100 mV ac-dc Transfer Standard Measurements with a Pulse-Driven AC Josephson Voltage Standard

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Abstract

In order to improve the low-voltage calibration service at NIST, we have constructed an ac Josephson voltage standard system with a maximum rms output voltage of 100 mV. Using this system, we synthesized sinewaves of various audio frequencies and measured ac-dc differences on the 220 mV range 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 data are well within the uncertainty budget of ac-dc difference calibrations made of this transfer standard using conventional techniques. At the conference, we will present additional results using new Josephson circuits capable of reaching 200 mV.

Introduction

It has taken 10 years since 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 voltage and, in particular, the single-tone ac sinewaves and dc voltages required for the calibration of thermal voltage converters and transfer standards. The unprecedented accuracy of the acJVS system derives from precise control of the perfectly quantized voltage pulses produced by arrays of Josephson junctions. The performance of this acJVS system was improved over previous prototypes [3] through the use of nano-stacked 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 100 mV acJVS system and the measurement technique used to extend the useful frequency range from a few kilohertz up to 100 kHz.

acJVS Operation

The acJVS produces audio-frequency waveforms by use of a digital-to-analog synthesis technique based on high-speed delta-sigma modulation [7]. The junctions are biased with a 15 GHz microwave drive and a 4 Mbit digital pattern clocked at 10 Gbit/s. Using this technique to drive two independently biased 2560-junction arrays, arbitrary waveforms with any desired rms voltage up to 100 mV 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. The pattern repetition frequency is determined by the pattern generator clock speed and the number of bits in the pattern and is limited by the 8 Mbit memory of our present commercial bitstream generator. The memory is divided into two halves that store two different patterns. For these experiments, we place the ac and dc bit patterns in the two memory locations and switch between them. In order to make ac-dc difference measurements and remove thermal voltages we require both dc polarities. The inverse dc polarity is obtained by inverting and phase shifting the bitstream generator output and then inverting the polarity of the dc bias.

The operating margins for all biases to each array must be checked for each waveform and frequency [3]. To ensure optimum bias conditions for each pattern, precision measurements of the acJVS output waveforms were made with Fluke 792A transfer standard and National Instruments PXI-5922 Digitizer [8]. Figure 1 shows an example of the measured output spectrum of a single array (50 mV) at 2.5 kHz. Note that no distortion harmonics, which would indicate incorrect waveform synthesis, are observed in the measured spectrum down to the digitizer noise floor. The low noise floor and accuracy of this commercial delta-sigma ADC digitizer allow us to more easily tune the acJVS and demonstrate the true performance of our quantum-based voltage source.

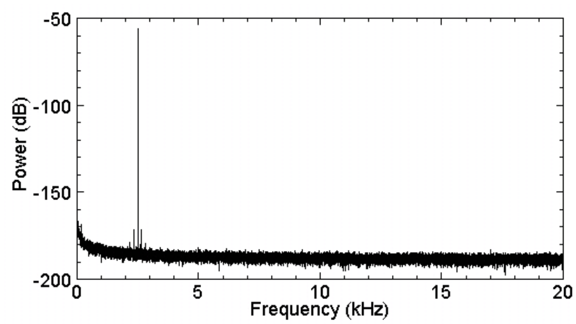

Figure 1. Digitally sampled spectral measurement showing –124 dBc [dB below the fundamental (carrier)] low distortion of the acJVS output. Just one Josephson array in the acJVS is generating a 50 mV (rms) sinewave at 2.5 kHz. The digitizer used 1 MΩ input impedance on the 10 V scale, 1 Hz resolution bandwidth, 10 averages, and a 100 KS/s sampling rate.

Measurements

Each ac-dc difference measurement is the average of four consecutive difference measurements of the triple voltage sequence, V_{ac}, V_{+dc} and V_{-dc}. A 7 s delay is programmed between each voltage to ensure that the biases to the array have switched and that the transfer standard has stabilized at each voltage. For each of the 12 voltage measurements the output of the transfer standard is averaged over 20 power line cycles with a nanovoltmeter. This complete measurement sequence is completed in under two min for each frequency point.

Although the rms voltages of our acJVS audio tones are accurate, the digital synthesis technique inherently produces digitization or quantization harmonics at high frequencies. Fortunately the oversampling ratio is large due to the 10 Gbit/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 ac metrology instruments, the acJVS output must be low-pass filtered to remove the digitization harmonics from the measured rms voltage.

We successfully used low-pass filters with cut-off frequencies of 3 MHz and 10 MHz and found ac-dc differences to be identical at 2.5 kHz. Although the filters worked well at 2.5 kHz, the large filter capacitance caused an excess frequency-dependent voltage for higher frequencies, which was observed as a large negative ac-dc difference of nearly 1 mV/V at 50 kHz.

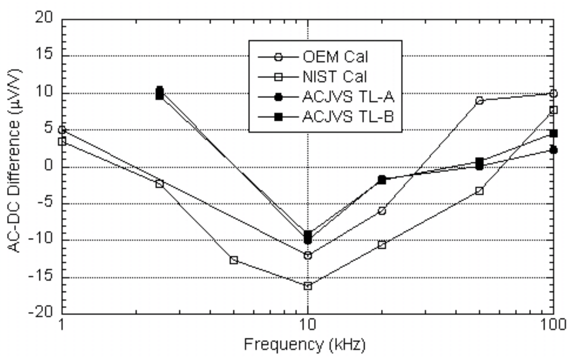

Figure 2. AC-DC differences vs. frequency for the same transfer standard. Solid symbols denote two acJVS measurements with the transfer standard floating (A) and grounded (B). Open symbols denote conventional calibrations.

In order to understand this error, we simulated the filters and the output transmission line. The transmission line consists of about 1 m of twisted pair inside the probe followed by about 0.5 m of 50 Ω coaxial cable. The low-pass filter is placed at the transfer standard input. The simulations correctly reproduced the measured error, which could then have been subtracted from the measured result. However, 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 this error at or below 1 uV/V over a bandwidth of about 100 kHz. Different output resistances were used for different filters with different cut-off frequencies and different numbers of poles. For example, a 3-pole 3 MHz filter required a 56.6 Ω total resistance, while a 9-pole 10 MHz filter required 66.6 Ω.

We implemented this modified output impedance by adding a 50 Ω resistor at 4 K and a room temperature pot that could be easily adjusted. Simulations and experments both showed that there was little difference between placing the remaining resistance at the bottom or the top of the cryoprobe. While measuring the 100 kHz sinewave where the transmission-line error is greatest, we tuned the pot until the measured rms voltage is close to the expected value. Although the ac-dc measurement at 100 kHz is no longer useful because we chose the ac amplitude, the transmission-line error is sufficiently subtracted that excellent reproducibility is achieved for the 50 kHz and lower frequency measurements. Furthermore, the experimental resistance values were within 1 Ω of the resistances expected from the simulations, giving us confidence that the resistance-tuning technique is valid. Secondly, we note that the ac-dc difference measurements for frequencies below 100 kHz were found to give the same result for a variety of filters.

Figure 2 shows the measured ac-dc differences of the acJVS with the transfer standard either grounded or floating. A 3 MHz 3-pole filter was used and the acJVS output resistance was increased from 1.5 Ω to 58.1 Ω for the grounded case to zero the error at 100 kHz. Also shown are calibrations of the transfer standard by NIST and by the manufacturer, which is traceable to NIST.

In conclusion, for the first time we have successfully measured ac-dc differences of the acJVS at 100 mV and found agreement within the calibrated uncertainty of the transfer standard. Measurements were made above a few kilohertz by tuning the acJVS output impedance to account for the required low-pass filters in the measurement circuit. Now that the absolute voltage accuracy has been demonstrated, the system will be re-engineered for use in the NIST calibration service and further development will focus on increasing performance for both higher voltage and higher bandwidth.

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[8] 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 the National Institute of Standards and Technology, nor does it imply that the equipment identified are necessarily the best available for the purpose.