Direct Comparison of a Pulse-driven Josephson Arbitrary Waveform Synthesizer and a Programmable Josephson Voltage Standard at 1 Volt

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Abstract — We have performed direct ac comparisons between two types of quantum voltage standards, a pulse-driven Josephson arbitrary waveform synthesizer and a programmable Josephson voltage standard, at 1 V rms amplitude and a frequency of 100 Hz. The system architectures for these two Josephson technologies are quite different. However, in the range where their capabilities overlap, they should produce identical results. This comparison under various test conditions is a powerful method for verifying ideal performance of the systems, and exploring a number of potential systematic errors in both measurement methods and system operations.

Index Terms — Josephson arrays, Signal sampling, Standards, Voltage Measurement.

I. INTRODUCTION

Programmable Josephson voltage standards (PJVS) are capable of generating stepwise-approximated reference waveforms with frequencies ranging from sub-hertz to a few kilohertz. Such waveforms, when combined with a sampling voltmeter and the differential sampling method, have been used to determine the root-mean-square (rms) output voltage of a commercially available high spectral-purity voltage source [1]. Recent improvements in superconductive circuit design and pulse generator electronics for the Josephson arbitrary waveform synthesizer (JAWS) have enabled 1 V rms output voltages and have extended the low end of the waveform frequency range down to 1 Hz [2]. With the JAWS and PJVS operating ranges now significantly overlapping, both indirect [3] and direct [4] comparisons between these two types of quantum voltage standards are possible.

Taking advantage of the intrinsic stability of the JAWS and the PJVS, direct comparison is an ideal tool to verify the parameter range where quantum accuracy is achieved in both systems. Subsequently, we can search for potential systematic errors associated with both the quantum voltage standards and the comparison technique. This paper presents initial results at 1 V and discusses the challenges associated with directly comparing the two quantum voltage standards.

II. DIFFERENTIAL SAMPLING

Both the JAWS and PJVS systems were operated in liquid helium with waveforms at rms amplitudes of 1 V and a frequency of 100 Hz. A commercially available digitizer measures the differential voltage between the low-voltage output lead of each system. The digitizer is battery powered, and therefore floating. All the instruments are locked to the same 10 MHz clock reference (NIST primary frequency standard). Synchronization between the two waveforms and the digitizer is achieved with optically coupled trigger signals generated by the PJVS electronics and connected to both the JAWS pulse generator and the digitizer. The relative phase between the two waveforms is adjusted by rotating the pattern of the JAWS waveform in order to minimize the differential voltage. Prior to every data acquisition, the average gain error of the digitizer is measured with a 60 mV peak amplitude PJVS waveform. The duration of each PJVS level is set to 125 µs ($N = 80$ levels/period and 100 Hz). We acquire 100 periods of the differential voltage with a sampling frequency of 10 MHz, average, and apply the previously mentioned gain correction for the digitizer [5]. The first 30 µs and last 10 µs of each PJVS level are discarded to remove the PJVS transients and the oscillations due to the finite impulse response filter of the digitizer. The JAWS sine wave is reconstructed by adding the corrected differential voltages to the nominal PJVS levels, and the fundamental of the JAWS sine wave ($V_{\text{MEAS(PJVS)}}$) is extracted with a sine-fit. The deviation from the nominal value $V_{\text{JAWS}}=1$ V is given by $\Delta V = V_{\text{MEAS(PJVS)}} - V_{\text{JAWS}}$.

III. MEASUREMENTS

Each data point represented in the manuscript is the mean value of 25 consecutive measurements. The error bars represent the Type-A uncertainty ($k = 2$). Measurements were repeated twice to show the repeatability. Figure 1 shows the effect of a dc current offset applied to the PJVS array (“S” shape, red squares) and the JAWS array (“U” shape, black
Note that with the JAWS-PJVS differential configuration the amplitude resolution obtained is a few nanovolts, which is a 20 times greater sensitivity than attained with previous methods (i.e., using the digitizer directly with the JAWS or PJVS).

Both measurements show that $\Delta V$ is constant over a range of offset detuning, namely “flat-spots” with magnitudes 1.4 mA (PJVS) and 1.5 mA (JAWS). Note the excellent agreement between PJVS and JAWS amplitude. $\Delta V$ is on the order of 10 nV over the full flat-spot range, corresponding to a measured relative difference of less than a few parts in $10^8$.

Fig. 2. Flat-spot measurement of $\Delta V$ vs. the JAWS compensation signal amplitude (repeated twice). The flat-spot boundaries correspond to a compensation amplitude variation of -0.2 mA to +0.7 mA relative to 10.5 mA ($\Delta i = 0$), the setting selected where the operating margin is maximum.

Direct comparison between the JAWS and the PJVS is a high-resolution diagnostic tool for measuring the operating range over which the various bias parameters retain quantum-accurate outputs of the JAWS and PJVS systems. For example, Fig. 2 presents the flat-spot obtained as a function of the JAWS compensation amplitude [2]. For clarity, the data on the y-axis are expressed as a relative quantity to highlight the effect of the dithered parameter. We plan to measure flat-spots for all of the JAWS and PJVS bias parameters.

Figure 3 presents the effect of detuning the PJVS amplitude from the ideal 1 V that matches the JAWS amplitude, thus forcing the digitizer to measure larger difference voltages. There is a small slope in Fig. 3 indicating that the measured error is proportional to $\Delta V_{PJVS}$. We applied a simple gain correction on the digitizer measured data (typically of the order of 6 parts in $10^5$), but a small, non-negligible, systematic error on the determination of $\Delta V$ remains. Further investigations on the non-linearity of the digitizer and its impact on $\Delta V$ are required in order to minimize this error.

IV. DISCUSSION

The results presented in Fig. 3 emphasize the critical importance of searching for and evaluating all potential systematic effects related to voltage differences ($\Delta V$). Among other potential errors, leakage currents are a critical component of the uncertainty budget that must be evaluated. Unlike PJVS to PJVS comparisons, where the various leakage resistances to ground are of primary importance, additional leakage effects due to the stray capacitances to ground are likely to be important when comparing ac voltage waveforms. We plan to perform the JAWS-PJVS comparison with various earth grounding configurations that may provide additional information to evaluate the Type-B uncertainty associated with leakage currents. Additionally, the voltage error contribution due to the on-chip inductors also needs to be evaluated as function of the waveform frequency.

Fig. 3. Measured linear dependence of the relative JAWS rms amplitude as a function of PJVS amplitude variation $\Delta V_{PJVS} = V_{PJVS} - 1$ V (repeated twice).

V. CONCLUSION

The agreement between the NIST JAWS and PJVS systems at 1 V rms and 100 Hz is presently measured to be a few parts in $10^6$. The reported offset current margins of 1.4 mA or more for both systems confirms that both Josephson standards retain large operating margins when connected in series. We will continue our work on JAWS-PJVS comparisons with additional measurements, including a detailed analysis of potential systematic errors associated with both the quantum voltage standards and the measurement method so as to present a complete uncertainty budget.

REFERENCES