Development of a 60 Hz Power Standard Using SNS Programmable Josephson Voltage Standards

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***Abstract*—We are implementing a new standard for 60 Hz power measurements based on precision sinusoidal reference voltages from two independent programmable Josephson voltage standards (PJVS): one for voltage and one for current. The National Institute of Standards and Technology PJVS systems use series arrays of Josephson junctions to produce accurate quantum-based dc voltages. Using stepwise-approximation synthesis, the PJVS systems produce sinewaves with precisely calculable rms voltage and spectral content. We present measurements and calculations that elucidate the sources of error in the rms voltage that are intrinsic to the digital-synthesis technique and that are due to the finite rise times and transients that occur when switching between the discrete voltages. Our goal is to reduce all error sources and uncertainty contributions from the PJVS synthesized waveforms to a few parts in 10^7 so that the overall uncertainty in the ac-power standard is a few parts in 10^6.**

***Index Terms*—AC measurements, Josephson arrays, Josephson devices, Josephson voltage standard.**

I. Introduction

FOLLOWING the development of the series arrays of intrinsically shunted Josephson junctions in the mid-1990s [1]–[3], there has been considerable work demonstrating their use as programmable Josephson voltage standards (PJVS). In addition to being essential for producing accurate and stable dc voltages, they have also been applied to ac metrology through the generation of waveforms approximated with a staircase series of constant voltages of equal duration or samples. These devices are used to produce a variety of arbitrary waveforms and can be used for high-accuracy ac–dc difference measurements at frequencies up to 1 kHz [4], [5] and fast reversed-dc comparisons between Josephson sources and thermal voltage converters [6], [7]. These systems are quite different from the ac Josephson voltage standard based on high-speed pulse-driven arrays, which are used primarily at frequencies above 1 kHz [8], [9]. By applying quantum-based ac synthesis using PJVS arrays, we hope to improve one of the dominant sources of uncertainty in the 60 Hz power calibration, namely, the accuracy of the voltage and current sources. This paper also supports efforts at the National Institute of Standards and Technology (NIST) to implement quantum-based standards in as many applications of electrical metrology as possible. In this paper, we present measurements that demonstrate the feasibility of using the PJVS as a quantum-based stepwise sinewave generator for a new ac-power standard.

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II. System Configuration

The sinusoidal Josephson voltages in the new 60 Hz power standard will consist of two independent PJVS circuits, each with separate amplitude and phase controls. Fig. 1 illustrates one possible configuration of the system, where $V_{\mathrm{PJVS}-V}$ is a 1.2 V_{rms} reference sinewave for the voltage channel, and $V_{\mathrm{PJVS}-I}$ is a 0.5 V_{rms} reference sinewave for the current channel. A 100× amplifier scales $V_{\mathrm{PJVS}-V}$ up to 120 V_{rms}, which is applied to the power meter under test (MUT). This same 120 V signal is then divided down by a factor of 100 by an inductive voltage divider and then compared in real time with $V_{\mathrm{PJVS}-V}$ so that any gain drift in the 100× amplifier can either be calibrated or actively stabilized by servo feedback. For the MUT current channel, $V_{\mathrm{PJVS}-I}$ is fed to a $V-\mathrm{to}-I$ converter to generate a current on the order of 5 A_{rms}. A multistage current transformer, with a precisely known burden impedance, is used to measure this current so that gain drift, in the $V-\mathrm{to}-I$ conversion, can be measured and again either calibrated out or removed using feedback. The system diagram in Fig. 1 shows one of the many potential system configurations and illustrates the role of the Josephson arrays. The focus of this paper is to demonstrate the waveform-synthesis capability using programmable Josephson arrays, and we will address the system engineering issues of the final implementation (including precise phase alignment at the MUT inputs and potential digital-sampling techniques) in future publications.

The Josephson circuits for this NIST application are double-stacked $MoSi_2$-junction superconductor-normal-metal-superconductor (SNS) arrays containing 67 408 SNS junctions connected in series to produce a maximum ±2.5 V output voltage and divided according to a ternary weighting scheme [10]. The six least significant bits use a standard ternary configuration with a resolution of 612 μV (equivalent to the smallest array of 16 junctions biased at 18.5 GHz drive frequency), which enables the array to generate 8427 different

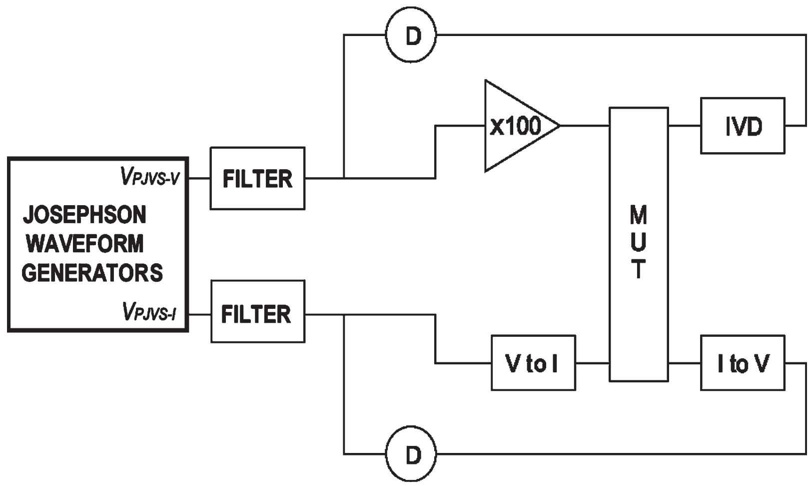

Fig. 1. Schematic of one possible implementation of the power standard with two Josephson reference voltage waveforms and other essential components. The symbol "D" denotes high-precision phase-sensitive detectors.

quantum-accurate output voltages. The sizes of the seven most significant bits (MSBs) are not a strict ternary implementation, but this enables the entire chip to have 2 mA current margins by not exceeding 8800 junctions in any array segment. Some MSBs have two, four, or eight junctions removed to improve the effective resolution to just two junctions (at less than 75% full-scale) by use of appropriate pairs of MSBs biased in opposition to each other. The chips are flex-mounted to ensure uniform microwave-power distribution and long-term cryopackage reliability [11]. The bias electronics we used were designed and constructed by the British National Physical Laboratory and have output drivers with a rise time of 5 ns [12].

III. Josephson Sinewave Measurements

The advantage of using Josephson voltage sources (instead of conventional semiconductor waveform synthesizers) for this 60 Hz power standard is that the samples have quantum accuracy. In a sinewave synthesized by use of the stepwise-approximation method, the harmonic content is reduced by increasing the number of samples. However, because the voltage is not precisely known during transitions between the quantum-accurate voltages, a large number of transitions decrease the fraction of time in the waveform, where the output voltage is precisely calculable. For this reason, optimizing the number of transitions requires finding the proper balance between high spectral purity and maximizing the precision of the rms voltage by spending sufficient time on each Josephson-quantized level.

Consider the case where the number of samples per cycle N equals 512. Fig. 2 shows the magnitude of the harmonics of up to 1 MHz (both measured and simulated) relative to the 60 Hz fundamental. The more prominent peaks are digitization harmonics that arise from the finite number of samples used in the stepwise-generated waveform, and the amplitudes of those harmonics decrease at higher frequencies, as shown. In our application, the first eight digitization harmonics are the most significant, and their effect on the rms voltage is summarized in Table I. Since we aim to produce a pure 60 Hz tone, we

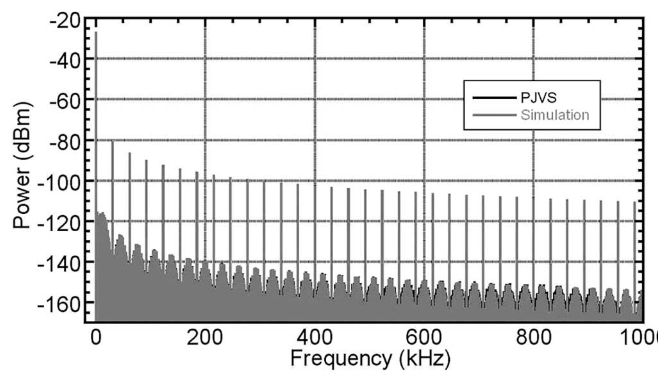

Fig. 2. Spectral measurement of a 512 sample 60 Hz sinewave generated by a Josephson array with 2.1 V amplitude zero-to-peak (1.5 V_{rms}). Measured harmonics from the Josephson array (black) is in excellent agreement with the numerical simulations (the gray simulation curve exactly covers the black measured data).

TABLE I
Calculated Values of the First Eight Digitization Harmonics for a Synthesized Sinewave at 60 Hz Using $N = 512$ Samples. The Last Column (the Error That Each Harmonic Would Individually Produce in the Total rms Voltage) Decreases Rapidly for Increasing Harmonic Number. These Values Are Consistent With Both the Measured FFT Spectra From the Josephson Array at 1.5 V_{rms} and Also FFT Simulation Analysis of the Ideal 60 Hz Josephson Waveform (Shown in Fig. 2)

Harmonic	Harmonic Number	Frequency (kHz)	Power (dBc)	Voltage (mVrms)	Error (μV/V)
N-1	511	30.66	-54.2	2.92	1.9
N+1	513	30.78	-54.2	2.92	1.9
2N-1	1023	61.38	-60.2	1.45	0.48
2N+1	1025	61.50	-60.2	1.45	0.48
3N-1	1535	92.10	-63.7	0.97	0.21
3N+1	1537	92.22	-63.7	0.97	0.21
4N-1	2047	122.82	-66.2	0.73	0.12
4N+1	2049	122.94	-66.2	0.73	0.12

refer to any harmonic that contributes more than one part in 10^7 to the rms voltage as an "error." Notice that there are pairs of digitization harmonics at 60 Hz $\cdot\, (m \cdot N \pm 1)$ for each integer multiple m of the number of samples. Another important

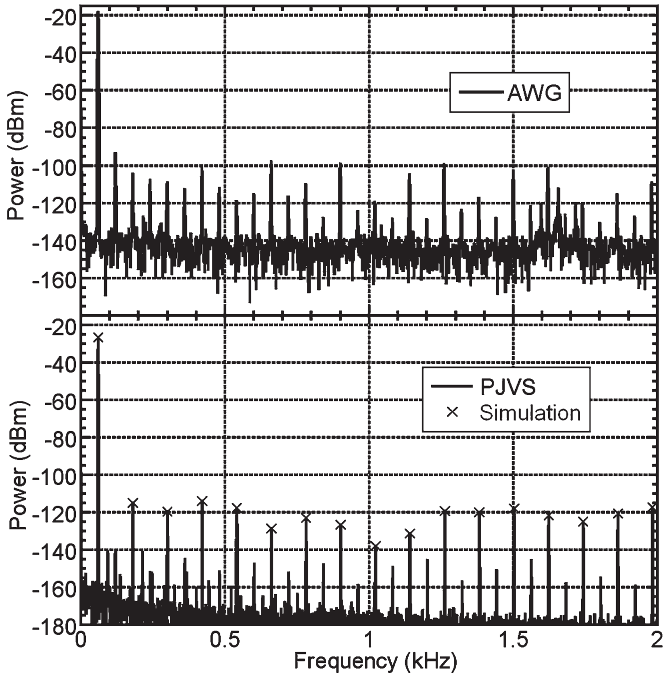

Fig. 3. Spectral content of a 512 sample sinewave at 60 Hz generated by a Josephson array with 2.1 V amplitude zero-to-peak (1.5 $V_{\rm rms}$). The PJVS measured spectrum (black, lower plot) shows excellent agreement with numerical simulations (gray). The upper plot shows the spectrum from a semiconductor AWG measured with the same digitizer and plotted on the same scale.

feature in Fig. 2 is the structure of all the other harmonics at integer multiples n of 60 Hz (from $n = 2$ to 16 667 on this scale). These harmonics represent waveform distortion caused by the specific voltage levels selected for the stepwise sinewave approximation. We examine these harmonics more closely in Fig. 3, where the 500× finer frequency scale shows how well the measured harmonics from the Josephson array agree with the calculated fast-Fourier-transform (FFT) harmonics for the exact voltage levels generated. The calculated values for odd-numbered harmonics are indicated with gray markers to illustrate how well they coincide with the corresponding tones of the measured spectrum. Since the odd harmonics are -90 dBc (decibels below the carrier) or less, their combined contribution to the rms voltage for all frequencies up to 1 MHz is still much less than one part in 10^7. Note that sufficient precision of the simulated voltages is required to accurately calculate these harmonics. We used nine significant digits in the simulation to represent the Josephson-output-voltage levels and found that the use of fewer significant digits (six or seven for example) introduced rounding errors that produced higher amplitudes (-80 dBc) for these harmonics.

Since the ideal waveform is perfectly symmetric positive to negative, the simulated FFT contains zero amplitude for all the even-numbered harmonics. Notice that in the measured spectrum, the even harmonics are approximately 20–30 dB lower than the adjacent odd tones and -110 dBc or less. These small and unexpected even harmonics may arise from a number of potential sources: measurement nonlinearity from the digitizer; small asymmetries in the PJVS synthesized waveform; or a combination of both effects. At such low amplitudes, however, they are insignificant with regard to the total rms voltage. In fact, until just recently, our best spectrum analyzers had noise floors above -100 dBc and were insufficient to resolve such small voltages.

More importantly, the ability to resolve these even harmonics with the high-resolution digitizer allows us to ensure that the PJVS circuit is synthesizing accurate waveforms. By observing the even harmonics while changing the bias parameters (microwave power and bias-current levels to the subarrays), we are able to verify that there is an operating range over which the PJVS output voltage is constant. Once the bias parameters move outside that range, the even harmonics increase dramatically because one (or more) of the voltage steps is no longer quantized.

Fig. 3(a) also shows a measured spectrum from a semiconductor-based commercial arbitrary-waveform generator (AWG) that was used to synthesize a 60 Hz stepwise-approximated sinewave with 512 samples. Notice that the AWG odd harmonics are roughly 20 dB higher than the Josephson array and the even harmonics are about 40 dB higher. These harmonics are large enough to produce a significant error in the rms voltage and illustrate the advantage of quantum-accurate waveform synthesis in terms of small harmonics near the fundamental, where filtering them would be difficult. Semiconductor sources have been optimized for this purpose [13], [14] and have better performance than our AWG, but their accuracy and reproducibility are not intrinsically guaranteed, as are the waveforms synthesized with PJVS-quantized voltages.

In this $N = 512$ example, the eight largest digitization harmonics cause the total rms voltage to be 5.4 μV/V higher than the fundamental amplitude (i.e., the square root of the sum of the squares of the 1.5 $V_{\rm rms}$ fundamental and the eight error values listed in Table I). This would be a significant measurable error for instruments with bandwidths greater than 100 kHz. The effects of these digitization harmonics can be managed in several ways, including 1) adding a carefully characterized low-pass filter to the SNS array output that attenuates these harmonics without appreciably changing the fundamental, thus taking advantage of the large gap in frequency between 60 Hz and the first digitization harmonic; 2) modifying the 100× amplifier and the $V-\mathrm{to}-I$ converter in Fig. 1 to perform this same low-pass operation; and 3) increasing the number of samples so that the digitization harmonics are at higher frequencies and lower amplitude and are thus easier or perhaps unnecessary to filter. The latter approach requires that transitions between quantum levels be more carefully characterized and/or directly measured, because the SNS arrays would be spending more time in transitions and less time on the perfectly quantized voltages.

IV. Filter Design

Actual implementation of a power standard utilizing stepwise-approximated sinewaves will most likely include filters on both PJVS outputs. The number of poles (and frequencies) in those filters will depend upon how we balance the errors associated with the number of samples and the fraction of time the arrays are on quantized-voltage levels. To select the proper filter cutoff frequency, consider Table II, which shows

TABLE II
FREQUENCIES AND ERROR CONTRIBUTION OF THE MOST SIGNIFICANT DIGITIZATION HARMONICS (THE FIRST PAIR) FOR A 60 Hz SINEWAVE WITH VARIOUS NUMBERS OF SAMPLES

Number of Samples	Freqs of the first pair of Digitization Harmonics (kHz)	Power at each of those freq (dBc)	Combined Error (μV/V)
256	15.30 and 15.42	-48.2	15.3
512	30.66 and 30.78	-54.2	3.8
1024	61.38 and 61.50	-60.2	0.95
2048	122.82 and 122.94	-66.2	0.24
4096	245.70 and 245.82	-72.2	0.06

the magnitude of the largest digitization harmonics (i.e., the first pair: $N - 1$ and $N + 1$) and their combined rms voltage error for different numbers of samples.

At $N = 2048$ samples, the error from the first pair of digitization harmonics is only 0.24 μV/V, even without any filtering. Decreasing N to 512 samples reduces the time of total transitions by a factor of four (reducing the total uncertainty due to transitions by the same factor) but requires a filter with a 3 dB point around 10 kHz to suppress the 5.4 μV/V total error from the first eight digitization harmonics. For $N = 256$ and below, the digitization harmonics are large enough that it would be difficult to filter them without negatively impacting the uncertainty at the fundamental. Clearly, to ensure that waveform digitization errors be less than 1 μV/V, we must choose $N \geq 512$, and if we hope to avoid using a filter, then $N \geq 2048$.

V. FINITE RISE TIME

In order to determine the maximum number of samples for the lowest uncertainty, we must understand precisely how finite rise time and switching transients impact the rms voltage. This is clearly a difficult but essential task for determining the absolute accuracy of the PJVS synthesized waveforms. In order to gain some insight regarding the impact of finite rise times on the rms voltage, both with respect to the amplitude of the fundamental and the harmonics within the measurement bandwidth, we calculated the resulting spectra of the 512-sample 1.5 V_{rms} waveform with the different effective rise times. For each rise time, we determined the rms voltage of the fundamental and also the total rms voltage within various bandwidths. We then determined the error associated with these harmonics relative to the amplitude of the fundamental for the fastest 3.2 ns rise time. The finite rise times were modeled with a linear transition between samples, which is an approximation that has shown by others [4], [12] to agree well with measured data in similar applications. We used 5 120 000 total sample points. Table III shows the calculated errors of harmonics at integer multiples of 60 Hz for different bandwidths, including the contribution of 1) the "smallest" harmonics up to the first two digitization harmonics; 2) all harmonics up to and including the first two digitization harmonics; and 3) all harmonics within a 1 MHz bandwidth. The total harmonic content above 1 MHz was less than 0.1 μV/V for all rise times; thus, the harmonic content up to 1 MHz is representative of the total rms voltage of each waveform.

TABLE III
CALCULATED ERROR IN THE rms VOLTAGE (i.e., DEVIATION FROM THE IDEAL DIGITIZED SINEWAVE) DUE TO ALL HARMONICS WITHIN THE SPECIFIED BANDWIDTH FOR DIFFERENT EFFECTIVE RISE TIMES FOR THE 1.5 V_{rms} 60 Hz SINEWAVE WITH 512 SAMPLES GENERATED BY THE PJVS

Rise Time (nsec)	Fundamental (n=1) (μV/V)	Smallest n ≤ 510 (μV/V)	First 2 Dig. n ≤ 513 (μV/V)	f ≤ 1 MHz n ≤ 16,666 (μV/V)
3.2	0.000000	0.0184	3.8331	6.1779
26	-0.000004	0.0184	3.8331	6.1776
104	-0.000064	0.0183	3.8329	6.1737
416	-0.001028	0.0173	3.8300	6.1158
1664	-0.016449	0.0019	3.7839	5.6518

The first column shows that the magnitude of the fundamental hardly changes with slower rise times. Even for the longest 1.66 μs rise time, which is 5% of the sample duration for each voltage, the fundamental amplitude decreases less than 0.02 μV/V. Although the changes to the fundamental are surprisingly small, significant changes occur to the higher harmonics. In effect, as the rise times increase, the higher harmonics decrease so that nearly all the harmonic content (and rms-voltage contribution) is more concentrated in the lowest harmonics. This is expected because the longer rise times cause the waveform to appear more like a continuous (nondiscretized) sinewave.

From these calculations, it would appear that the 5 ns rise time of our bias electronics is more than sufficient for guaranteeing an accurate rms voltage for a 60 Hz waveform. However, the idealized perfectly linear rise times used in our aforementioned calculations do not account for all the real imperfections exhibited in the experimental system, and thus, we certainly do not expect that rise times above a few hundred nanoseconds will be practically useful. Further calculations are required to determine whether other, more complex, nonideal transitions, such as transients, overshoot, randomly varying rise times, timing jitter, and other nonideal effects that would break waveform symmetry, will also have minimal impact on the fundamental amplitude or the total rms voltage. We expect similar behavior (but with smaller rms contribution from harmonics) for waveforms using a larger number of samples.

VI. CONCLUSION

We have discussed one approach to using PJVS circuits to construct a new standard for 60 Hz power measurements based on stepwise quantum-based synthesized sinusoidal waveforms. We have shown that knowledge of the harmonics over the full-measurement bandwidth is critical for the successful implementation of the PJVS synthesizer. With optimized filter design and appropriately synthesized waveforms, this system should be able to generate reference sinewaves with suitably low errors due to undesirable harmonics from the digital-to-analog synthesis. Future work will include additional detailed analysis of the transitions for waveforms with more than 512 samples in order to determine how to provide the lowest total uncertainty at the 60 Hz fundamental.

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