AC-DC Transfer Standard Measurements with a Josephson Arbitrary Waveform Synthesizer at 200 mV

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***Abstract*—Thermal voltage converters and transfer standards are critical components in AC electrical metrology. In order to improve the low-voltage (< 1 V) calibration of such transfer standards at NIST, we have developed an AC Josephson voltage standard (ACJVS) capable of an rms output of 200 mV from a single Josephson array. Such voltages are possible because the array operates in the $n = 2$ quantum voltage state. Using this ACJVS, we synthesized dc and sinusoidal waveforms spanning the range 1 kHz to 100 kHz and measured ac-dc differences with a commercial transfer standard. The results are in good agreement with prior measurements of this particular transfer standard, using an earlier, lower-voltage ACJVS.**[1]

***Index Terms*—Digital-analog conversion; Josephson arrays; Quantization; Signal synthesis; Standards; Superconducting integrated circuits; Voltage measurement**

I. INTRODUCTION

The pulse-driven ac Josephson voltage standard (ACJVS) was first conceived nearly 20 years ago [1]. Early development of the ACJVS focused on appropriate biasing arrangements [2], superconducting Josephson junction technology [3], on-chip microwave circuit design [4], and robust chip packaging [5]. These improvements were highlighted in prior work, where NIST successfully calibrated a transfer standard at rms voltages up to 100 mV, with the junctions operating in the $n = 1$ quantum state [6]. More recently, efforts have turned to improving the microwave pulse electronics, to allow operation at the $n = 2$ quantum state, where the junctions generate two quantized voltage pulses for each input pulse — effectively doubling the output voltage of the ACJVS. Presently, the ACJVS can synthesize arbitrary waveforms with quantum-accurate rms voltage in excess of 200 mV with a single array of 6400 Josephson junctions. In principle, this method should allow scaling to rms voltages up to 1 V with 4 arrays. In the context of ac voltage metrology, increasing the ACJVS output voltage decreases the number of artifact standards needed for scaling at voltages below 1 V.

II. OPERATION OF THE ACJVS

Arbitrary waveform synthesis in the ACJVS is based upon digital-to-analog conversion of a high-speed bit pattern, or bitstream. The output voltage of the ACJVS is quantum-referenced because the Josephson junction array acts as a perfect quantizer. The bitstream is derived from delta-sigma (Δ-Σ) modulation of the ideal waveform using a simulation routine in MATLAB [7]. Each 6400-junction array is biased with a 14.4 GHz continuous wave (CW) microwave drive and a 3.6 MB bitstream clocked at 28.8 Gbps, which are combined at room temperature with a 10 dB directional coupler before being fed to the array at the bottom of the cryoprobe, which is immersed in liquid helium. The ratio of the bit rate to the pattern length yields a pattern repetition frequency of 1 kHz. Arbitrary waveforms may be constructed by choosing the appropriate amplitude and phase of harmonics of this frequency.

For each voltage and frequency desired, a different bitstream pattern is required, and the biases for each so-called *state* must be tuned and the operating margins optimized prior to any metrological measurements. For this purpose, we employed a precision digitizer from National Instruments (model PXI-5922)[2]. The low noise floor and excellent linearity of this instrument allowed us to precisely adjust the bias parameters required for proper operation of the ACJVS. A representative output spectrum of the tuned ACJVS is shown in Fig. 1.

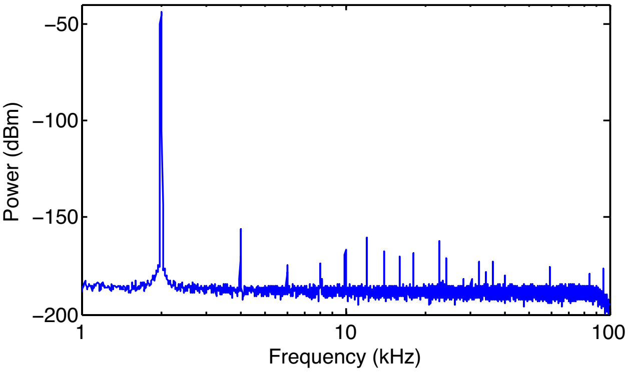

Fig. 1. Digitally sampled spectral measurement showing the low distortion of the ACJVS output. A single 6400-junction array is generating a 200 mV (rms) sinewave at 2 kHz. The lines in the spectrum above 2 kHz are predominantly due to the nonlinearities of the digitizer.

Among the recent improvements to the ACJVS is the integration of the CW microwave source, the pattern generator, and the current bias drive into a single enclosure. In addition to simplifying the equipment required for operation, the drive electronics now share a common, high-speed clock. This new

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[1] Contribution of the U.S. government, not subject to copyright.

[2] Certain commercial instruments are identified in this report to facilitate understanding. Such identification does not imply recommendation or endorsement by NIST, nor does it imply that the instruments are necessarily the best available for the purpose.

timing scheme enables continuous synchronization between the CW and pattern signals. This arrangement enables improved margins for the $n = 2$ state, and makes fully automated calibration possible.

III. AC-DC MEASUREMENTS

A. *Transfer Standard*

Each transfer standard has a characteristic ac-dc difference that is a function of voltage and frequency. For our measurements, we characterized the same Fluke 792A transfer standard that we used in previous measurements [8], because of its ubiquity in the ac-dc metrology community. The 792A uses a semiconductor rms detector, as well as signal conditioning components at its input to ensure that the internal detector is always near a single operating point, even when the input voltages may vary by roughly two orders of magnitude. For voltage ranges at or below 700 mV, the input impedance of the 792A is 10 MΩ || 40 pF. However, because the operating state of the ACJVS needs to be verified for each ac-dc measurement with the digitizer, the overall load impedance seen by the ACJVS is the parallel combination of the impedances of the 792A *and* the digitizer. This combined impedance was nominally 1 MΩ || 100 pF.

B. *ac-dc Difference Measurements*

Each ac-dc difference reported is the average of four consecutive difference measurements, in which the voltage sequence proceeds as V_{ac}, $V_{\mathrm{dc}+}$, V_{ac}, $V_{\mathrm{dc}-}$, V_{ac}. This sequence allows us to correct for drift and thermal voltages in the wiring and within the transfer standard. For each voltage in the sequence, we record the average of 16 measurements of the output of the 792A with a nanovoltmeter. A 20 s delay is programmed between each step in the sequence to allow the biases to the array and the transfer standard to stabilize.

Note that direct ac-dc difference measurements are only performed at 1 kHz. The remaining differences are inferred by ac-ac comparisons of higher frequencies against the 792A output at 1 kHz. This procedure substantially reduces the time needed for the measurements, with only a small uncertainty penalty (well below 1 μV/V). Transmission line effects were simulated with SPICE software, and the connection between the ACJVS and transfer standard was modified to ensure an appropriately band-limited measurement.

IV. RESULTS

Figure 2 shows the measured ac-dc differences of the ACJVS using the 792A. The data presented are uncorrected for transmission line response or the capacitive load of the 792A. These effects are responsible for the monotonic increase in the differences above 10 kHz. For $V = 100$ mV, the agreement between the present ACJVS and the earlier (2007) system is quite good, especially considering that the two systems utilized completely different drive electronics and transmission lines. Differences for the new ACJVS operating at 200 mV ($n = 2$ state) exhibit a similar trend with frequency as the 100 mV data, with a small offset at audio frequencies that may be due to the level coefficient of the 792A.

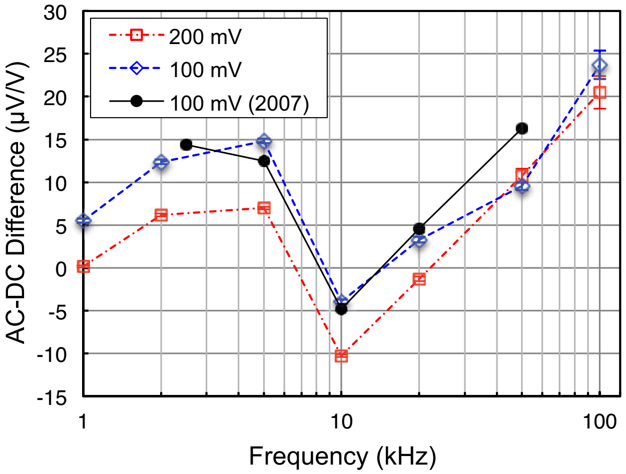

Fig. 2. ac-dc difference measurements vs. frequency for this 792A transfer standard at the 220 mV input range. Shown (open symbols) are data for the $n = 2$ state at rms voltage 200 mV, and the $n = 1$ state with rms voltage 100 mV. For reference, we also show data from Ref. [8] (solid symbols) of the same transfer standard measured with an earlier ACJVS operating at the $n = 1$ voltage state with rms voltage 100 mV. Lines are intended as guides to the eye.

V. CONCLUSION

In conclusion, we have successfully measured ac-dc differences of the ACJVS operating at the $n = 1$ and $n = 2$ states. The ac-dc differences of the two states are very similar, with a small offset at low frequencies that may reflect the nonlinearity of the transfer standard. Furthermore, we have shown that our new ACJVS yields ac-dc difference characteristics for this particular 792A that are in excellent agreement with measurements performed with an early ACJVS operating with different bias electronics.

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