Calibration of an AC Voltage Source Using a Josephson Arbitrary Waveform Synthesizer at 4 V

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***Abstract*—This paper describes a method for calibrating an ac source using a Josephson Arbitrary Waveform Synthesizer (JAWS) by summing the sources in series and tuning the magnitude and phase of the JAWS to null the combined output voltage. The method requires an ac source that can generate a signal that is phase-synchronous with the JAWS. As a demonstration of this method, we measure the output of a calibrator at an rms output of 4 V and a frequency of 1 kHz.**

***Index Terms*—Digital-analog conversion, Josephson junction arrays, measurement standards, signal synthesis, superconducting integrated circuits, voltage measurement.**

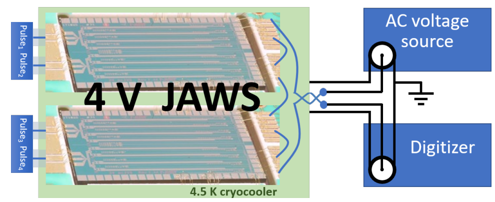

Fig. 1. Diagram of the JAWS source (low-frequency biases are not shown), an ac voltage source under test, and a digitizer used to determine the residual difference between the voltages generated by the JAWS and the source.

I. Introduction

AC voltage metrology is currently based on thermal transfer standards. These standards are broadband rms detectors that typically achieve better than 10 μV/V accuracy and 1 μV/V repeatability in determining the voltage generated by an ac source at voltages less than 10 V and frequencies less than 100 kHz [1]. However, rms detectors are inherently unable to provide information about the spectral purity and phase stability of a source; thus, the measured value incorporates the rms contribution of all input signals spread over the greater-than 10 MHz bandwidth of the detector.

We can improve on this approach based on thermal rms-detectors by directly comparing ac voltage source signals to quantum-based ac voltages generated by a Josephson Arbitrary Waveform Synthesizer (JAWS). A JAWS-based approach results in quantum-based calibrations that are directly linked to the revised SI, and offers a different paradigm of source-based, instead of detector-based, ac metrology. It could also lead to shorter calibration times and improved accuracy.

The basic measurement setup is effectively an ac bridge measurement, shown in Fig. 1. The JAWS source is in series with the output of the ac voltage source under test, and a high-impedance digitizer is used to measure the summed voltage. Since the JAWS is a floating voltage source, it is placed on the "high" side of the ac voltage source and digitizer. The "low" side of the ac voltage source and digitizer are grounded.

Using this setup, the magnitude and phase of the quantum-based JAWS source is tuned to null the voltage measured at the digitizer. Use of a null measurement reduces the importance of the digitizer calibration, and makes it significantly easier to measure small changes in the relative phase and magnitude over time. It is also crucial to confirm that the JAWS source is operating correctly during the measurement. There are two steps to this test. First, it is important to measure the full quantum-locked range (QLR) of the JAWS at the required output voltage magnitude and phase, that is, to confirm that the output of the JAWS source is independent of the JAWS bias parameters over a reasonable range of bias parameters. Second, mini-QLRs should be taken during the ac voltage comparison by making changes to the JAWS bias parameters, which are small enough that the changes are not expected to affect the JAWS output but large enough to observe problems [2].

II. AC Source Requirements

This null measurement approach requires that the ac source be able to operate in a phase-synchronous manner with the JAWS source. There are a number of different ways this requirement can be achieved. One approach is to have the JAWS and ac source share a fast clock signal, typically at 10 MHz, which ensures that the two instruments have synchronous waveforms. Then the two signals can be phase-synchronized by having one system provide a trigger signal at the beginning of a waveform period. Another approach is to force the ac voltage source to phase-lock to a signal provided by the JAWS system at the frequency of interest.

The key feature of both of these approaches, and the requirement for other phase-locking schemes, is that the magnitude and phase of the JAWS output voltage can be changed relative to the ac voltage source in a stable, repeatable manner.

III. Preliminary Results and Discussion

As a demonstration of this technique, we use a JAWS to measure a Fluke 5700A calibrator[1] generating an rms voltage

[1]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 is necessarily the best available for the purpose.

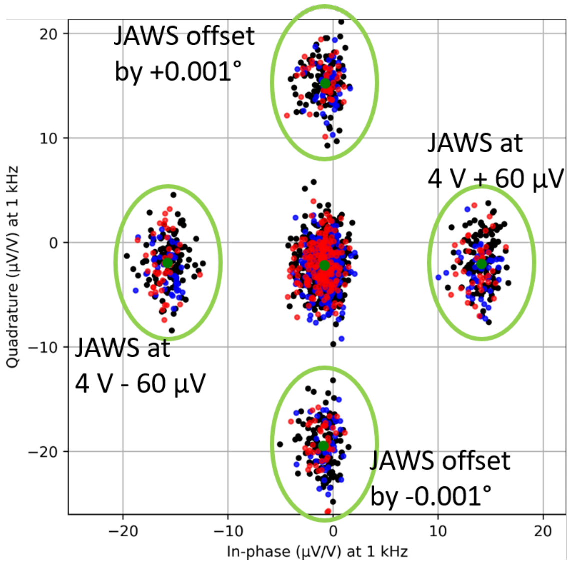

Fig. 2. Residual difference between the 1 kHz 4 V waveforms generated by the JAWS and a calibrator over 13 hours, plotted in the complex plane. The difference after optimizing the JAWS output is in the center (not circled). The JAWS output is also offset by $\pm 0.001°$ or ± 60 μV (labeled green circles). We also take mini-QLRs during the measurement: a JAWS DC bias current of 0 mA (black), +0.5 mA (blue) or -0.5 mA (red) is applied to test the JAWS operation.

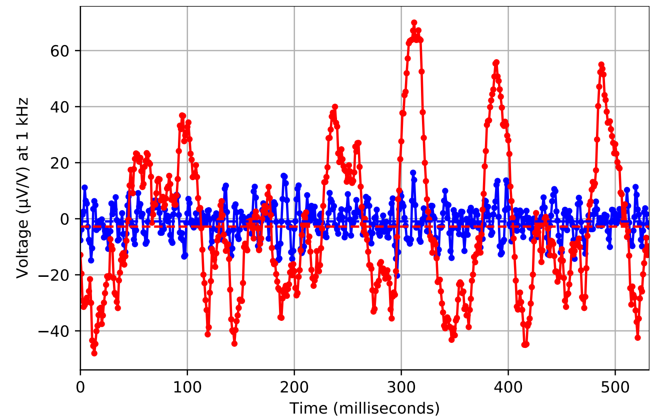

Fig. 3. Residual difference between the 1 kHz 4 V waveforms generated by the JAWS and calibrator plotted versus time. The short-term fluctuations in the quadrature component of the data (red, proportional to phase) are significantly larger than those in the in-phase component (blue, proportional to amplitude).

of 4 V at 1 kHz. To phase-lock the two systems, the JAWS source provides a stable, optically isolated, 1 kHz square wave to the "PHASE LOCK IN" port of the calibrator. The phase of the JAWS source is then tuned relative to this square wave, along with the magnitude of the JAWS source, to minimize the voltage measured at 1 kHz on a Zurich Instruments MFLI digitizer. After optimizing the JAWS source, the dc offset current QLR of the JAWS is greater than 1.4 mA with the calibrator generating 4 V and the JAWS generating 4 V in opposition at 1 kHz.

In Fig. 2, we show the results of this measurement over 13 hours. Each data point is the result of analyzing 0.5 s of data. The data are plotted in the complex plane, with small differences in phase along the quadrature/vertical axis and small differences in amplitude along the in-phase/horizontal axis. We also changed the JAWS output by $\pm 0.001°$and ± 60 μV to characterize the digitizer. Finally, we performed mini-QLRs by applying a dc bias offset of ± 0.5 mA to the JAWS arrays during some of the measurements. Since we did not observe any resolvable effects or trends due to these bias variations, we conclude that JAWS produced accurate voltages during the entire measurement. Using all of these data, we note that the calibrator produces a 4 V signal that is, on average, +0.8 μV/V or 3 μV larger than 4 V.

This technique can also be used to look at the short-term phase stability of ac voltage sources. In Fig. 3 we show the results of analyzing in finer detail the data that were used to create a single point in Fig. 2. In Fig. 3, we separately plot the in-phase and quadrature data as a function of time; each data point is taken from four periods of the 1 kHz waveform. We detect short-term changes in the relative phase of the systems which are both significantly larger than the amplitude changes and clearly resolvable over the system noise; similar phase jitter has been seen before [3].

These results demonstrate the important aspects of this measurement method. At CPEM 2020, we will provide more results and a more detailed uncertainty analysis for evaluating phase and amplitude stability of ac sources. We will also provide results of measurements taken over a wide range of amplitudes and frequencies.

A similar type of analysis can also be used to characterize distortion in ac signals by either directly using the higher frequency information gathered by the digitizer or by distorting the JAWS waveform to cancel the higher frequency content generated by the ac source. The first approach may require calibration of the digitizer, but digitizer non-linearity is less important because the fundamental tone is the predominate signal, and it has already been nulled by the JAWS signal in opposition. The second approach removes any dependence on the digitizer calibration, but requires that the distortion produced by the ac source be stable.

IV. Conclusion

We demonstrated that a quantum-based JAWS voltage source can be used to calibrate other ac voltage sources using a null measurement method where the magnitude and phase of the JAWS is tuned to cancel the other ac voltage source. In the future, this approach can also be used to investigate the short-term stability and distortion of ac voltage sources.

References

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