An AC Josephson Voltage Standard for AC–DC Transfer-Standard Measurements

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***Abstract*—In order to improve the National Institute of Standards and Technology (NIST) low-voltage calibration service for thermal-voltage converters, we have constructed an ac-Josephson-voltage-standard (ACJVS) system that can synthesize accurate rms voltages of up to 100 mV. Using this system, we synthesized dc voltages and audio-frequency sine waves in order to measure ac–dc differences on the 22 mV and 220 mV ranges of a commercial thermal transfer standard. By modifying the output resistance of the low-pass-filtered transmission line, we were able to extend our measurement frequency from a few kilohertz up to 100 kHz. Our ACJVS measurements agree with the uncertainty budget of ac–dc difference calibrations made of this transfer standard by use of conventional techniques. We also show the progress toward extending the output to 200 mV using new Josephson circuits.**

***Index Terms*—AC measurements, ac voltage standard, Josephson arrays, Josephson devices.**

I. Introduction

IT HAS TAKEN ten years since the conception of the pulse-driven ac Josephson voltage standard (ACJVS) [1] to develop the superconducting Josephson junction technology, circuit designs, and bias techniques [2] needed to assemble the first metrologically useful system. This 100 mV ACJVS system can generate arbitrary waveforms with quantum–mechanically defined voltages and, in particular, the single-tone ac sine waves and dc voltages required for the calibration of thermal voltage converters and transfer standards. We expect the ACJVS to have a dramatic impact at voltages below 100 mV, such as at 2 mV, where measurement uncertainties with conventional techniques can be as high as 300 μV/V at audio frequencies for national measurement institutes [such as National Institute of Standards and Technology (NIST)] and over 1 mV/V for commercial calibrations. The unprecedented accuracy of the ACJVS system derives from the precise control of the perfectly quantized voltage pulses produced by arrays of Josephson junctions. The performance of this ACJVS system was improved over the previous prototypes [3] through the use of nanostacked Josephson junction arrays [4], better on-chip filters [5], state-of-the-art microwave packaging [6], and a well-controlled output transmission line. In this paper, we describe the operation of the 100 mV ACJVS system and the measurement technique used to extend the useful frequency range from a few kilohertz up to 100 kHz for use with rms detectors. Over this frequency range, we used synthesized voltages from 2 mV to 100 mV to characterize the ac–dc differences on the two lowest voltage ranges, 22 mV and 220 mV, of a thermal transfer standard.

II. ACJVS Operation

The ACJVS produces audio-frequency waveforms by using a digital-to-analog synthesis technique based on a high-speed delta–sigma modulation [7]. In order to increase the output voltage to 100 mV, two 2560-junction series arrays are independently biased and connected in series through the low-pass on-chip filters. The arrays are biased with a 15 GHz microwave drive and a 4 Mb digital pattern clocked at 10 Gb/s. Using this technique, arbitrary waveforms with any desired rms voltage up to 107 mV (95% of the rms voltage corresponding to the $\pm$159 mV maximum dc peak voltage) can be accurately synthesized by choosing an appropriate bit pattern. Arbitrary waveforms are constructed by choosing the desired amplitude and phase of harmonics of the 2.5 kHz pattern-repetition frequency, which is determined by the pattern-generator clock speed and the number of bits in the pattern. The pattern length is limited by the 8 Mb memory of our commercial bit-stream generator, which we divide into two equal halves to store two different patterns. For ac–dc comparisons, we place the ac and dc bit patterns in the two memory locations and switch between them. Likewise, we use two ac patterns for ac–ac comparisons. Both dc polarities are required to remove the effect of the thermal voltages for ac–dc difference measurements. The inverse dc polarity is obtained using the same dc pattern but with inverted and phase-shifted bit-stream generator output and inverted polarity of the dc bias to the arrays. Different bit patterns are required for each frequency and voltage. We typically use single arrays, leaving off the biases to the other array, to synthesize voltages at exactly half the maximum output voltage.

The accuracy of each waveform is ensured by optimizing the operating margins for each array by tuning all five biases: pulse, microwave and compensation amplitudes; and the two relative phases between these three biases [3]. If any one of these parameters is incorrectly tuned, the synthesized waveform is "off margins," because it will not yield an intrinsically accurate and calculable voltage. The optimum bias conditions are determined through precision measurements of the ACJVS output by the use of either a Fluke 792A transfer standard or a National Instruments PXI-5922 digitizer.[1] The transfer

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[1]These commercial instruments are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by NIST, nor does it imply that the equipment identified are necessarily the best available for the purpose.

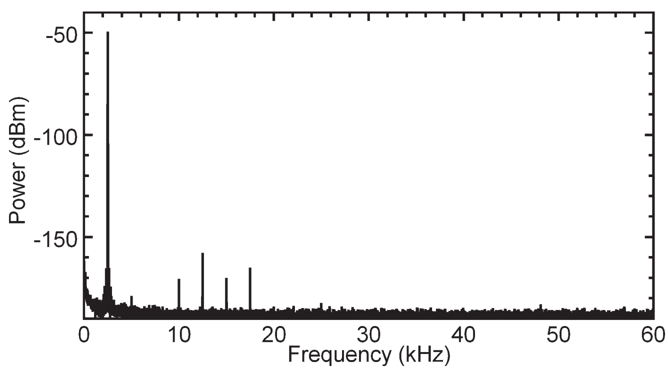

Fig. 1. Digitally sampled spectral measurement showing harmonic distortion tones at -110 dBc [in decibels below the fundamental (carrier)] for the 2 V range of the digitizer and attributed to digitizer nonlinearities. Both Josephson arrays are used to generate the 100 mV (rms) sine wave at 2.5 kHz. The digitizer used 1 MΩ input impedance, 10 Hz resolution bandwidth, ten averages, and 1 MS/s sampling rate.

standard is used to accurately characterize the ACJVS operating margins. For routine operation, we take advantage of the low noise floor and accuracy of the delta–sigma analog-to-digital converter digitizer to quickly tune the ACJVS bias parameters and ensure proper operation as we change waveforms. Fig. 1 shows the spectra for a 100 mV (rms) 2.5 kHz waveform (with both arrays operating) when measured on the 2 V input range of the digitizer.

Distortion harmonics are present in this measurement, primarily at and above 10 kHz. However, these harmonics are not observed on the 10 V digitizer range (not shown) for the same ACJVS waveform. Distortion harmonics are caused either by nonlinearities in the measurement instrument or by inaccurate ACJVS synthesis when one of the biases is off margin. When a bias parameter to either array is improperly tuned, the measured spectra show distortion harmonics over the full-measurement bandwidth (typically 500 kHz). We believe that the distortion harmonics in Fig. 1 are attributable to the digitizer nonlinearities, because the different ranges, which have different amplifier stages, produce different harmonics. Another clue is that the frequency and amplitude of the harmonics change depending on the digitizer calibration (also not shown). Finally, when the arrays are independently operated at 50 mV, no distortion is measured down to -124 dBc [8] on the 10 V range but distortion does appear for different digitizer calibrations and on the 2 V range. Even with the intrinsic nonlinearities, the digitizer is a powerful tool that allows us to quickly evaluate the performance of the ACJVS. These measurements also demonstrate how the high-performance waveforms of the quantum-based ACJVS can be used to better characterize state-of-the-art commercial digital or analog instruments.

III. Transfer-Standard Measurements

Accurate ac-voltage measurements are routinely made by use of either thermal converters or transfer standards that combine input amplifiers with thermal sensors to reduce measurement uncertainties for voltage ranges below 1 V. Using such a transfer standard, we made ac–dc and ac–ac difference measurements with ACJVS-synthesized voltages. In previous work [8], we performed ac–dc measurements at each frequency and voltage. In the work reported here, we performed ac–dc measurements at 2.5 kHz and used this value to infer the ac–dc values at higher frequencies through ac-to-2.5 kHz difference measurements. This allows easier measurements through the comparison of two voltages instead of three and reduces errors from thermal voltage drift, especially at lower voltages.

Each ac–dc difference measurement is the average of four consecutive difference measurements of the triple-voltage sequence; $V_{\rm ac}$, $V_{+\rm dc}$, and $V_{-\rm dc}$. A 7 s delay is programmed between each voltage measurement to ensure that all biases have switched and that the transfer standard has stabilized. For each of the 12 voltage measurements, the output of the transfer standard is averaged over either 20 or 100 power-line cycles with a nanovoltmeter. Similarly, averages of 6 $(V_{\rm ac1}, V_{\rm ac2})$ pairs of voltage measurements are used for the ac–ac differences. The measurement sequences are completed in about 2–3 min for each frequency point.

The digital-synthesis technique inherently produces digitization harmonics at high frequencies [2], [7]. Fortunately, the oversampling ratio is large due to the 10 Gb/s clock frequency, so the amplitudes of these harmonics are negligible below about 10 MHz. Nevertheless, the measurement bandwidth of thermal converters and transfer standards is larger than 10 MHz, where the digitization harmonics are not negligible. Thus, for use with rms-detection-based ac-metrology instruments, the ACJVS output must be low-pass filtered to remove the digitization harmonics from the measured rms voltage.

Low-pass filters with cutoff frequencies of 3 MHz and 10 MHz produced identical ac–dc differences at a synthesized frequency of 2.5 kHz [8]. Although the filters adequately removed the unwanted high-frequency digitization harmonics, we found that the large filter capacitances produced an excess frequency-dependent voltage, whose magnitude increases with frequency and with higher filter capacitance. For example, this voltage component is observed as a large negative ac–dc difference of nearly 1 mV/V at 50 kHz.

In order to understand this error, we simulated circuits with the appropriate filter models and output transmission lines. The transmission line consists of about 1 m of twisted-pair magnet wire inside the cryoprobe followed by about 0.5 m of 50 Ω coax. The low-pass filter is placed at the transfer-standard input. The simulations correctly reproduced the measured errors for the different filters.

This error could have been mathematically subtracted from the measured result, but a simpler approach was found that produced accurate direct measurements. We found, not unexpectedly, that by increasing the output impedance of the ACJVS, a better match could be made to the output transmission line and the 50 Ω-designed low-pass filter. By increasing the output resistance from 0 Ω to a specific value near 60 Ω, we could maintain a flat frequency response $(= 1\ \mu\text{V/V})$ over a 100 kHz bandwidth. Slightly different output resistances were required for different filters with different cutoff frequencies and different numbers of poles. Since nearly identical ac–dc differences were measured with different filters using this transmission-line-tuning technique [8], we feel confident in the method's validity.

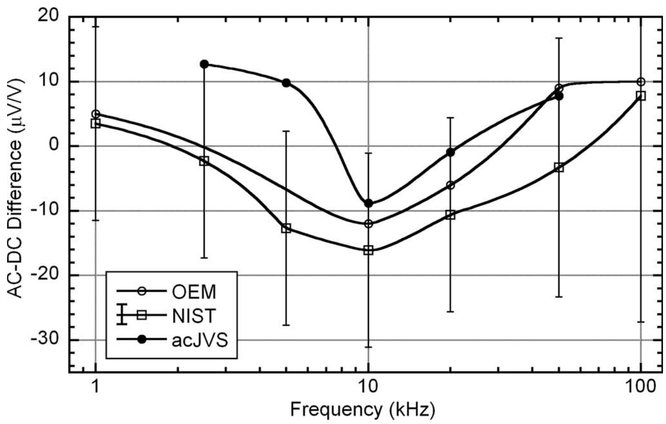

Fig. 2. AC–DC differences versus frequency for 100 mV rms signals measured on the 220 mV range of the transfer standard, comparing the manufacturer (OEM) and NIST calibrations (open symbols) with the corrected ACJVS measurements (solid symbols). Error bars show the NIST calibration uncertainty.

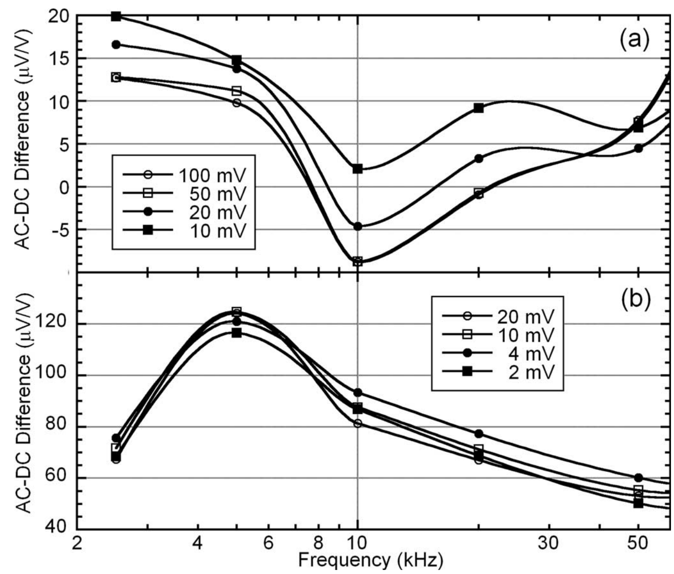

Fig. 3. AC–DC differences versus the frequency for the different rms voltages (2 mV to 100 mV) on the (a) 220 mV and (b) 22 mV ranges of the transfer standard, derived from ACJVS-synthesized waveforms. Connecting lines are merely guides to the eye.

Since the transmission-line-filter error is corrected using measurements at 100 kHz, where the transmission-line error is greatest, we present only the data at lower frequencies, where the transmission-line error is negligible and excellent reproducibility is achieved. A 3 MHz three-pole filter and a 59.7 Ω output resistance are used for the measurements in this paper. One drawback of this method is that the output resistance causes a small voltage drop at the transfer standard. If the transfer-standard input impedance were constant, the voltage drop $(60\ \Omega/10\ \mathrm{M}\Omega)$ would be the same for all measurements and would have no effect on the ac–dc differences. However, it is known that the input impedance of the transfer standard decreases with increasing frequency [9]. Our measurements of a number of transfer standards show that the 10 MΩ dc input impedance decreases to 7.8 MΩ at 2.5 kHz, 6 MΩ at 10 kHz, and 3.3 MΩ at 100 kHz, so the measured ACJVS voltages decrease with increasing frequency. Therefore, we have corrected all ac–dc ACJVS measurements in this paper, starting from $-1.7\ \mu$V/V at 2.5 kHz and decreasing to $-8.5\ \mu$V/V at 50 kHz.

Fig. 2 shows the resulting measured and corrected ac–dc differences of the 100 mV ACJVS waveforms for the 220 mV range of the transfer standard. Also shown are the calibrations of the transfer standard by NIST and by the original equipment manufacturer (OEM), whose calibrations are traceable to NIST. The ac–dc differences measured with the ACJVS reside within the NIST measurement uncertainty for all values except at 5 kHz and are well within the 50 μV/V OEM-specified uncertainty (not shown). Our measurements agree well with previous ACJVS measurements [8] made with a different chip with different on-chip filters, which demonstrates the reproducibility of the ACJVS measurements. Clearly, the ACJVS values are consistently higher than those found with the conventional calibration methods, suggesting that a systematic error likely remains and requires further investigation.

Using different digital patterns for each voltage and frequency, we measured ac–dc differences for additional voltages on the same 220 mV range and also on the 22 mV range of the transfer standard. Fig. 3 shows the resulting ac–dc differences on these two ranges, after being inferred (from ac 2.5 kHz measurements and ac–dc measurements at 2.5 kHz) and corrected (for the voltage-divider effect of the frequency-dependent transfer-standard input impedance) as described above. At each frequency, the ac–dc differences for the different voltages are very similar, within about 10 μV/V or less. In fact, the ac–dc differences on the lower 22 mV range appear similarly well behaved compared to those on the higher range.

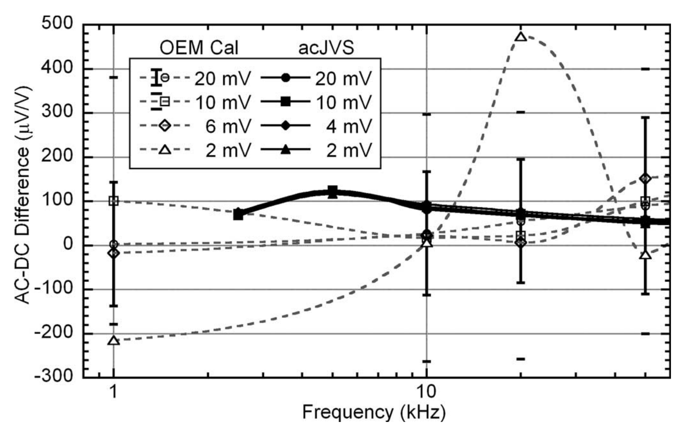

Fig. 4. AC–DC differences versus the frequency on the 22 mV range of the transfer standard with rms amplitudes ranging from 2 mV to 20 mV. Solid symbols denote ACJVS measurements. Open symbols denote the manufacturer's specified calibration, with error bars (20 mV) or error "caps" (10 mV) shown for the two largest voltages. Connecting lines are merely guides to the eye.

As mentioned earlier, calibrations and measurements at these lower voltages are very challenging for conventional methods. In Fig. 4, we compare the manufacturer's NIST-traceable ac–dc calibration and uncertainties for the 22 mV range with that of the ACJVS measurements. The conventional calibration method shows the ac–dc differences at each frequency varying over 100 μV/V and up to 500 μV/V at 20 kHz. This is ten to 50 times larger than the range of ac–dc differences found with the ACJVS. The corresponding OEM specified uncertainties

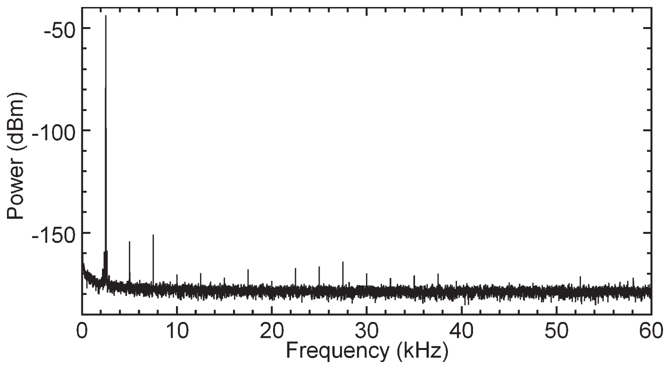

Fig. 5. Digitally sampled spectral measurement of a 200 mV sine wave at 2.5 kHz synthesized by use of new ACJVS circuits with twice the number of junctions. These observed distortion harmonics are attributed primarily to inaccurate ACJVS operation.

($\geq$ 140 μV/V at 20 mV and twice that at 10 mV) are representative of the difficulty of these measurements. In particular, the specified measurement uncertainty for 2 mV on this range is 1600 μV/V, which is too large to practically display in the figure. We are hopeful that the ACJVS will enable us to significantly reduce the measurement uncertainty, particularly for these low voltages, when the system is implemented in the NIST voltage-calibration laboratory.

IV. Higher Output Voltages

In order to fully characterize the 220 mV range of the transfer standard and to begin making practical direct measurements of some thermal voltage converters, we need to double the ACJVS output voltage to 200 mV. Increasing the output voltage requires doubling the number of Josephson junctions in each array, while still maintaining their bias uniformity and, therefore, their operating margins. This is a challenging task, requiring new circuit designs that will be described elsewhere [10], [11].

However, we have made significant progress toward demonstrating accurate 200 mV signals and hope to soon demonstrate useful operating margins and begin making ac metrology measurements. Preliminary measurements look promising because we have demonstrated individual arrays operating at 100 mV with 0.5–1.0 mA operating margins. Measurements of these 100 mV waveforms from single arrays produce spectra identical to those shown in Fig. 1, which were made with two independently biased arrays. Higher voltage for each array is a major accomplishment, and the low-distortion spectrum gives us some assurance of the accuracy of these larger voltage waveforms synthesized with the double-sized arrays. Unfortunately, when both arrays are operating simultaneously to produce 200 mV, the arrays appear to be off operating margins and not generating accurate waveforms. The resulting spectrum is shown in Fig. 5 where many distortion harmonics are apparent. Note that the distortion harmonics continue over a much wider bandwidth, even up to 1 MHz (not shown in the figure). From this result and other measurements in which we have changed the array wiring, we believe that RF signals (10–800 MHz) from digitization harmonics in the bit-stream generator bias are coupling between the arrays and destroying the operating margins. We are confident that by further improving the isolation between the arrays, we can solve this problem.

V. Conclusion

We have, for the first time, successfully measured ac–dc differences of the ACJVS at voltages from 2 mV to 100 mV and found agreement within the calibration uncertainty of the transfer standard on its two lowest voltage ranges. Measurements were made above a few kilohertz by tuning the ACJVS output impedance to correct for voltage errors caused by the low-pass filter needed to remove the high-frequency digitization harmonics intrinsic to the digital-to-analog synthesis techniques of the ACJVS. Now that the performance of the ACJVS has been demonstrated, a duplicate dedicated system has been installed in the NIST Voltage Metrology Laboratory for incorporation into the ac–dc difference calibration service. We have also made progress toward doubling the maximum output voltage to 200 mV and hope to soon make metrologically useful measurements at this higher voltage using the ACJVS.

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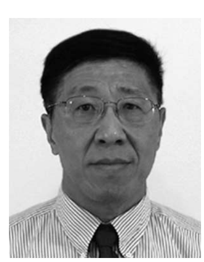
Mr. Kinard is the recipient of two U.S. Department of Commerce Silver Medals and the R&D 100 Award.



Yi-hua Tang received the Ph.D. degree in low-temperature physics from the University of Florida, Gainesville, in 1987.

He worked in the private sector from 1991 to 1996 in the field of Josephson arrays and voltage standards. In January 1997, he joined the Quantum Electrical Metrology Division, National Institute of Standards and Technology (NIST), Gaithersburg, MD, where he is currently working on the Josephson voltage standard and its applications in metrology. He is responsible for maintaining the U.S. legal volt and providing for the dissemination of an internationally consistent and traceable voltage standard tied to the SI units. His research interest is to develop applications of Josephson technology for dc and ac voltage metrology.

Dr. Tang is a member of the American Physical Society.