

HIGH-PERFORMANCE TWO-PHASE SINE WAVE GENERATOR FOR IMPEDANCE BRIDGES

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Abstract – The paper describes the experimental study of a two-phase sine wave generator intended for use in an impedance metrology. It is based on a 20-bit digital-to-analog converter (DAC) based on the R-2R architecture. Some tests for evaluation of the generator were carried out. The excellent parameters of the DAC made possible achieve a very good stability of the complex voltage ratio which is about ± 0.25 part in 10^6 for the amplitude ratio and less than ± 0.25 μ rad for the phase difference.

Keywords: digital waveform synthesis, impedance bridge, precise measurement

1. INTRODUCTION

One of the many functional blocks in AC measurement systems, like impedance bridges, is a generator. A special role in this field is played by digital multi-phase sine wave generators based on the digital frequency synthesis. Thanks to a precise adjustment of the amplitude, phase and frequency as well as good time and temperature stability of the generated signals, these generators can essentially influence on metrological properties of the bridges. Furthermore, the ability to automatically adjust the mentioned parameters allows relatively easy to automate the process of balancing the bridge.

In modern high-precision impedance bridges the digitally synthesized AC voltage generators can be used for various purposes. The two-phase generators, reproducing the complex voltage ratio, ensure the main balance of a bridge and directly determine the accuracy of the impedance comparison [1,2,3]. Additionally, the application of digital multi-phase generators to the compensation of voltages in the selected nodes of the bridge allows comparing four terminal-pair impedances by full digital bridges [4,5,6] as well as digitally assisted bridges [7,8,9].

Crucial part of the generator based on digital waveform synthesis is a digital-to-analog converter (DAC). Its parameters influence significantly on the parameters of the generated signals. In the generator presented in this paper the first commercially available 20-bit R-2R DAC AD5791 with 1 ppm resolution and integral nonlinearity was used. Its temperature drift is less than 0.05 ppm/°C. The above-mentioned DAC parameters were confirmed by the independent research [10].

2. HARDWARE OF THE GENERATOR

The commercial availability of the DAC with very good parameters seems to open up new possibilities in the design of very stable generators for the impedance measurements. To check it, a prototype of a two-phase generator based on the mentioned DAC was designed. Fig. 1 presents its block diagram. The calculation of the discrete values of sinusoidal signal samples and sending them to the DAC are performed by means of an ARM Cortex-M4 series microcontroller with a single precision floating point unit. To achieve the high update rate, each DAC is controlled by the separate microcontroller.

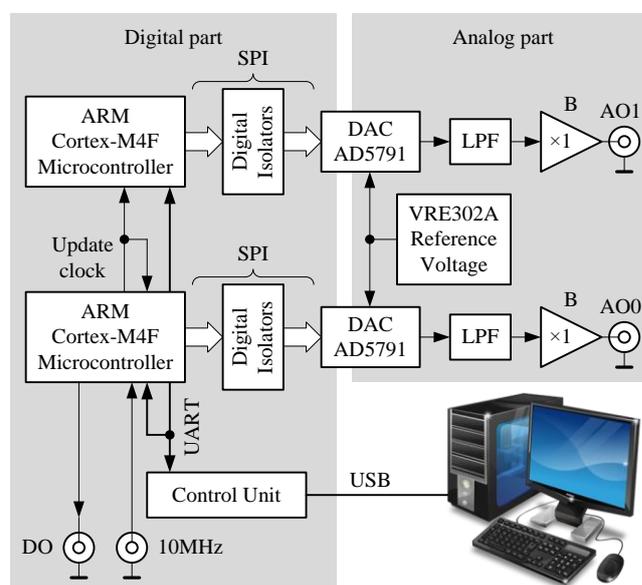


Fig. 1. Block diagram of the two-phase sine wave generator.

An update clock with a frequency of 400 kHz is derived from an external 10 MHz signal by an internal timer of the microcontroller. Each falling edge of the update clock starts the procedure of sending a new code, through the SPI interface, to the DACs and the rising edge updates the voltage at the DACs outputs. To allow the DACs to operate with separate ground references, isolators between the microcontroller and the DAC was applied. To enable an easy synchronization of the generator with other devices,

such as lock-in amplifiers, the logic signal of the same frequency as the frequency of the signals at the analog outputs AO0 and AO1 is generated at the DO output.

As the reference voltage, common for both channels of the generator, the VRE302A chip was used. It is high precision 2.5 V reference with the temperature coefficient of 0.6 ppm/°C [11]. The reference output voltage was amplified to the 5 V and applied to the positive reference voltage input of each DAC. To the negative reference voltage input the same amplified but also reversed voltage was applied. Therefore, the DACs output voltage range was ± 5 V. To remove images, appearing around each integer multiple of update rate, a 40-kHz low-pass third-order Butterworth filter (LPF) was connected to each DAC output. The last stage of each generator channel is a buffer amplifier (B).

The generator can be controlled through a PC. The communication between the generator and the PC is realized via the USB interface. The application, running on the PC, allows setting the amplitude, phase and frequency of the generated signals.

3. PERFORMANCE

In the case of application of the two- or multi-phase generator in the impedance measurements not absolute accuracy but the stability of amplitude ratio and the phase difference between the generated signals are important. The linearity and resolution of the amplitude and phase setting as well as spectra of the generated signals are also important.

3.1. Spectral purity

Fig. 2 shows a measurement system for determination of the spectral purity. Its main part is the National Instruments PXI-4461 sampling module which acts as a digitizer [12]. To obtain coherent sampling during tests, the sampling frequency in the digitizer is synchronized on the same 10 MHz clock signal which is used to derive the update rate in the generator.

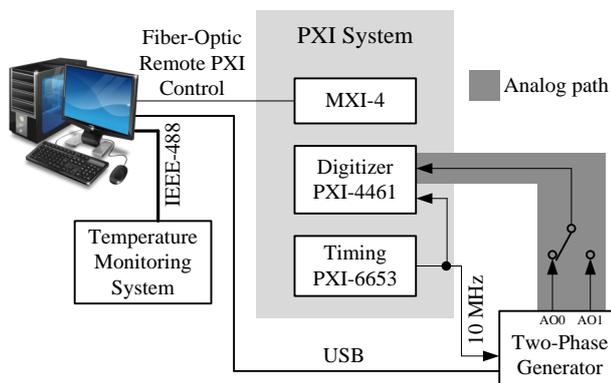


Fig. 2. Measurement system for evaluation of the spectral purity of the two-phase sine wave generator.

To determine the spectral purity of the generated signals their amplitude spectra was computed and a spurious-free dynamic range (SFDR) was determined. Tests were

performed with the 200 kHz sample rate. Fig. 3 shows the output spectrum of the signal from one channel of generator with amplitude close to the maximum value and the frequency of 1 kHz. The obtained spurious behaviour appears very good, with all spurs at least 96 dBc below the signal.

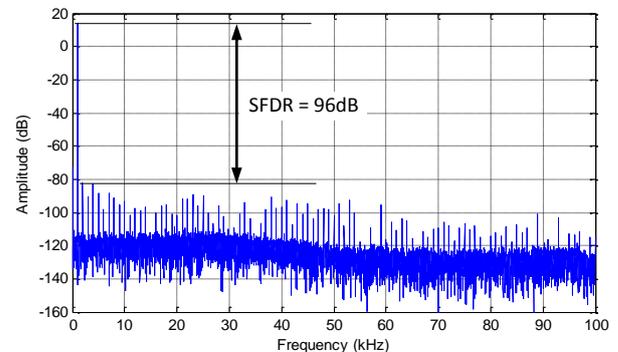


Fig. 3. Amplitude spectrum of 1 kHz signal with amplitude close to the maximum value.

Based on the amplitude spectrum two additional parameters have been calculated: a total harmonic distortion (THD) and a total harmonic distortion plus noise (THD+N). Both parameters were determined for the whole Nyquist bandwidth. For the mentioned signal THD and THD+N are not greater than 0,004%.

In Fig. 4 the spectrum of signal with the amplitude of 1 V is presented. As would be expected, for this amplitude of a signal the spurs are higher. This leads to nearly 11 dB lower SFDR which is 85.2 dBc. In this case, THD as well as THD+N are lower, reaching the value of about 0.013%.

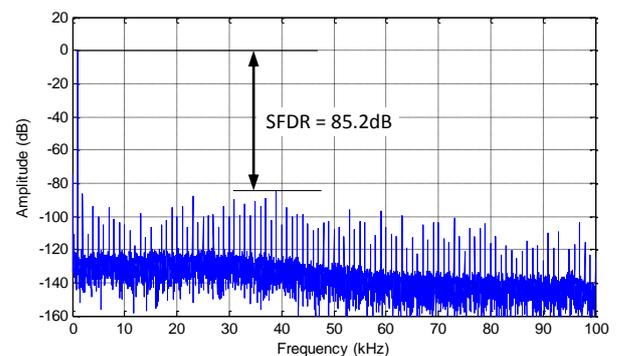


Fig. 4. Amplitude spectrum of 1 kHz signal with amplitude 1 V.

3.1. Stability

The stability of the amplitude ratio and phase difference was carried out independently in the two different measuring setups. In Fig. 5 the measurement system based on the PXI-4461 (acting as a digitizer) is presented. The two generated voltage signals are sampled sequentially by the one channel of the digitizer. The use of the digitizer in the single-channel mode instead of the dual-channel mode significantly reduces the influence of the ambient temperature changes on the measurement results [13]. Both

generated signals were provided to the digitizer by using a home-made two-channel multiplexer (MUX).

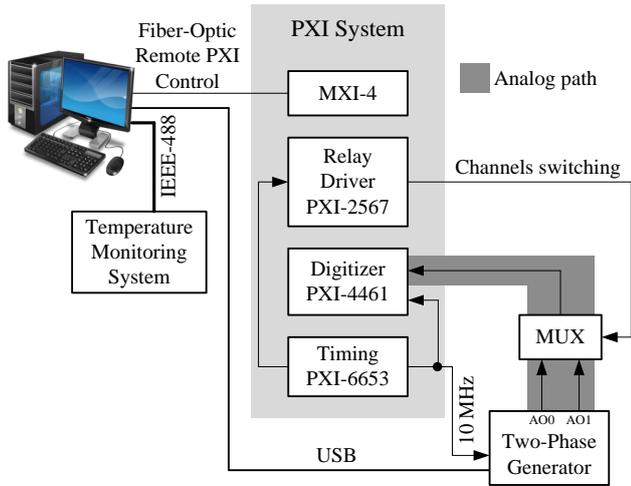


Fig. 5. Measurement system for evaluation of the amplitude ratio and phase difference stability by the digitizer.

Just like during test of the spectral purity, to achieve the coherent sampling, the sampling frequency in the digitizer is synchronized on the same 10 MHz clock signal which is used to derive the update rate in the tested generator. The switching frequency of the multiplexer is also synchronized on the 10 MHz clock signal.

The measurements were performed for the following conditions: the signal frequency of 1 kHz, the amplitude close to the maximum value, i.e. 5 V, and the 400 kHz update rate of the DACs. Every 0.08 s the digitizer sampled sequentially two signals with the sampling rate of 51.2 kHz. Only 1024 samples within the middle of each sequence were taken to calculate the discrete Fourier transform and then the amplitude ratio and phase difference. Changes of the ambient temperature during the execution of the measurements do not exceed $\pm 0.5^\circ\text{C}$.

The computed data were used to calculate the Allan deviation for the amplitude ratio and phase difference. The obtained result is shown in Fig. 6. Up to 100 s of an averaging period τ the Allan deviation decreases linearly with the slope of $-1/2$. It means that the white noise is dominating in the measurements. For the phase difference and τ greater than 100 s the Allan deviation is constant which means that no improvement of the uncertainty can be expected because a $1/f$ noise floor is reached. Therefore, the lowest standard deviation for 100 s of the measuring time is obtained and its value for the amplitude ratio is $0.03 \mu\text{V/V}$ and $0.016 \mu\text{rad}$ for the phase difference.

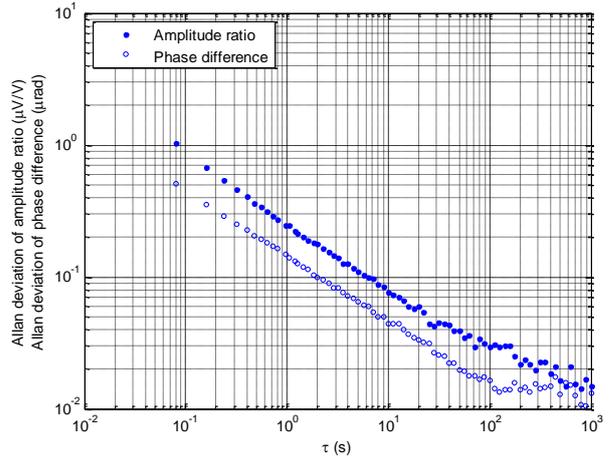


Fig. 6. Allan deviation of the amplitude ratio and phase difference.

To show the fluctuation of the both parameters in short-term time (one hour), the computed every 0.08 s amplitude ratios and phase differences are averaged in the period of 10 s. Fig. 7 and 8 present the obtained results.

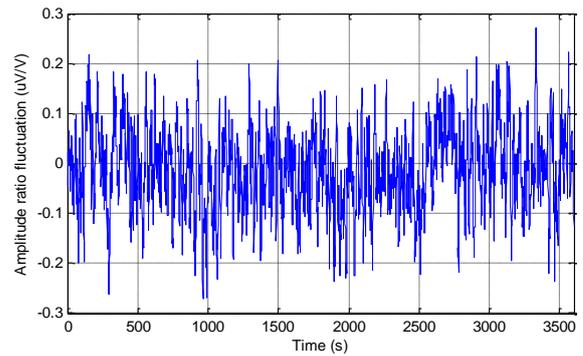


Fig. 7. Amplitude ratio stability measured by the digitizer.

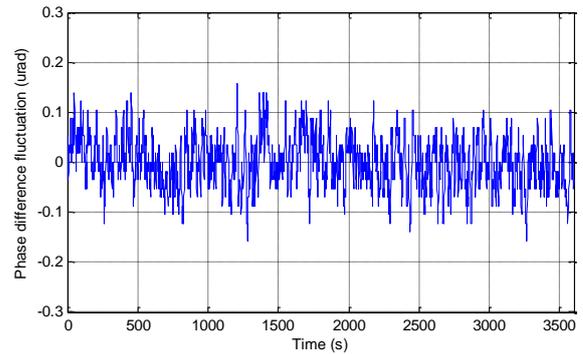


Fig. 8. Phase difference stability measured by the digitizer.

As can be seen, the amplitude ratio stability is $\pm 0.27 \mu\text{V/V}$ and the phase difference stability is $\pm 0.16 \mu\text{rad}$.

To be sure that the obtained results are correct the generator settings are preserved and the same measurements are carried out but in a different measuring system presented in Fig. 9.

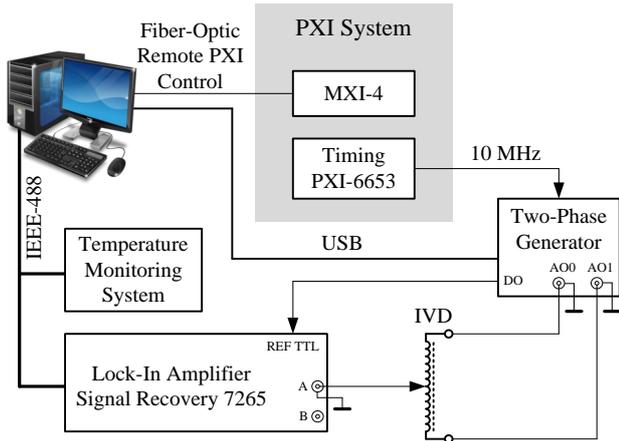


Fig. 9. Measurement system for evaluation of the amplitude ratio and phase difference stability by the lock-in amplifier.

The outputs of the generator are connected to an inductive voltage divider (IVD) as shown in Fig. 9, and the voltage ratio of the divider is set to a value of 0.5. It can be proved (see [14]) that if the generated signals are opposite in phase then the relative change of the amplitude ratio δ_R is proportional to the real part of the imbalance voltage U_D measured by the lock-in amplifier

$$\delta_R \approx 2 \frac{\text{Re}\{U_D\}}{U_0} \quad (1)$$

and the phase difference φ is proportional to the imaginary part of this voltage, i.e.

$$\varphi \approx \arctan\left(2 \frac{\text{Im}\{U_D\}}{U_0}\right) \quad (2)$$

where U_0 is the root mean square of the voltage generated in channel AO0. The results of the fluctuations of the amplitude ratio and phase difference obtained for the time constant of the lock-in amplifier set to 10 s are presented in Fig. 10 and 11, respectively.

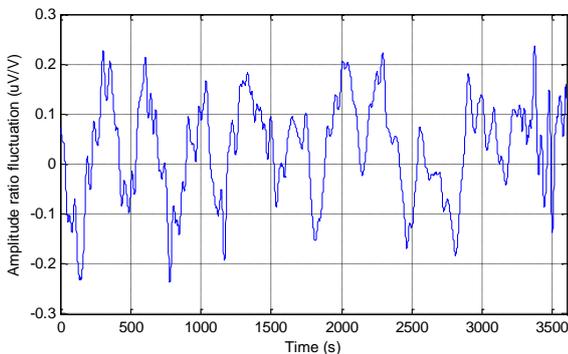


Fig. 10. Amplitude ratio stability measured by the lock-in.

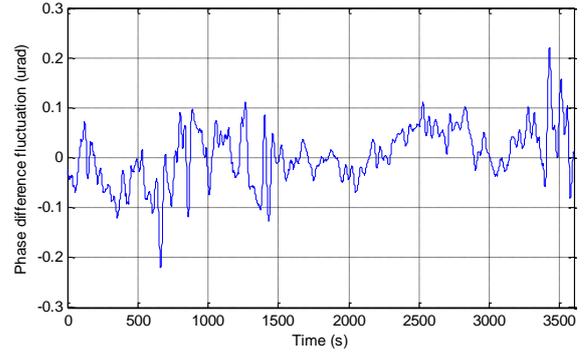


Fig. 11. Phase difference stability measured by the lock-in.

As can be seen the amplitude ratio stability over one hour is $\pm 0.24 \mu\text{V/V}$ and the phase stability is $\pm 0.22 \mu\text{rad}$.

3. CONCLUSIONS

The first evaluation of the prototype of the two-phase sine wave generator based on the Analog Devices AD5791 DACs shows its good spectral purity with SFDR reaching 96 dBc when the generated signal is of the maximally available amplitude. The stability of the amplitude ratio and phase difference is verified in two measurement systems. The one-hour fluctuations of the amplitude ratio are in the range of $\pm 0.27 \mu\text{V/V}$, and the fluctuations of the phase difference are in range of $\pm 0.22 \mu\text{rad}$. It seems that the further improvement of the generator design can yet slightly enhance the presented results.

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