Operating Margin Measurements for an AC Josephson Voltage Standard

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Abstract

For a number of years, NIST has been developing a Josephson arbitrary waveform synthesizer as an ac Josephson Voltage Standard (ACJVS). The effort has primarily focused on increasing the output voltage to practical levels. Recent advances in circuit design and superconducting integrated circuit fabrication have enabled us for the first time to demonstrate waveforms with a 242 mV peak voltage. This larger output voltage now allows us to perform practical metrology measurements with rms amplitudes up to 170 mV. The new system can generate a variety of precision voltage waveforms, including ac sinewaves as well as dc voltages so that the system can be used as a quantum-based voltage source for ac metrology. In this paper, we present experimental measurements of 2.7 kHz and 3.3 kHz waveforms synthesized by the ACJVS measured with both a FFT (fast Fourier transform) spectrum analyzer and an ac/dc transfer standard. This work demonstrates the feasibility of a practical ac Josephson voltage standard based upon a quantum voltage source that delivers precisely calculable ac and dc rms voltages.

Introduction

NIST has recently made a number of improvements to the Josephson circuits, cryogenic probes, and measurement system for the ACJVS that allow it to be operated at output levels up to 242 mV (zero-to-peak) for ac waveforms and ±254 mV for dc voltages. The present system utilizes a chip containing two Josephson arrays with a total of 8200 junctions and a common digital-to-analog conversion technique called delta-sigma modulation [1], which allows arbitrary waveforms to be generated using a sequence of pulses at a high data rate. In our case, the digital data rate is 10 Gbit/s. We then combine this digital signal with a 15 GHz sinusoidal drive signal to effectively increase the maximum bipolar pulse repetition frequency to 15×10^9 pulses/s. This combined signal is then fed to the Josephson junctions, which precisely quantize the pulses, thus producing a nearly ideal delta-sigma pulse train and a precisely known output waveform. The unprecedented accuracy of this technique for generating ac and dc waveforms for voltage metrology has been discussed previously [2,3,4].

Our latest chip designs for the ACJVS use two Josephson arrays connected in series in order to increase the total output voltage, as shown in Fig. 1. This requires that the broadband pulse drive signal to each array be split into a high-frequency component (10 MHz to 30 GHz) and a low-frequency component (dc to 10 MHz) that are separately delivered to the junction arrays. This is accomplished by using 10 MHz dc blocks on both digital drive signal lines that bias each

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Josephson array so that only the high-frequency component is transmitted. A second function of the dc blocks is to allow the two arrays to be connected in series on-chip so that their output voltages add and the low-frequency drive component can be supplied to the arrays with a separate sinusoidal current at the fundamental frequency. This configuration enables the two arrays to operate simultaneously while also allowing the 8200 junction array circuit to be connected directly to ground. This essential feature allows the ACJVS output to be connected directly to spectrum analyzers, ac/dc transfer standards, thermal voltage converters (TVC), and other ac and dc voltage metrology instruments. There are a number of circuit innovations on the chip that make this configuration possible, and those details have been presented elsewhere [5].

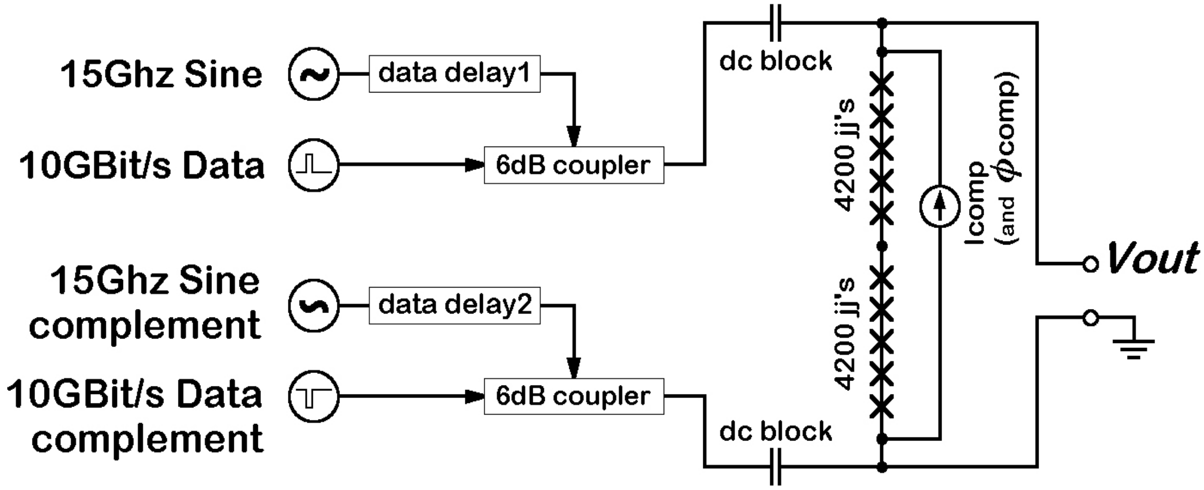

FIGURE (1) Diagram showing the system configuration and 8 individual bias parameters for the ACJVS system based on a chip containing two Josephson arrays.

Figure 1 also illustrates the bias configuration for the two Josephson arrays that comprise the ACJVS. Note that the bottom array is driven with pulses of the opposite sign. There are presently 8 independent operating parameters that must be set correctly in order for the system to produce the correct output voltage: (a) Data amplitude and (b) data complement amplitude are the voltage amplitudes for the two 10 Gbit/s digital data signals for the two arrays. Data complement is the inverse of the data signal; (c) Microwave amplitude and (d) microwave complement amplitude are the power levels for the 15 GHz sinusoidal drive provided to the two arrays; (e) Data delay1 and (f) data delay2 are the phase shifts between the digital data signals and the microwave sinusoidal signals; (g) I_{comp} is the amplitude of the compensation current that provides the low frequency bias at the fundamental frequency; (h) compensation phase, ϕ_{comp}, is the adjustment of the phase of I_{comp} with respect to the digital data signals.

Operating Margin Measurements

To prepare the ACJVS for comparison with other instruments and reference standards, we must first measure the operating margins for the Josephson circuit to determine the setpoints for each of the 8 bias parameters listed above. We use the term "operating margins" to represent the region in the 8 parameter space where each junction in each array is generating precisely one quantized pulse for every input pulse. We use several instruments in conjunction with the ACJVS in order to determine the operating margins. We start with an analog oscilloscope and a dither-current module that applies a triangle wave of several milliamperes to the array while it is generating an ac waveform. This visual technique allows us to get the 8 bias parameters into roughly the correct range for the Josephson chip. Then we disconnect the oscilloscope and dither current, and connect the chip output directly to a spectrum analyzer. The spectrum analyzer is used to examine the synthesized waveform in the frequency domain, so we can tune the bias parameters to their approximate center values by observing the fundamental and by minimizing the first few harmonics (higher harmonics are generally smaller and can typically be ignored). If any of the junctions are not within their operating margins, distortion harmonics will appear and the precision amplitude of the fundamental may be compromised. Figure 2 shows a typical measured spectrum of the Josephson array after the operating margins have been optimized. Notice that the largest distortion harmonic is –95 dBc (i.e., 95 dB below the fundamental tone). At that level, the effect of such a harmonic on the total rms voltage output is negligible ($<10^{-3}$ μV/V or 1 nV/V) because it combines as a RSS (root sum squares) contribution. This particular plot is for a 242 mV sinewave (zero-to-peak) at 3.3 kHz produced with a 3000064 bit code using two series-connected Josephson junction arrays, for a total of 8200 junctions.

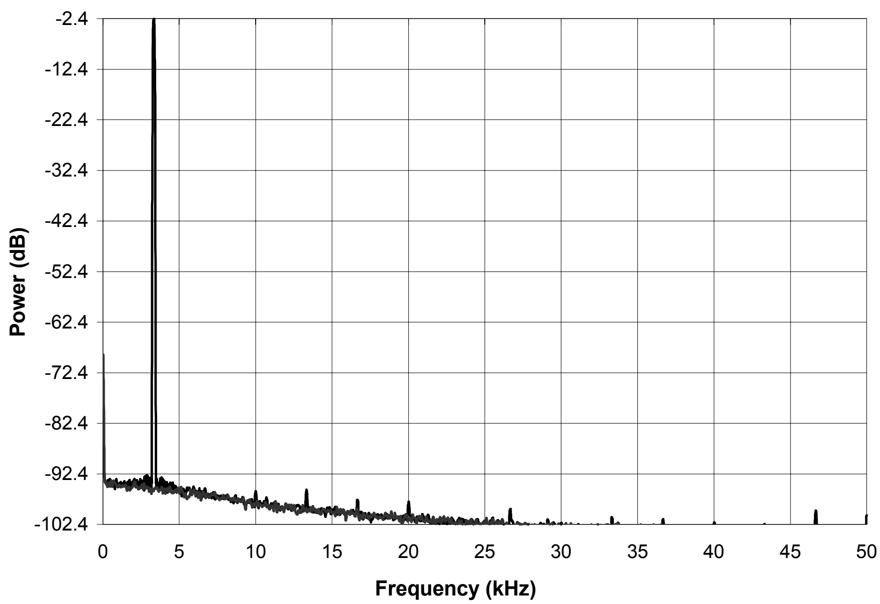

FIGURE 2. Spectrum analyzer measurement demonstrating –95 dBc low distortion for the ACJVS with two Josephson arrays generating a 242 mV (zero-to-peak) sinewave at 3.3 kHz using 8200 junctions at 10 Gbit/s. The spectrum measurement used 100 Hz resolution bandwidth and 100 averages.

Another important ACJVS measurement that the spectrum analyzer is well suited to make is to directly measure error voltages caused by the large-magnitude current (roughly 10 mA) of the low-frequency compensation current, I_{comp}. We refer to these error terms as V_{induc}, which is the voltage generated at the fundamental frequency by I_{comp} flowing through the on-chip inductance, and V_{io}, which represents input/output coupling from I_{comp} to the ACJVS output leads. The sum of these error voltages can be measured directly by turning off the digital data and rf sinewaves to the chip, so the only bias current flowing though the 8200 Josephson junctions is I_{comp}. The spectrum analyzer can then directly measure the combined error voltage of V_{induc} and V_{io}, provided that I_{comp} is less than the critical current of the arrays (I_c). If I_{comp} is larger than the critical current, then we can still make the measurement by decreasing I_{comp} to slightly below I_c and appropriately scaling the measured error voltage. The result of this measurement for the chip and system configuration presented in Fig. 2 was a magnitude of –80.1 dBc for the combined error voltages of V_{induc} and V_{io}. This result is for our latest generation cryoprobe, which shows an improvement in V_{io} of roughly 17 dB compared to previous models. The magnitude and phase of this measured error voltage can be used in two different ways. The first method would be to include the measured error in our final calculation of rms value and uncertainty for the ACJVS output voltage. The other method is to use an "error correction signal" that adds a small series voltage at the fundamental frequency to the ACJVS output. Using the spectrum analyzer display, the amplitude and phase of the correction signal can then be tuned to exactly cancel the undesired peak observed for V_{induc} and V_{io}. This technique has been demonstrated to provide significantly improved performance of the ACJVS system at audio frequencies [6], but was not used for the measurements presented in this paper.

Precision "Flatspot" Measurements

In order for the ACJVS system to truly meet the definition of an "intrinsic" ac and dc standard, there must be a finite range for each bias parameter over which the output voltage does not measurably change [3]. This "flat spot" in the operating margins needs to be confirmed every time the ACJVS system is used for precision measurements, and for each synthesized output waveform generated by the Josephson array. For the ACJVS to be a useful standard, every bias parameter must have a range over which the output voltage does not change at the level of parts in 10^7.

As illustrated in Fig. 2, our spectrum analyzer has enough dynamic range to confirm that distortion harmonics are –90 dBc or lower, which is sufficient to verify that contributions to the rms voltage due to those harmonics are well below the required level of precision. The spectrum analyzer is a very convenient tool for this purpose because it performs many spectrum measurements per second, and responds quickly to any parameter adjustment that affects the distortion harmonics with respect to the fundamental tone. As such, it is a quick and reliable way to set the bias parameters within a few percent of their optimal values. However, since the spectrum analyzer is always measuring such a large signal at the fundamental frequency, it has limited ability to measure error signals occurring at that same frequency. For full characterization of the ACJVS we need to be able to verify that a "flat-spot" exists with respect to in-phase error sources at the fundamental, because they will add directly to the output rms value (not as an RSS contribution as in the case of distortion harmonics)[6]. For example, a very small –100 dBc distortion or error signal in the ACJVS output at the fundamental (with a relative phase of 0° or 180°) would be undetected by the spectrum analyzer, but would still produce an error in the rms voltage of 10 parts in 10^6. Thus in order to perform the final high-precision ACJVS flat-spot tests, we use an ac/dc transfer standard.

The ac/dc transfer standard uses a power detector to measure rms voltage much like a traditional TVC (thermal voltage converter). We use the instrument on its 220 mV full-scale range where it has a high-impedance buffer amplifier on its input so that the ACJVS supplies a minimal load current in these experiments. The transfer standard measures the total rms voltage delivered to its input over a wide bandwidth (dc to many MHz), so everything that the ACJVS generates in that band is included in the rms voltage measurement by the transfer standard. For our ACJVS flat-spot measurements, the transfer standard allows us to determine the range for each of the 8 bias parameters over which the Josephson output signal remains constant to better than a part in 10^6. Figure 3 illustrates the use of this method to obtain flatness measurements of the four most critical parameters for the ACJVS when generating a 193 mV sinewave (zero-to-peak) at 2.7 kHz using the 8200 Josephson junction two-array configuration (in this case we used an 8 Gbit/s data-rate and 12 GHz microwave frequency). During the 15 minutes over which these measurements were made, the median output voltage of the transfer standard was 1.238502 V with a small amount of noise and drift that scattered the measurements by no more than ±1 part in 10^6. In approximately one minute per parameter, the transfer standard allows us to confirm the existence of a flat range for each ACJVS bias parameter at the level of a part in 10^6. If we perform these measurements for five minutes per bias parameter, we can confirm flatness at the level of a few parts in 10^7. The data in Fig. 3 were taken at the fastest data rate for which we were able to measure a flat spot for all 8 bias parameters, 8 Gbit/s. At that data rate, the peak sinewave amplitude synthesized by the ACJVS is 193 mV. We also performed these measurements at the maximum data rate for our system of 10 Gbit/s which produces an ac waveform with a 242 mV peak voltage (the same conditions as for the data in Fig. 2). However, at the higher data rate we were unable to find a completely flat region for all bias parameters. We would need to further improve the operating margins in order to fully utilize the ACJVS at this higher output level.

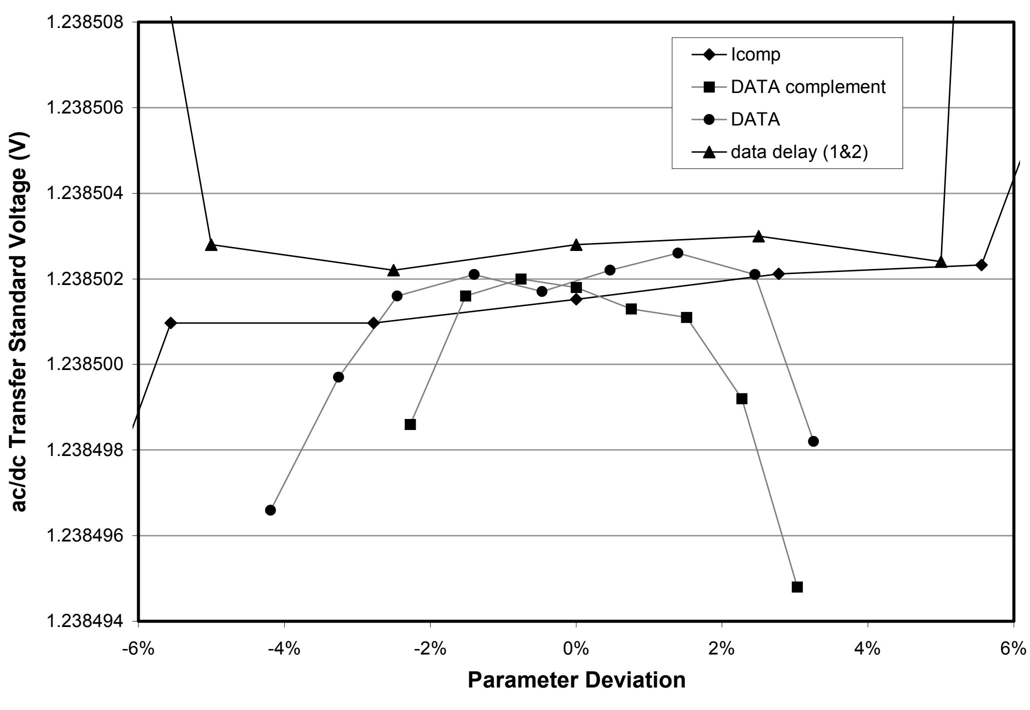

FIGURE 3. Plot showing the operating margins obtained at 8 Gbit/s using the ac/dc transfer standard and illustrating the "flat spots" for the 4 tightest parameters: amplitude (data), amplitude (data complement), data delay (both 1 & 2 moved together), and I_{comp}. One vertical division in this graph represents about 1.6 parts in 10^6.

The complete list of all 8 bias parameters, setpoints, and margins for the two-array configuration are shown in Table 1, which includes the data from Fig. 3. We define the "operating margin" to be the range over which each parameter was adjusted where the deviation in the ACJVS output measured by the ac/dc transfer standard was below the noise level (about a part in 10^6). Clearly the largest margins for the ACJVS are for the microwave powers. The smallest margin listed is the compensation phase since it is only ±0.2°, but this setpoint is actually just as easy to find and maintain as the others because it corresponds to an alignment in time of ±0.2 µs for the 2.8 kHz output waveform which is easily achievable. As the table suggests, the smallest margins are the amplitudes of data and data complement. Nevertheless, the stability and resolution of the data-generator outputs allow us to easily maintain those parameters within the required limits.

Table 1 – ACJVS Operating Margins at 8 Gbit/s for all 8 bias parameters.

Parameter	Setpoint	Margin
Amplitude (data)	1.07 V	±2.5%
Amplitude (data complement)	1.32 V	±1.5%
RF Power (sine)	-2 dBm	±17%
RF Power (sine complement)	-1 dBm	±13%
Data Delay (data)	-46 ps	±5%
Data Delay (data complement)	-46 ps	±5%
I_{comp}	8.8 mA	±5.5%
ϕ_{comp} (compensation phase)	0°	±0.2°

Conclusion

We have demonstrated that the ac Josephson voltage standard can produce audio sinewaves up to 242 mV (zero-to-peak) using a two-array configuration of 8200 junctions. We showed that this waveform (at 10 Gbit/s) has low -95 dBc harmonic distortion, but this low distortion level was insufficient to achieve a flat spot in the ACJVS output of a part in 10^6 over all parameters. At a 20% lower data rate, we were able to find a flat spot in the operating margins for all 8 different drive parameters, and using an ac/dc transfer standard we confirmed the ACJVS output flatness to be better than a part in 10^6.

These successful precision flat spot measurements were at a digital code data-rate of 8 Gbit/s with a corresponding microwave drive frequency of 12 GHz for a resulting ac sinewave output of 193 mV (zero-to-peak) at 2.8 kHz. The optimization techniques used to obtain these data demonstrate that the flatness measurements for the ACJVS could be automated, which will enable us to move toward a more user-friendly ACJVS system in the future.

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