Synthesizing Accurate Voltages with Superconducting Quantum-Based Standards

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Over the past three decades, the quantum behavior of superconducting Josephson junctions has been exploited to dramatically improve the accuracy of dc voltage measurements. Within the past couple of years, new superconducting devices, circuits, systems and measurement techniques have been developed that have begun to impact ac voltage applications. This article reviews the capabilities and measurement techniques of three unique quantum-based systems and summarizes their use as accurate dc and ac references for voltage and power metrology and as low-distortion arbitrary-waveform sources for the characterization of stability and nonlinearities in analog and digital electronics.

Quantum-based and Artifact Standards

The quantum Hall and Josephson effects revolutionized electrical metrology by enabling resistance and voltage to be reproduced and accurately measured in any laboratory. Every system based on one of these quantum effects produces exactly the same resistance or voltage as every other system. Prior to the development of the Josephson voltage standard (JVS), artifact voltage standards high-performance electrochemical batteries called Weston cells were used to maintain the standard unit of voltage at national measurement institutes (NMIs). Although the cells served the metrology community very well, their voltages drifted with time and environmental conditions, which resulted in different voltage realizations in different NMIs. The use of *single Josephson junctions* as JVS voltage references at a few millivolts allowed the voltage variations between labs to be quantified without the uncertainty associated with transporting artifact standards [1], [2]. In 1984, a number of developments came together that allowed series arrays of junctions to produce output voltages up to 1 V. Improvements in superconducting integrated circuit fabrication technology led in 1987 to the first conventional JVS arrays capable of producing 10 V. As a result of these higher output voltages from arrays, the agreement of dc voltage measurements between laboratories increased by four orders of magnitude [1], [2]. Figure 1 shows the timeline of development.

Josephson Devices Development

The conventional JVS with output voltages up to 10 V is now used worldwide by standards laboratories and NMIs to realize dc voltage with quantum accuracy, but a number of essential innovations were required to achieve this relatively large 10 V quantum-accurate voltage. The primary innovation was the discovery of a bias scheme that produced perfectly quantized voltages in thousands of junctions without the need to individually bias each junction, namely, the use of metastable steps at zero dc bias current. Other important innovations were:

- a circuit design that distributed power uniformly to all junctions in multiple arrays,
- understanding the junction and the materials properties that could produce metastable steps [3], and
- the development of refractory materials compatible with microfabrication and thin-film deposition techniques.

A Josephson junction is a weak link between two superconductors that can produce a series of accurate voltages, $V_n = n(h/2e)f$, or “steps” in response to an applied microwave frequency f, where the proportionality constant is Planck’s constant, h, divided by twice the charge of the electron, e. Since junctions are typically biased at (15 to 70) GHz frequencies, a single junction can produce only very small, (30 to 150) µV, step voltages. Series arrays of junctions are therefore required to increase the voltage to practical values of (1 to 10) V. Because the junction response is a quantum effect, all the junctions produce precisely the same voltage with the same applied frequency. However, the performance of a series array, namely the maximum current range of the combined step voltage, depends on variations in the electrical characteristics of each junction as well as the applied microwave power. The electrical characteristics of junctions are determined by their materials and their dimensions, particularly those of the normal-metal or insulating barrier that forms the weak link. Significant improvements to the junction fabrication process, the use of new materials, and improvements to the microwave design all contributed to increasing the junction and step uniformity, enabling the first 10 V JVS circuits to be realized in 1987 [1], [2].

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DC Voltage Applications

Conventional JVS circuits are typically microwave biased at frequencies near 70 GHz and have about 20,000 junctions. Because the current ranges of the zero-crossing steps are typically only ~20 μA (Fig. 2), the input and output leads are highly filtered to reduce the effects of noise on the measurement. Computer control of the bias voltage and impedance allows the selection of any one of the ~65,000 steps between 0 V and 10 V. Conventional JVS systems are routinely used to calibrate Zener voltage standards and digital voltmeters with accuracies of parts in 10^7. They are also used to make intercomparisons between JVS systems at different NMIs with agreement to parts in 10^{10}. A disadvantage of conventional JVS systems is the relatively long time (~100 ms) required to select a step and the tendency to spontaneously jump between steps. This is not a problem for Zener and DVM calibrations as the step voltages remain quantized and software can detect and correct for step transitions.

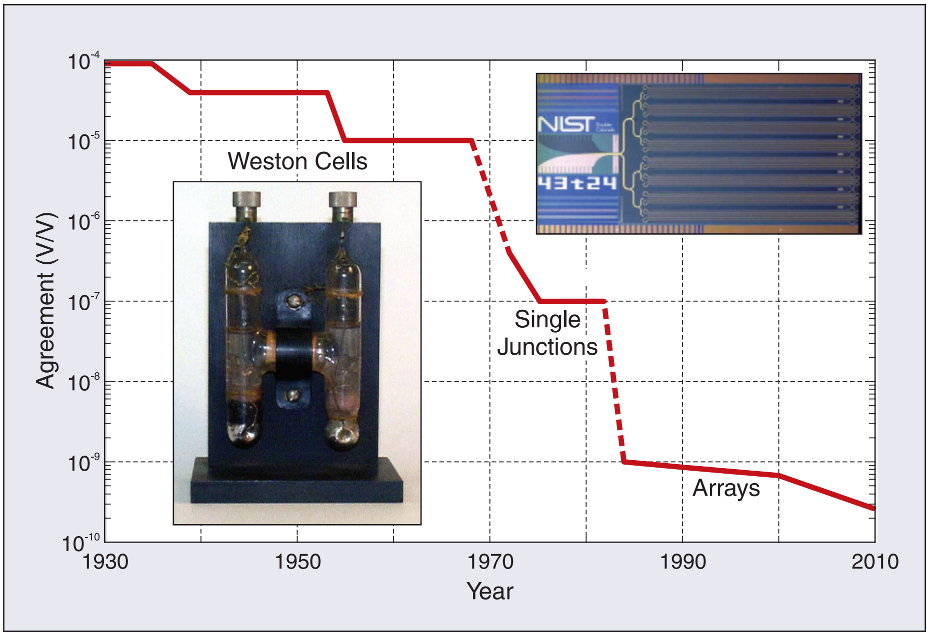

Fig. 1. Agreement in voltage measurements between national metrology laboratories vs. time showing four orders of magnitude improvement as the quantum voltage increased from millivolts for single junctions to 10 V for conventional JVS arrays. Insets show an electrochemical Weston cell and a conventional JVS superconducting integrated circuit (1 cm x 2 cm). Credit: chip photo by C. J. Burroughs, 1992.

To obtain the features of intrinsically stable and rapidly programmable dc voltages, the programmable JVS (PJVS) was developed. In the mid-1990s, improvements in fabrication processing and the development of a new junction technology and microwave design allowed arrays of junctions to be made with intrinsically stable steps. The superior junction uniformity allowed arrays with large numbers of junctions to be biased with a common dc current source. The PJVS circuit design produces programmable voltages by dividing all the series-connected junctions into either a binary or ternary configuration of sub-arrays [2]. The total voltage of the circuit is programmed by current biasing the different sub-arrays to one of their three lowest junction voltage states, $n = -1, 0,$ or $+1$. The disadvantage of PJVS circuits is that they operate on the lowest $|n|$ voltage states, which requires three- or four-fold more junctions than the conventional JVS. Even more junctions are required when junctions with normal metal barriers are used, because their electrical characteristics operate best at three-fold lower frequency, around (15-20) GHz. Junctions with more complex insulator-normal metal-insulator barriers operate at 70 GHz and require fewer junctions to achieve the same output voltage, but they have low fabrication yield.

PJVS systems with 1 V output voltage and around 30,000 junctions have been available since 1997. Their ability to produce stable accurate voltages is important in precision measurement applications, such as the watt-balance determination of h. A few NMIs have integrated PJVS systems into their voltage calibration chains. Their rapid programmability has been used to determine the linearity of high-resolution voltmeters.

However, PJVS systems are not as widely used and have not replaced conventional JVS systems because there are very few fully functional PJVS circuits that operate at 10 V. The first 10 V PJVS was demonstrated in 2000. Because they require 10-times more junctions than 1V PJVS circuits, 10 V PJVS circuits are far more difficult to yield in fabrication. In the past few years, a new metal-silicide barrier technology, which dramatically improves junction fabrication yield, has enabled fully functional 10 V PJVS circuits for designs that operate at either 18 GHz (Fig. 3) or 70 GHz drive frequencies. PJVS circuits with this new junction technology have the potential to replace conventional JVS systems and finally offer stable and programmable quantum accuracy at 10 V to all NMIs [4].

AC Voltage Applications

Thermal voltage converters (TVC) and thermal transfer standards are the primary means of ac voltage calibration at NMIs. A TVC compares the rms voltage of a sine wave with a dc voltage, and the resulting difference in the rms signals is less sensitive to environmental conditions than the individual voltage measurements. The lowest calibration uncertainty, about 1 μV/V, is in the audio frequency range at a few volts, as Figure 2 illustrates. These are the uncertainties provided by the NIST ac-dc calibration service for voltage. The uncertainties increase for higher and lower values of both frequency and voltage parameters.

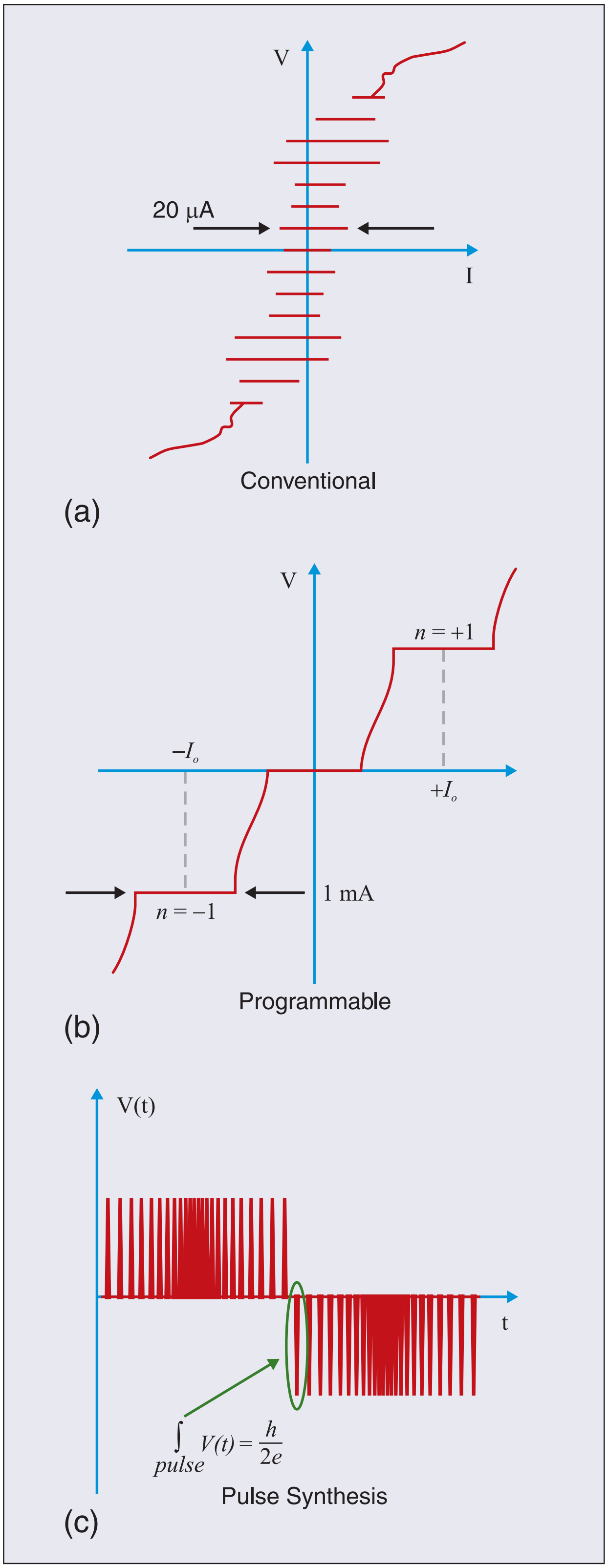

Fig. 2. Typical electrical characteristics for three types of JVS systems: Conventional JVS has metastable zero-crossing steps with typical voltage interval of 150 μV (72 GHz). Programmable JVS has intrinsically stable steps with typical voltage interval of 31 μV (15 GHz). Pulse-driven Josephson arbitrary waveform synthesizer is driven by 30 ps-wide pulses generating perfectly quantized voltage pulses based on a digital pulse-pattern sequence for a sine wave.

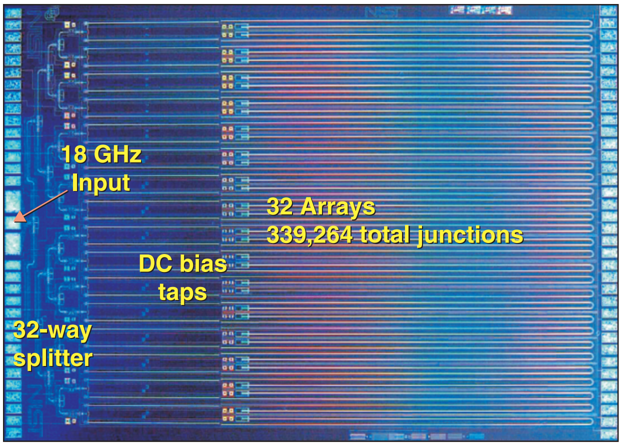

Fig. 3. NIST 10 V PJVS chip (12 mm x 17 mm) of 339,264 total triple-stacked junctions divided into 32 arrays. Credit: photo by P.D. Dresselhaus, 2008.

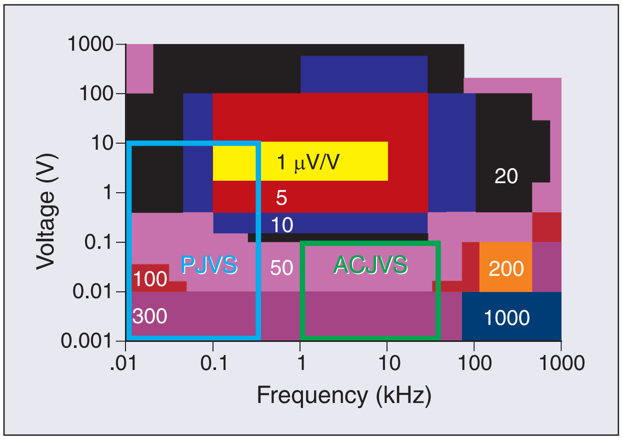

Fig. 4. Voltage vs. frequency plot showing the uncertainty boundaries (in units of μV/V) for ac voltage calibrations at NIST (courtesy of T. Lipe and J. Kinard, NIST). Blue and green boxes indicate regions impacted by the PJVS and ACJVS quantum-based voltage sources.

The programmable JVS circuit was originally intended for ac voltage applications. In particular, the goal was to extend quantum-accurate voltage calibration to TVCs. In the early 1990s, current drives needed to switch the voltage levels were limited to about a 300 ns risetime. This limitation in switching speed between the voltage levels resulted in an impractically large uncertainty in the rms voltage, which prevented the widespread application of the programmable JVS circuit. Faster switching components are now available, which has led to renewed interest in rms measurements with PJVS systems. Extensive investigations have shown that variations in all the bias parameters, including dc bias currents and microwave power, will affect the rms voltage accuracy. These effects make it difficult to achieve uncertainties less than 1 μV/V for frequencies at and above 60 Hz.

With the PJVS system, ac voltage measurements of lowest uncertainty are achieved by use of a differential sampling method [5]. In this approach, typically using a time-integrating sampler, the step-wise approximated sine wave synthesized by the PJVS is subtracted from the sine wave to be calibrated, and the resulting small difference voltage is sampled with twice as many samples as the number of quantum voltage levels, as Figure 5 shows. By discarding the integrations that occur during the PJVS voltage transitions and using only those containing the quantized voltage (grey bars), the measurement uncertainty can be a few parts in 10^8 for frequencies below 100 Hz, with sufficient integration time and a stable voltage source. Although this differential sampling approach is also limited to a few hundred hertz, due to the sampling speed limitations, it has proven particularly useful for calibration of signals relevant to the power industry for frequencies at 50 Hz and 60 Hz. In 2007, NIST completed a new ac power standard, called the Quantum Watt, which includes a 2.5 V PJVS system and exploits the differential sampling technique for calibrating both the voltage and current signals [6]. The system also includes a novel voltage amplifier and a stable waveform synthesizer to complete the system. This system can achieve a residual uncertainty of 2 μW/VA (k = 1) at 60 Hz. The blue rectangle in Figure 4 shows the present region of impact for voltage measurements with PJVS systems.

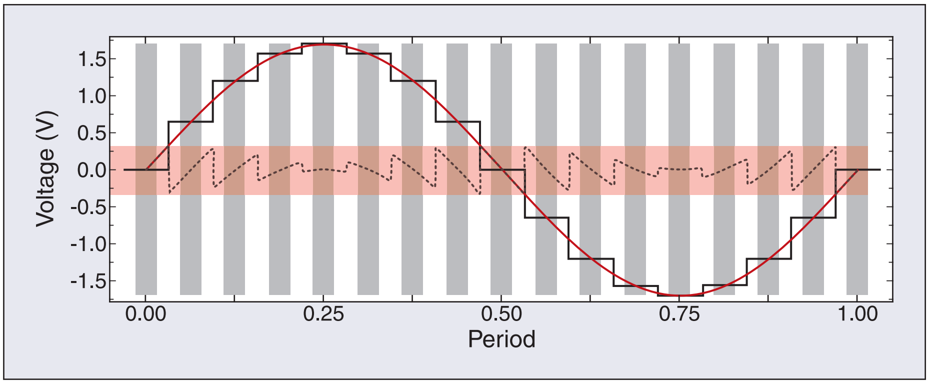

Fig. 5. Waveforms produced in a PJVS differential sampling measurement. Difference voltage (dotted) from the PJVS step-wise waveform (solid black) and the sine wave under test (red). Grey bars show the "on-step" sampled regions, while the inverse white sampled regions are discarded (© *2009 IEEE, IEEE Trans. Inst. Meas.*, used with permission) [5].

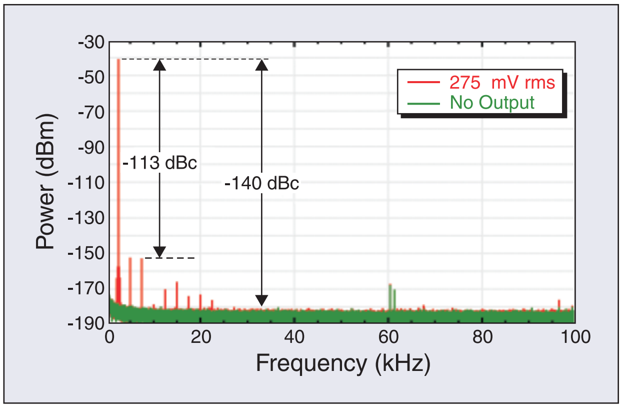

Fig. 6. Digitally sampled spectral measurement of a 275 mV, 2.5 kHz ACJVS sine wave. The digitizer used 1 MΩ input impedance, 10 V input range, 2 Hz resolution bandwidth, 10 averages, and a 500 kS/s sampling rate. Green shaded data show the digitizer noise floor and spurious signals with the ACJVS pulses off. The –113 dBc measured distortion is produced by the digitizer's nonlinearities.

Waveform Synthesis with Quantum Accuracy

Step-wise approximated sine waves, such as those that can be generated with the PJVS system, do not have intrinsically accurate ac voltages and inherently contain harmonic tones related to the number of samples. Fortunately, a third voltage standard system exists that can synthesize pure tones with quantum accuracy and with unprecedented low in-band harmonic content. This system goes by many names, including the pulse-driven Josephson digital-to-analog converter, the ACJVS, and the Josephson arbitrary waveform synthesizer (JAWS). The ACJVS operates on a bias technique completely different from that of the previous two systems, because it is driven with high-speed pulses instead of a continuous wave at a single frequency. There are a number of different pulse-bias approaches, using either two-level or three-level pulse-pattern generators, that allow the junctions to produce voltage pulses of both polarities, which is a requirement for generating bipolar arbitrary voltage waveforms (Fig. 2). Instead of voltage steps that are perfectly quantized and proportional to the bias frequency, the junctions in the ACJVS system produce perfectly quantized voltage pulses whose time-integrated areas are precisely $h/2e$.

Arbitrary waveforms, including sine waves, can be synthesized by choosing an appropriate digital data stream that determines the timing and polarity of the pulses. The pulse-patterns are created by use of a delta-sigma modulation algorithm of either first- or second-order and a low-pass noise-transfer function filter [2]. With a typical sampling frequency of 10 GHz, most of the digitization harmonics (or quantization harmonics from the digitization process, not the Josephson quantization) are pushed to frequencies well above 10 MHz and far above typical measurement bandwidths. The main advantages of this ACJVS system are the intrinsic accuracy, stability, and signal purity (no distortion) of the synthesized voltages. The quantum accuracy of the waveform is guaranteed, provided that every junction produces exactly one quantized voltage pulse for every bias pulse of the pattern generator. Circuits containing two Josephson junction arrays have been made that have synthesized pure single tones with maximum rms voltage of 275 mV (Fig. 6). Higher voltages have not yet been produced because synchronizing multiple pulse-pattern generators is challenging. Synthesized ACJVS sine waves have been used to characterize the low-voltage ranges of thermal transfer standards.

One of the challenges with this system is accurately transmitting the ACJVS signals from the superconducting circuit at the bottom of a liquid helium Dewar to the instrument under test. The transmission line to the measurement device,

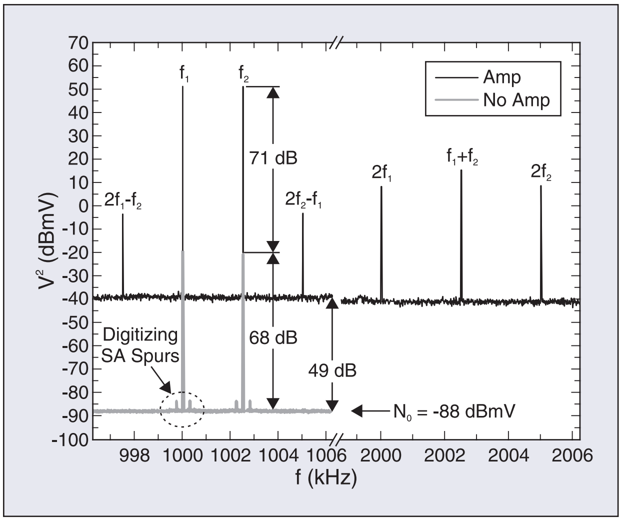

Fig. 7. Two-tone signals from ACJVS source (grey) reveal an amplifier's distortion products (black). The -88 dBmV noise floor is determined by the noise of the digitizing spectrum analyzer. The -39 dBmV noise floor is that of the amplifier. Units of dBmV are used because our voltage amplifier has input impedance much greater than 50 Ω (© 2009 IEEE, Trans. Appl. Supercond., used with permission) [9].

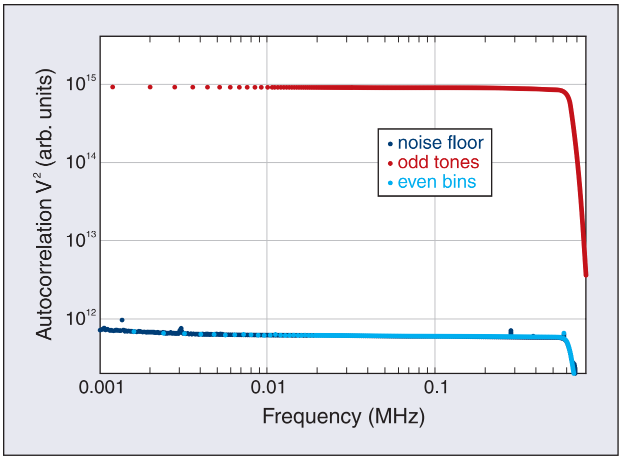

Fig. 8. Measured spectrum of the Johnson noise thermometer amplifier chain with QVNS-synthesized comb of odd harmonic tones showing 600 kHz cutoff of low-pass filters and no distortion products in even frequency bins.

as well as its impedance, will affect the measured voltage, especially at frequencies above 20 kHz. If the measurement bandwidth of an rms detector is larger than 10 MHz, then the harmonic signals produced by the digitization process may contribute to the measured voltage. If a filter is used to remove these signals, as is typically the case, then the filter transfer function must be characterized.

The present region of impact for the ACJVS system is for frequencies up to 20 kHz and rms voltages below 275 mV, represented by the green rectangle in Figure 4. NIST has integrated the ACJVS into its ac voltage calibration service at frequencies below 20 kHz [7], and NRC in Canada and VSL in the Netherlands are in the process of making ACJVS measurements. The uncertainties in calibrating transfer standards are limited by the stability of the transfer standard, especially that of the dc signals, although they are typically better than a part in 10^6 at a few kilohertz. The ACJVS systems are being used by these NMIs to reduce their calibration uncertainties for the applicable voltages by at least an order of magnitude and even more for the lowest voltages. Once pulse-pattern generators are developed that have eight channels and a pattern memory of at least 10 Gb, the useful rms voltage range of the ACJVS system should reach 1 V, and the low frequency limit should decrease to below 50 Hz [8]. Increasing the accuracy of voltage measurements to frequencies above 50 kHz will require careful characterization of the transmission line and measurement circuit as well as the minimization and characterization of parasitic signals with the ACJVS system.

Low-distortion Arbitrary Waveform Synthesis

An interesting application of quantum-based waveform synthesis with the ACJVS system is the characterization of linearities and amplitude-frequency response of both analog and digital components and instruments. The ACJVS system can produce intrinsically accurate, stable, and low-distortion single and multitone waveforms [2], [9]. If one wishes to determine the voltage and frequency response of an amplifier or analog-to-digital converter (ADC), it is necessary to have a signal source that is programmable in both voltage and frequency and, more importantly, has lower distortion characteristics than those of the device under test. The ACJVS waveform harmonic content is determined entirely by the digital pattern, which in turn is determined by the parameters used in the digitization algorithm. For a second-order modulation algorithm sampling at 10 GHz, the amplitudes of all the harmonic signals below 1 MHz are usually far below the measureable noise floor and at least 100 dB below the amplitude of the fundamental "carrier" tone (-100 dBc).

We have used the ACJVS to demonstrate the low distortion produced by a commercial sampling ADC with the largest harmonic distortion signals being -113 dBc. (See Fig. 6.) Figure 7 shows the harmonic distortion and second- and third-order intermodulation products produced by a high-gain amplifier that is driven by a two-tone signal synthesized by the ACJVS system. Such nonlinearities can be characterized as a function of signal amplitude and frequency, as well as the relative phase of the multitones, which can help to isolate distortion related to slew rate in some types of ADCs. These techniques have been used to dramatically improve the low-noise amplification and sampling electronics of the NIST Johnson noise thermometry (JNT) experiment, which is being used as a quantum-based electronic thermometer and, hopefully, will produce a useful measurement of Boltzmann's constant [10].

A low-voltage version (only eight junctions) of the ACJVS, called the "quantized voltage noise source" (QVNS), is used in this thermometric system to produce a comb of harmonic tones of identical amplitudes and random relative phases.

This "pseudo-noise" waveform with quantum voltage accuracy is used to characterize the gain-frequency response of the noise thermometry electronics over its 1 MHz Nyquist measurement bandwidth (Fig. 8). Accurate and low distortion multitones and single tones have allowed us to characterize and minimize the nonlinear response (by replacement or modification) of all the active components, the measurement transmission line, and the sampling ADC.

Summary

A new generation of Josephson voltage standards is providing new features of stability and programmability for dc voltages and precision sine wave and arbitrary waveform synthesis. New measurement techniques have been developed, especially for ac voltage applications, and the new systems are beginning to be integrated into ac and dc voltage calibration services at NMIs. Although the new systems and newly developed measurement techniques have not yet revolutionized ac voltage metrology, as the earlier conventional JVS system did for dc voltage, they are addressing a wide range of applications in precision voltage measurement.

Acknowledgement

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