Method for Ensuring Accurate AC Waveforms with Programmable Josephson Voltage Standards

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***Abstract* — The amplitudes of stepwise-approximated sine waves generated by programmable Josephson voltage standards (PJVS) are not intrinsically accurate because the transitions between the quantized voltages depend on numerous conditions. We have developed a method that ensures that the total rms output voltage of arbitrary ac waveforms synthesized by the PJVS are accurate and referenced to the quantized Josephson voltages. This is accomplished by digitizing the entire output waveform, utilizing the quantum voltages to correct digitizer gain, noise, and nonlinearity, and then applying our understanding of the interplay between measurement bandwidth, risetime, and harmonic content to precisely tune the bias parameters. Our goal is to develop an AC standard source for voltage metrology that can directly synthesize voltages with the accuracy expected of a quantum-based standard without the use of a thermal voltage converter.**

***Index Terms* — Josephson arrays, digital-analog conversion, signal synthesis, standards, voltage measurement.**

I. Introduction

Since the introduction of series arrays of intrinsically shunted Josephson junctions in the mid 1990's [1], PJVS systems have been used to generate stepwise-approximated waveforms with the intent of bringing Josephson accuracy to the field of ac voltage metrology. Significant progress has been made for a number of ac metrology applications, most usefully with sampled comparisons [2]. Unfortunately, the inherent error in the output voltage caused by the transitions between the quantized voltages remains a fundamental and unsolved weakness after all these years. Consequently, thermal voltage converters (TVCs) remain the primary standards for ac voltage worldwide. Various measurement schemes have been investigated that utilize combinations of TVCs and stepwise PJVS synthesized waveforms working together. Nevertheless, TVCs are still the primary standards, because the PJVS waveforms do not provide the required accuracy without employing a TVC measurement.

PJVS-synthesized waveforms are fundamentally different from the harmonically pure tones produced by the ac Josephson voltage standard that is based on high-speed pulse-driven arrays, and are typically at frequencies above 1 kHz and have output voltages up to a few hundred millivolts. The main advantage of PJVS systems is their relatively high output amplitude (up to 10 V) based upon output waveforms that are constructed with quantized voltages from multiple Josephson-junction series arrays driven by a fixed microwave signal. This approach offers the promise of an accurate ac and dc voltage source for frequencies below a few kilohertz; but unfortunately, the PJVS stepwise-synthesis method has a critical limitation in that the output voltage is not precisely known during the transitions between the quantized voltages. More importantly, the generated rms voltage depends on the exact timing of the bias-current transitions, as we have previously described [3, 4]. The transition timing is affected by: (a) the precise shape of the voltage-current (*VI*) characteristic of each array, (b) the values chosen for bias-current setpoints, and (c) variations in the delivered bias currents from those target values. Any bias parameter that changes either the *VI* characteristics or the bias-current setpoints changes the transition timing (and to a lesser degree the transition shape), which significantly alters the rms voltage of the stepwise-approximated ac waveforms.

II. Systematic Error in PJVS Waveforms

Due to the dependence on transition-timing, the PJVS rms output voltage depends simultaneously on all of the following conditions: bias-current setpoints, microwave power, chip temperature (and dewar pressure), bias settling behavior, and interaction between bias signals and/or drive channels during transitions. For rms measurements, the PJVS should be considered an "adjustable" voltage source (not an intrinsically accurate ac standard), because it generates a relatively stable, nearly accurate waveform, but its stability and accuracy depend on many conditions. Thus, PJVS systems do not qualify as "intrinsic" ac voltage standards because they cannot produce rms amplitudes that are calculable only from the Josephson quantization.

II. Error Correction Scheme

In pursuit of accurate determination of the PJVS synthesized rms voltage without the use of a TVC, we have been optimizing the following procedure: (a) digitize the entire stepwise waveform with a sigma-delta analog-to-digital converter, (b) calibrate the sections of the fully settled steps based on the known quantized voltages to correct the gain and dc offset of the digitizer (and also remove any time-dependent drift in those quantities), (c) average thousands of waveform cycles to reduce measurement noise and correct small nonlinearities of the digitizer, and (d) account for effects due to the finite bandwidth of the digitizer.

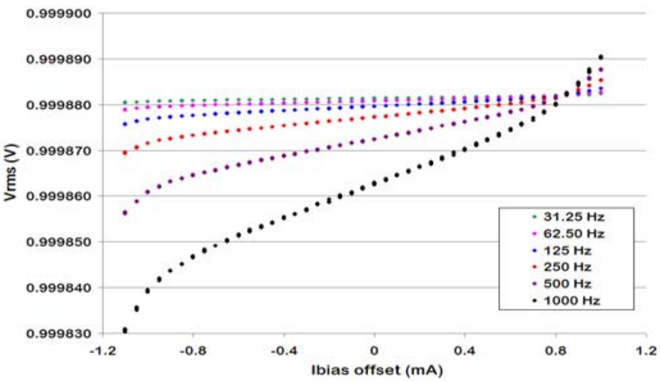

Fig. 1. PJVS rms voltage measured by a digitizer and corrected for noise, gain, and nonlinearity, but not measurement bandwidth (i.e., some of the waveform harmonics are outside the digitizer cutoff frequency).

All this data processing yields a value for the rms voltage of the PJVS waveform, but the analysis also requires careful evaluation of systematic errors in this complex measurement process. Fortunately, the PJVS has other characteristics that help reveal systematic errors in the digitization. Specifically, the transition timing shifts that make the ac PJVS output "adjustable" have a magnitude that scales directly with PJVS output frequency. For example, the rms voltage vs. bias current setpoint at 1 kHz will have a specific slope (due to the rise time of the bias electronics), and at 2 kHz (and 3 kHz) the measured slope will be exactly 2-times (and 3-times) higher.

Furthermore, since these curves at different frequencies have different slopes, the plots have to intersect each other somewhere, and as many PJVS researchers have observed [3-5], it often happens that the curves intersect around a common point over a significant range of PJVS output frequency, as shown in Fig. 1. Our new method utilizes our knowledge of the slopes and the nature of the intersections to derive further information about the PJVS rms voltage, and then to compare predicted behavior with measured data from the digitizer.

IV. Preliminary results

The traces in Fig. 1 show a relatively tight intersection point, but drawing conclusions from how closely the various frequency points land on top of each other can be misleading. In this case, we know that some of the harmonic content in the PJVS waveform is outside the digitizer bandwidth, and thus not included in the measured rms voltage. With our knowledge of digitizer behavior as a function of frequency (in the vicinity of the cutoff frequency) and the PJVS rise time and harmonic spectrum, we can apply a correction to the rms values that restores the rms contributions of the harmonics excluded by the digitizer. The result is shown in Fig. 2, where the intersection of the traces for different frequencies is again very tight, but occurs at a current bias "operating point" that is quite different from that in Fig. 1. By properly correcting the various non-idealities of the digitizer, and carefully considering harmonic content and bandwidth, we believe that we have a measurement method capable of producing accurate rms voltages within a few parts in 10^7 at 1 kHz. This will allow us to finally reach our objective of creating PJVS step-wise synthesized waveforms with calculable rms voltage without the use of either ac-dc transfer or a TVC reference.

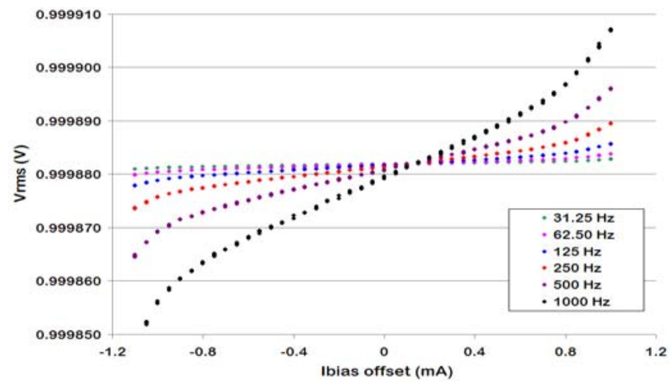

Fig. 2. PJVS rms voltage after full correction algorithm has been applied, including the final analysis that incorporates measurement bandwidth, rise time, and harmonic spectrum.

V. Conclusion

We describe a method for tuning a PJVS so that it can synthesize ac waveforms with precisely calculable and accurate rms voltage. The method corrects for systematic errors by exploiting measurements and information from a sampling analog-to-digital converter and the quantized Josephson voltages. Further research is required to determine a full uncertainty budget. We are hopeful that this method will enable the PJVS to be a practical AC standard source suitable for voltage metrology with accuracy of a part in 10^6 or better at audio frequencies.

References

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