ_{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 (τ_{AN} = 1 s). Results of several consecutive τ_{AM} measurements are shown in Fig.2.

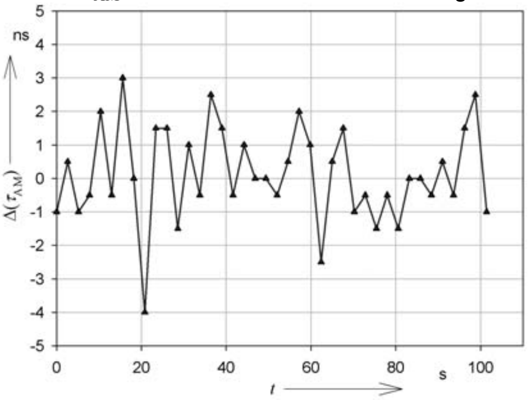

Fig.2. Dispersion of results of measurement of the integration time τ_{AM} of the Agilent 3458A multimeter

Relation between f_o and f_{SYNC} is known with very high accuracy [7]. Because τ_{AM} is measured in relation to f_{SYNC} it is possible to use the measured value of τ_{AM} to correct the frequency error of the Agilent 3458A sampler. In practice, it is made by insertion of the corrected frequency f_{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_{UNCAL} is calcuated from:

$$f_{UNCAL} = f_{SET} \frac{\tau_{AM}}{\tau_{AN}}, \tag{8}$$

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

In practice, the relative difference between f_{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_{AC} = 4 V and T_{meas} = 90 s is shown in Fig.3.

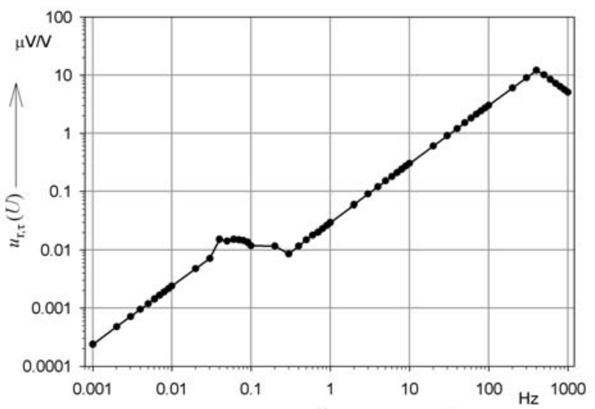

Fig.3. Relation between combined standard uncertainty of the integrating sampling method and frequency f_o of the signal generated by the calibrated DSS for T_{meas} = 90 s

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 µV/V. Standard combined uncertainty of the integrating sampling method at 4 V is lower than 1 µV/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 µV in frequency range from 0.001 to 100 Hz.

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