Systematic Error Analysis of Stepwise-Approximated AC Waveforms Generated by Programmable Josephson Voltage Standards

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***Abstract*—We have measured stepwise-approximated sine waves generated by a programmable Josephson voltage standard (PJVS) with several different output configurations. These data are analyzed to characterize the dominant error mechanisms for RMS applications, such as ac–dc difference measurements of thermal voltage converters (TVCs). We present detailed explanations of the fundamental causes and consequences of systematic errors that arise from transitions and consider the overall uncertainties for PJVS ac metrology using this synthesis method. We show that timing-related errors are sufficient to make this waveform synthesis approach impractical for RMS audio-frequency applications. The implications of providing the load current required by devices of low input impedance, such as TVCs, are also discussed.**

***Index Terms*—Digital–analog conversion, Josephson arrays, Josephson voltage standard, signal synthesis, voltage measurement.**

I. Introduction

Since the introduction of series arrays of intrinsically shunted Josephson junctions in the mid-1990s [1]–[3], ac programmable Josephson voltage standards (ACPJVSs) have been used to generate stepwise-approximated waveforms for a number of ac metrology applications, including ac–dc difference measurements at frequencies of up to 1 kHz [4], [5], fast reversed dc (FRDC) measurements of thermal voltage converters (TVCs) [6], [7], and, more recently, impedance and power metrology [8]–[10]. The advantage that ACPJVS systems have over other sources in these applications is that the generated waveforms are constructed with quantum-accurate voltages from an intrinsic Josephson voltage standard. This approach offers the promise of a fundamentally accurate ac and dc voltage source for frequencies of below a few kilohertz and amplitudes of up to 10 V. These systems are quite different from the ac Josephson voltage standard based on high-speed pulse-driven arrays, which are primarily used at frequencies of above 1 kHz [11], [12].

The ACPJVS stepwise synthesis method has an important limitation, however, because the output voltage from the Josephson chip is not precisely known during the transitions between the quantized voltages. More importantly, the generated RMS voltage depends on the exact timing of the transitions, as we have recently described [13]. In this paper, which was presented at the Conference on Precision Electromagnetic Measurements 2008 with a brief summary in the proceedings [14], we explain in detail how the transition timing is affected by the following: 1) the precise shape of the Josephson voltage–current characteristic of each Josephson subarray; 2) the *chosen* values for the bias-current setpoints; and 3) any deviations in the *actual* bias currents from those target values.

In our previous investigations of PJVS transition behavior [13], we focused on errors caused by the finite transitions between quantized voltages for two frequency ranges for which we have applications of interest, i.e., 50–60 Hz for electrical power metrology and 1–10 kHz for TVC ac metrology. For 60-Hz frequencies, we advocated that the overall magnitude of the transition-related errors is sufficiently small to reach our desired uncertainties of a few parts in 10^7. However, we also demonstrated that it is essential to precisely model the behavior of every transition to achieve such uncertainties. In this paper, we present a more comprehensive understanding of the nature of the transitions and discuss the practical limitations for the ACPJVS stepwise ac synthesis method.

Before discussing the complex details of transition behavior, we briefly review why transition timing is important [13]. To precisely calculate the RMS voltage of an ac waveform at the chip output pads, we need to know the quantized Josephson voltages that compose the waveform (which are precisely calculable from the quantum behavior of the junctions) and the exact shape and precise position in time of every transition between those voltages. Unfortunately, the latter transition-timing behavior is not intrinsically defined but depends on the details of the bias electronics, bias transmission lines, and electrical characteristics of the Josephson arrays. To achieve the accuracy required for state-of-the-art metrology, these transition details must accurately be measured or modeled.

The transition rise time between the voltages for present ACPJVS systems is in the range of approximately 20–25 ns. The absolute position in time of each transition with respect to a trigger event at the start of the ACPJVS waveform cycle can be measured with a digital oscilloscope. For each of those time measurements, there will be an associated uncertainty Δt that directly translates into an uncertainty in the RMS amplitude.

Table I shows the calculated uncertainty in the RMS voltage for various amounts of this "timing error" Δt at three relevant

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TABLE I
CALCULATED UNCERTAINTIES OF STEPWISE-APPROXIMATED SINE WAVES FOR DIFFERENT TIMING ERRORS

Time Placement Accuracy Δt (of every transition)	Uncertainty (μV/V)		
	at 60 Hz	at 1 kHz	at 10 kHz
±2 ns	**±0.48**	**±8.0**	**±80**
±1 ns	±0.24	±4.0	±40
±500 ps	±0.12	±2.0	±20
±200 ps	±0.05	±0.8	±8

The timing errors are the upper and lower limits of the absolute placement in time of every transition. This result is independent of sample number for waveforms with more than 32 samples.

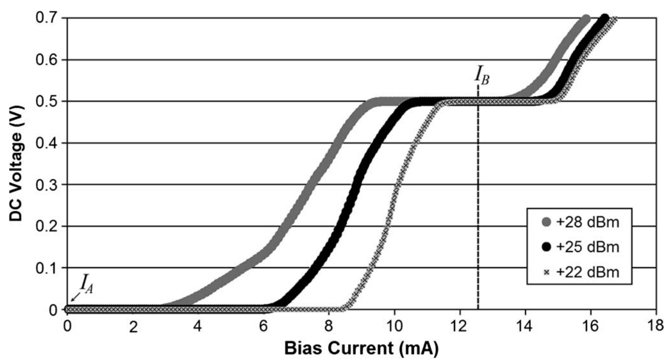

Fig. 1. Measured dc V–I characteristics at three different microwave powers for an individual ACPJVS subarray with 13 200 junctions. The range of current over which the output voltage is perfectly "flat" differs in each case, but bias points I_A and I_B are verifiably "on step" at each power and were used for the ac synthesis example that follows.

frequencies. These surprisingly large uncertainties are due *only* to time placement (not rise time). As will be explained in detail, achieving $\Delta t = \pm 2$ ns for *all* the transitions of a multilevel waveform will be quite challenging with currently available electronics. Fundamental changes in bias electronics and system design will be required to achieve timing errors of less than 1 ns. Table I shows the result of waveform simulation for various numbers of samples ranging from 16 to 512, which are calculated with column 1 as the upper and lower bounds for shifting transition time placement. Interestingly, the results in Table I are identical for waveforms with 32 samples or more so that synthesizing waveforms with more steps does not resolve this systematic error.

II. SINGLE-CELL TRANSITION BEHAVIOR

To quickly illustrate the importance of transition timing, consider the voltage–current (V–I) characteristics of a typical PJVS subarray (which is also referred to as a *cell*) with 13 200 junctions driven by an 18.3 GHz microwave frequency, as shown in Fig. 1. Each measured curve contains dc voltage steps (at precisely 0 and 0.499 505 89 V). For the three microwave powers shown, the subarray has overlapping but distinctly different ranges of current, over which the "0" and "1" step voltages are perfectly quantized. The step voltages are given by the Josephson equation $V = nf/K_{J-90}$, where n is the number of junctions, f is the applied microwave frequency, and K_{J-90} is the Josephson constant with a value of 483 597.9 GHz/V. For dc metrology, the current can be set to any value within step limits, and the PJVS will produce exactly the same output voltage for the different microwave powers. The reason dc PJVS systems qualify as "intrinsic" standards is there is a finite range for every bias parameter (bias current, microwave power, chip temperature, etc.) over which the output voltage is verifiably constant. For stepwise-synthesized ac waveforms, however, the RMS voltage is not intrinsically accurate, as will be demonstrated in the remainder of this paper.

First, we describe the behavior of this individual subarray for ac synthesis, starting with the simplest case of a square wave with two transitions. With bias points $I_A = 0$ mA for the "0" step and $I_B = +12.5$ mA for the "1" step, the bias electronics switches between the two states with a 50% duty cycle. The resulting time-dependent voltage waveforms, as shown in Fig. 2, are all slightly different because of the different V–I curve shapes for the different values of microwave power. Examination of the curves in Fig. 1 reveals the relationship between the V–I characteristics and the measured timing shifts in Fig. 2, which are on the order of ± 2 ns. As the microwave power is increased, the transition region between steps shifts to an overall lower current (i.e., the 0 step size becomes smaller, and the bottom corner of the 1 step moves lower). For transitions from "0 to 1," the voltage of the subarray will increase (through the transition region) *earlier* in relation to the trigger event, with the opposite transition from "1 to 0" occurring slightly *later*. Since the transition edges move in opposite directions as the microwave power is varied, the RMS voltage generated by the subarray has a direct (although not necessarily linear) dependence on microwave power.

Table II shows the impact of this dependence at various output frequencies for this simple example. The measured transition data of Fig. 2 have been extrapolated to lower frequencies, where it would be desirable to use the ACPJVS for stepwise ac synthesis. Bias currents I_A and I_B were verified to be "on step" in each case. The inferred RMS voltage varies with both square-wave frequency and microwave power, and differs by as little as 0.25 μV/V at 60 Hz and as much as 4 μV/V at 1 kHz. This systematic timing error (which, in this case, is caused by different microwave powers) prevents the usefulness of these RMS voltages for audio frequencies (above 1 kHz), because the variation is greater than 1 μV/V, even though the ± 2 ns timing shifts are relatively small (as observed in Fig. 2). Another worrisome discrepancy is that *none* of the ACPJVS voltages in Table II exactly match the "ideal" 0.353 204 00 V RMS voltage of an "ideal" square wave synthesized with quantized voltages for this subarray with zero rise-time transitions and exactly 50% duty cycle. Disagreement from the ideal RMS voltage is due to both the rise-time and timing errors of the transitions.

In this first example, we varied the microwave power to see the transition-timing effect. However, any bias parameter that changes either the V–I characteristics or the bias-current setpoints produces a similar systematic error. In fact, due to this dependence on transition timing, the ACPJVS ac output voltage simultaneously depends on *all* of the following: bias-current setpoints, microwave power, chip temperature (i.e., Dewar pressure), bias electronics settling behavior, interaction between drive channels during transitions, and cryoprobe wiring, bandwidth, and grounding. For RMS applications, the

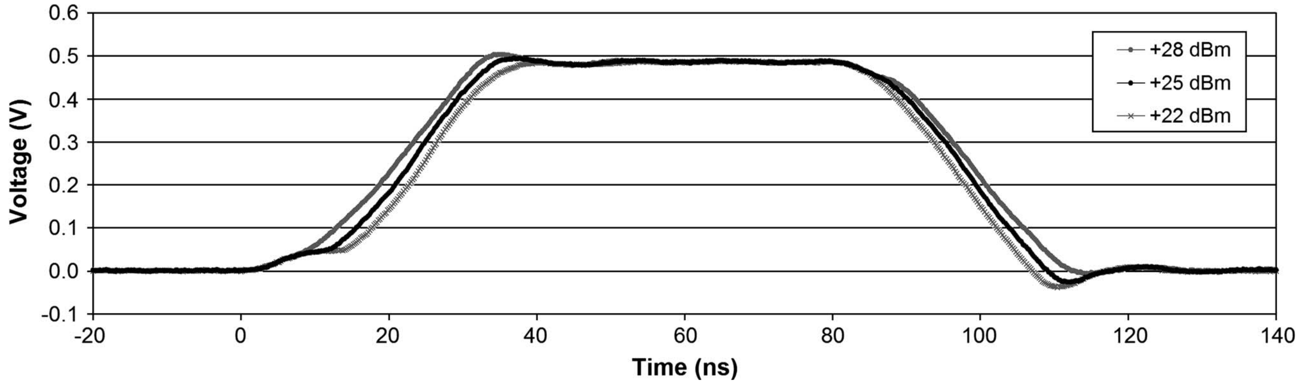

Fig. 2. Measured PJVS transition-edge timing for a 0.5-V zero-to-peak square wave from an individual subarray. Transitions begin at precisely 0 and 80 ns, and identical trigger conditions were used for all three traces. The quoted microwave power was applied at the cryoprobe input. For a given trace, the transitions move in opposite directions by approximately 2 ns each: moving away from (or toward) each other for higher (or lower) power.

TABLE II
UNIPOLAR SQUARE-WAVE RMS VOLTAGES VERSUS MICROWAVE POWER

Microwave Power	Voltage (V) at 60 Hz	Voltage (V) at 1 kHz	Voltage (V) at 10 kHz
+22 dBm	0.353 203 74	0.353 199 65	0.353 160 48
+25 dBm	0.353 203 83	0.353 201 06	0.353 174 61
+28 dBm	0.353 203 91	0.353 202 48	0.353 188 74
Variation	0.24 μV/V	4.0 μV/V	40 μV/V

Voltages were calculated from the measured transition data in Fig. 2 for the individual PJVS sub-array. Bottom row shows the voltage variation for each 3 dB change in microwave power (i.e., the difference from each row to the one below it).

ACPJVS should be considered an "*adjustable*" voltage source (not an *intrinsically* accurate ac standard), because it generates a relatively stable nearly accurate waveform, but that stability and accuracy depend on the details of the aforementioned parameters. When one of these parameters changes, the ACPJVS produces a slightly different RMS voltage. Reproducibility of the RMS voltage is determined by the reproducibility of each bias parameter. Thus, ACPJVS systems utilizing stepwise synthesis do not qualify as "intrinsic" voltage standards for ac metrology, because they cannot produce RMS amplitudes that are calculable only from the Josephson quantization. Their RMS voltages depend on the details of the transitions, which are affected by the entire system performance.

Uncertainties in the RMS voltage accuracy for audio frequencies will be reduced to below 1 μV/V only by directly accounting for the transient-induced systematic errors through careful characterization of the current–voltage characteristics and the timing of each subarray, which is difficult, because the dependencies are complex. Fig. 3(a) shows the "0" and "1" step heights for the same subarray in the previous example (cell 4 of a 3.9 V chip) over a range of microwave power. The subarray was programmed to generate a bipolar sequence of "0 1 0 -1" at 100 Hz. The RMS voltage, as shown in Fig. 3(b), was measured by an ac–dc transfer standard (Fluke 792A[1]). We chose the RMS voltage at $+26.5$ dBm microwave power

[1]Commercial instruments are identified in this paper to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology (NIST), nor does it imply that the equipment identified are necessarily the best available for the purpose.

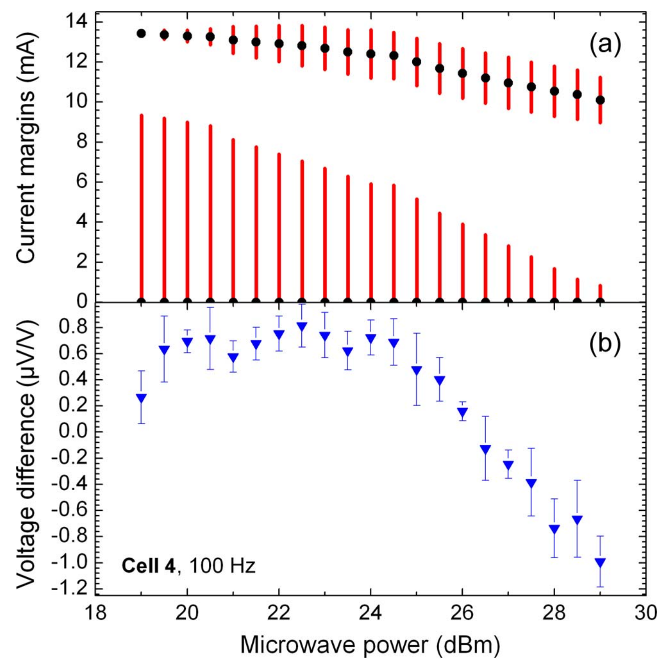

Fig. 3. (a) Measured current margins of the "0" and "1" constant voltage steps. (b) Corresponding RMS square-wave voltage measured by an ac–dc transfer standard, both as a function of the applied microwave power.

(the typical operating point for this chip) as a reference voltage for calculating the "relative" voltage difference and for interleaving with the other measurements to remove first-order drift (from the transfer standard and the DVM). At each microwave power, the dc voltages of the subarray were measured with a nanovoltmeter to center the bias currents at the center of each step's current range. Under these conditions, the $\pm 0.8\,\mu$V/V total variation in the output voltage is due to changes in the transitions. Note that this error would be ten times larger at 1 kHz.

A further complication for ACPJVS transition modeling is that the subarrays each have unique V–I characteristics due to differences in fabrication uniformity, number of junctions, and on-chip transmission line length, which affects microwave-power uniformity. The same measurements, as shown in Fig. 3, were also performed on two cells at various frequencies, and their dissimilar characteristics are shown in Fig. 4. Again, at

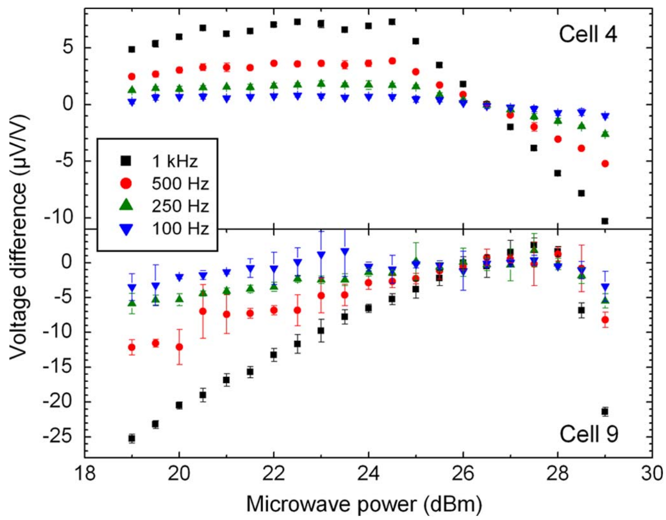

Fig. 4. RMS square-wave voltage at several frequencies for two subarrays (cell 4 with 13 200 junctions and cell 9 with 1944 junctions), as measured with an ac–dc transfer standard as a function of the applied microwave power.

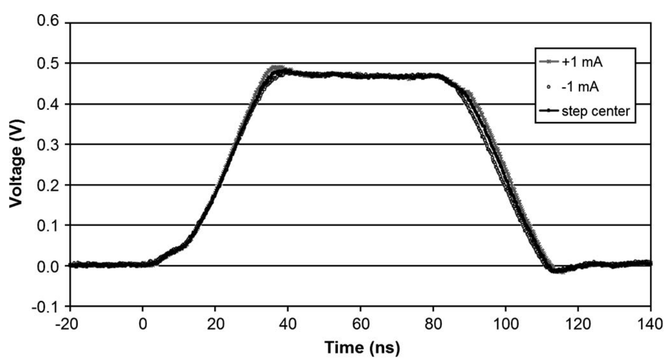

Fig. 5. Measured voltage versus time illustrating the shift in transition edges for an individual ACPJVS subarray. Moving the current setpoint on the positive step +1 mA speeds up the arrival time on the "1" step and, likewise, delays the departure time. Since the transitions move away from each other, the RMS voltage increases as the bias current is increased.

every power level, the bias currents were checked to ensure that the setpoints were properly "on step" so that the observed variations result from changes in the transitions and, in particular, the timing error.

Of course, microwave power is just one bias parameter that affects transition timing. Another parameter that is easily varied is the bias-current setpoint, which we investigated in detail in a recent paper [13]. For the voltage versus time traces shown in Fig. 5, the timing of the transition edges moves with varying setpoint current in a way that is similar to how it moves with varying microwave power in Fig. 2. This effect is most noticeable on the decreasing transition, where the transition begins later for the higher setpoint (+1 mA).

The data in Figs. 1 and 2, and Table II were measurements on an isolated subarray for which we physically disconnected the coaxial drive lines for all the other subarrays at the chip pads. This procedure ensured that we would observe proper correlation between the V–I curves in Fig. 1 and the voltage waveform in Fig. 2. However, in Figs. 3–6, we used the usual ACPJVS wiring configuration; thus, every cell was connected

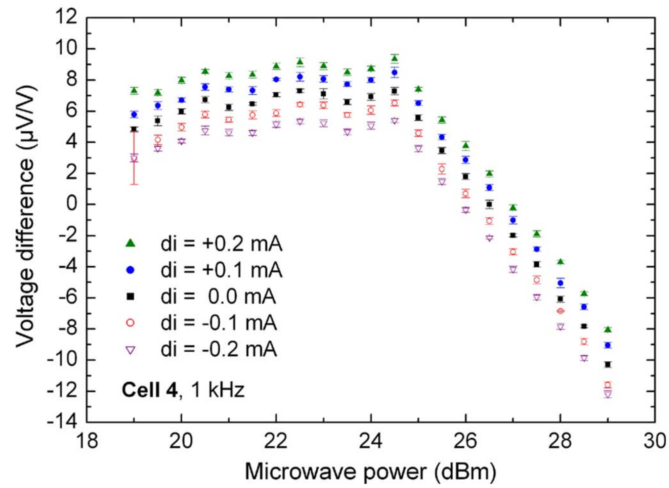

Fig. 6. Measured RMS voltage of a "0 +1 0 −1" waveform synthesized with a single subarray (13 200 junctions, with the same cell 4) and measured with an ac–dc transfer standard as a function of the applied microwave power for small (di) setpoint variations on the "1" step. All voltages are referenced to the voltage for +26.5-dBm power and $di = 0$ mA.

to its current driver through a coaxial bias cable. In these measurements, we programmed waveforms for only one subarray at a time (either cell 4 or cell 9), but all the other cells were active and programmed to remain in their "0" state. Interestingly, the RMS voltages of cell 4 *increased* with increasing microwave power when measured in the isolated configuration for Fig. 2 (as we would expect); however, with the entire Josephson array connected in Figs. 3, 4 and Fig. 6, the dependence shows the RMS voltage of cell 4 *decreasing* with increasing microwave power (from +24 to +29 dBm), because, in addition to cell 4's own behavior, we have a complex interaction with the other subarrays producing an entirely different net result.

Fig. 6 shows how the RMS voltage of cell 4 varies with both microwave power and bias setpoint (with all the subarrays actively connected), and we see at each microwave power that increasing di results in increased RMS voltage, which is consistent with our expectations and previous measured data [13]. These data emphasize the important point that modeling the transition behavior of the entire PJVS array is much more complicated than understanding the behavior of an isolated subarray.

III. PJVS Waveforms With Many Transitions

The various measurements presented above for single subarrays illustrate that the position in time of the transitions between quantized voltage steps depends on any parameter that affects either the V–I characteristics or the bias-current setpoints. This behavior has significant implications for the synthesis of multistep waveforms that use all 13 subarrays of the chip. An ACPJVS output waveform contains many transitions, each requiring changes in the bias current in some or all of the subarrays. Furthermore, there is significant interaction between the subarrays, because the voltage at the low end of each subarray is determined by the sum of the subarray voltages below it (common-mode effect). Furthermore, since the V–I

characteristics of every subarray are significantly different, their transitions may occur at different times.

As we just discussed, changing the microwave power changes the V–I characteristics of all the subarrays, and each changes in its unique way, which greatly complicates modeling. However, in our previous investigation of bias-current dependence [13], we found that the RMS voltage of an entire waveform depends on the bias-current setpoints in a more predictable manner. We found that even small bias-current changes on the order of tenths of a milliampere produce timing shifts of hundreds of picoseconds (in opposite directions) for the rising and falling waveform edges. Such shifts may seem insignificant, but as shown in Table I, they significantly impact the RMS voltage, particularly for frequencies of more than a few hundred hertz.

An interesting outcome of the detailed calculations summarized in Table I is that, for multilevel sine waves of 32 samples or more, the uncertainties resulting from a given shift applied to all the transition edges do not change as the number of samples increases. This phenomenon was experimentally encountered in previous work [13], where it was found that the transition timing shift due to varying the bias-current setpoint was basically identical for 64, 128, 512, 1024, and 2048 samples. We will not repeat the detailed explanation here, but the fundamental conclusion is that increasing the number of samples does not improve the transition-timing systematic error. The rising and falling waveform transitions move in opposite directions in response to changes in bias setpoint (and microwave power, etc.), and the resulting increase in RMS voltage due to these shifts is similar, regardless of the sample number. In fact, as we described in our previous paper that discussed harmonic content [9], increasing the number of samples to more than the number required to reduce RMS contributions from digitization harmonics serves only to decrease the time spent at quantized voltages, thus increasing the opportunity for systematic errors during transitions.

IV. PJVS Output Configurations

To determine whether the systematic errors related to transition timing differ, depending on how the ACPJVS chip is connected to room-temperature measurement devices, we briefly consider three different output configurations. The operational details of NIST PJVS systems have extensively been documented [15]–[17], so our descriptions here will focus on the circuitry external to the PJVS. The measurement configurations differ from each other in the magnitude of the error mechanisms affecting the voltage accuracy and the overall uncertainty. However, the method for evaluating potential errors is the same in each case: We vary each relevant system parameter and determine its effect on the output voltage (as in Figs. 2–6).

In the simplest "A" configuration, the PJVS output leads are directly connected to a high-impedance measurement instrument, such as the buffer amplifier of a TVC or digital voltmeter. This has the advantage that no significant current flows in the output leads, and there is negligible voltage drop due to the output lead resistance. The disadvantage is that the output is not properly terminated, so the measured voltages include some ringing (following each transition) that must be considered in the uncertainty analysis.

TABLE III
Measured RMS Output Voltage Versus Bias-Current Shift, With the Load Current Supplied With a Separate Source

Number of Samples	Measured change in rms voltage as a function of offset current [μV/(V·mA)]	Type B uncertainty contribution (μV/V)
>32	0.52 ±0.02	0.1
16	0.41 ±0.02	0.08
8	0.32 ±0.02	0.06
4	0.19 ±0.02	0.04

Measurements were of a 50 Hz stepwise-approximated PJVS sine wave with the offset current applied through all cells. The Type B component is calculated assuming a ±0.2 mA set-point accuracy (which is not the *entire* Type B uncertainty introduced by this systematic error). The load current was supplied with a synchronized commercial room-temperature source.

In an alternative "B" configuration, we connect the PJVS to an instrument with a relatively low input impedance (50–200 Ω) and provide the required load current with a synchronized commercial room-temperature source. This method allows the PJVS output to be terminated by its characteristic impedance with little ringing. However, this configuration is challenging, because the current-assisting source must set the voltage across the load to exactly match the PJVS voltage to ensure that minimal current (less than 1 μA) flows between the two sources. Otherwise, a voltage drop occurs across the output lead resistance, which results in a systematic error. It is difficult to ensure that this error will be less than a few parts in 10^7. This approach was used in the early days of PJVS synthesis for the FRDC measurements of TVCs.

Another configuration, i.e., "C," which we explored for the FRDC measurements, directly connects the PJVS output cable to a load, such as a 50 Ω TVC, and supplies the load current with the bias drivers at each end of the PJVS array. This technique has the advantage that the tolerance on the setpoint for the load current is easily met, given the large current margins of superconductor–normal–superconductor arrays. The penalty is that the reference plane is at the chip output pads, and the voltage drop across the output lead resistance is significant. Fortunately, this effect is both measurable and correctable for both ac and dc voltages.

In previous investigations of PJVS transitions [13], we used configuration A. We found that the RMS output voltage dependence on the bias-current setpoint shift in all cells was about 0.5 $\mu\mathrm{V}/(\mathrm{V} \cdot \mathrm{mA})$ for a stepwise-synthesized 50 Hz sine wave. For comparison, we recently investigated configuration B using a commercial waveform generator to provide the load current. This approach required that the source's amplitude and phase be closely matched to that of the PJVS signal. The results are summarized in Table III, where we show that, for sine waves with 32 or more samples, we measure the same 0.5 $\mu\mathrm{V}/(\mathrm{V} \cdot \mathrm{mA})$ dependence that was found for configuration A.

The identical voltage dependence on the bias-current setpoint occurs for configurations A and B because any small difference current, which results from differences between the two voltage sources, primarily flows through the Josephson array. The PJVS behaves like a short in comparison to the load and completely determines the time-dependent voltage and, therefore, the timing of each output transition (for 32 samples or more). Thus, the voltage-to-bias-current dependence of configuration B is exactly the same as that of configuration A (which does not have an assisting source). For samples fewer than 32, the difference current exceeds the current range of the Josephson step for longer times, which allows the current-assisting source to have more influence on the timing. Thus, for fewer samples, the current-assisting source reduces the bias-current dependence of the RMS voltage.

V. Conclusion

We have demonstrated that changes in bias parameters produce shifts in transition timing that significantly alter the RMS voltage of stepwise-approximated ACPJVS waveforms. We had hoped that the investigation of the various PJVS output configurations and better understanding of the dependence of transition timing on bias parameters would reveal a way to reduce these errors for ACPJVS stepwise synthesis. Unfortunately, present PJVS chips and existing bias electronics cannot execute the transitions between quantized voltages with sufficiently minimal transition times and accurate timing to reach desired uncertainties on the order of microvolts per Volt in the audio range. To reach this goal, ACPJVS systems will need to be completely redesigned to have faster jitter-free bias electronics and a completely different chip design that responds at least ten times faster (perhaps a multi-segment implementation of a pulse-driven Josephson voltage standard).

One might hope to improve the RMS accuracy of the existing ACPJVS technology by thorough detailed measurements of all subarray transitions and extensive modeling of the subarray response to all the bias parameters. However, such a Herculean effort to characterize the transitions will not reduce the timing uncertainties Δt shown in Table I; it will simply determine them more accurately. As described in the previous section, the use of assisting-current sources also does not resolve the timing errors. Such additions to the measurement circuit can have an impact on waveforms with fewer samples in measurements with load current requirements. However, such waveforms have significant harmonic content, which also unnecessarily complicates the RMS voltage, as compared with pure sine waves.

Considering all of these, we conclude that ACPJVS synthesis is currently practical for RMS measurements only for frequencies of below 100 Hz, where a total uncertainty of a few parts in 10^7 might be achievable. Thus, it is probably still useful for RMS measurements in electrical power applications. The greatest potential for present ACPJVS technology to impact ac metrology is through sampling techniques that have been shown to have equivalent or superior uncertainties over a much wider range of frequencies.

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