AC-DC Difference of a Thermal Transfer Standard Measured with a Pulse-Driven Josephson Voltage Standard

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***Abstract* — An upgraded pulse-driven AC Josephson voltage standard system at the National Research Council Canada allows the generation of quantum-accurate root-mean-square voltages up to 1 V at frequencies down to 10 Hz. The system is used to determine the AC-DC difference of a commercial thermal transfer standard, and an uncertainty budget is presented. Such quantum voltage systems could replace aging multi-junction thermal converters.**

***Index Terms* —Josephson arbitrary waveform synthesizers, Josephson voltage standards, pulse-driven thermal transfer standards, thermal converters.**

I. INTRODUCTION

Traditionally, AC voltage has been traceable to DC voltage by means of the AC-DC transfer difference of sets of thermal voltage converters (TVCs). Joule heating at the resistive element inside a TVC gives rise to a local temperature increase, which generates an electromotive force across an output thermocouple. The AC-DC difference is defined as the relative difference between the AC voltage and the polarity-averaged DC voltages that produce the same output [1].

Acquired and setup in 2008, the pulse-driven AC Josephson voltage standard (also known as the Josephson Arbitrary Waveform Synthesizer [JAWS]) at the National Research Council Canada (NRC) generated voltages up to 250 mV at frequencies ranging from 2.5 kHz to 1 MHz. It was used in international comparisons of a commercial thermal transfer standard (TTS) [2,3]. Recent advances in JAWS technology resulted in higher voltages and lower frequencies [4-6].

In this paper, we report on measurements performed at NRC with an upgraded JAWS system, with new components acquired from the National Institute of Standards and Technology (NIST)[1] and High Speed Circuit Consultants (HSCC)[2] to generate waveforms with root-mean-square (rms) voltages as high as 1 V and frequencies as low as 10 Hz. We compare the AC-DC voltage difference of a commercial TTS at 0.6 V obtained from the JAWS to results obtained by conventional methods. A basic lead correction scheme is applied to the data taken at higher frequencies, and a quantum locking range study and an uncertainty budget are presented.

II. UPGRADED JAWS SYSTEM AT NRC

The upgraded JAWS system at NRC is based on a NIST chip with 4 subarrays of 12,810 Josephson junctions (JJs) each. Biases are provided by the HSCC ABG-2 bitstream generator and AWG-1 low-frequency compensation source. The JAWS chip is mounted in a cryoprobe dipped in liquid helium. The 28.8-gigabit-per-second bitstream generator combines a digital pulse pattern (i.e., the 3-level, sigma-delta, digital-to-analog conversion of the desired waveform) with a 14.4 GHz continuous-wave microwave signal. The resulting train of current pulses is injected into the arrays through on-chip Wilkinson dividers [6]. The ABG-2 is connected to the NRC 10 MHz reference frequency signal to ensure frequency traceability. DC blocks inside the cryoprobe effectively serve as a high-pass filter for the input pulse train. The low-frequency current components are restored using the battery-operated AWG-1.

Current margins are determined using a digitizer and a current bias sweep from additional AWG-1 channels. If the current pulses are within the margins of the $n = 1$ quantized steps of the JJs, the time integral of each resulting voltage pulse is precisely quantized to a flux quantum, and the fundamental component of the output voltage pulse train becomes calculable. Due to the limited bandwidth of the cryoprobe, the high-frequency components of the output voltage pulse train are filtered, such that the desired quantum-accurate waveform remains.

III. AC-DC DIFFERENCE OF THE TTS

We first determine the AC-DC difference of the TTS at 0.6 V in its 700 mV range (input resistance ~10 MΩ) using conventional references: a multi-junction thermal converter (MJTC) (0.01 kHz-50 kHz) and another TTS (100 kHz-500 kHz).

To compare the TTS to the JAWS system, the JAWS output is connected to the TTS input with a short adapter directly at the top of the cryoprobe to minimize losses in AC voltage that result from the 1.4 m long leads between the chip and the TTS. AC-DC measurements are made by generating a sequence of DC+, DC-, and AC voltages of calculable amplitudes with the JAWS. The results are shown in Fig. 1:

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[1] Contribution of the U.S. Government, not subject to copyright.

[2] Certain commercial equipment, instruments, or materials are identified to facilitate understanding. Such identification does not imply recommendation or endorsement by NIST, nor does it imply that the materials or equipment are necessarily the best available for the purpose.

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there is excellent agreement: the difference between the results from two methods is zero within uncertainties.

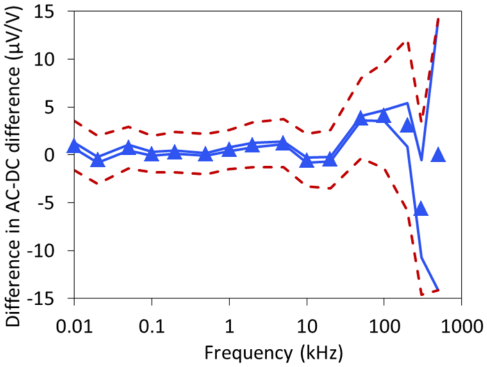

Fig. 1. Difference between the AC-DC difference of the TTS at 0.6 V in its 700 mV range measured using the JAWS and conventional references (triangles). Expanded uncertainties at $k = 2$ are shown for the JAWS (solid line) and the conventional references (dashed line).

IV. UNCERTAINTY ANALYSIS

A typical standard deviation of the mean of 10 sequences of AC-DC measurements is used for the type A uncertainty. To appreciate whether the AC-DC difference depends on the bias parameters giving optimal margins, we repeat the AC-DC measurements at 1 kHz with different dithers in the bias parameters. In the case shown in Fig. 2, the applied dither ranges from −5% to 5% of the bias parameter settings. A linear fit and its statistics reveal an uncertainty on the intercept at 0 % dither of 0.027 µV/V.

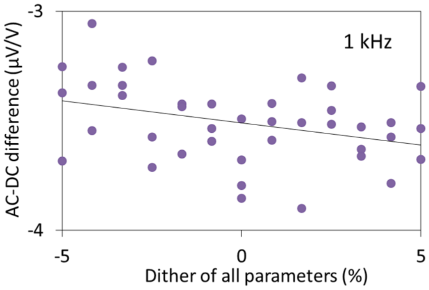

Fig. 2. Measured quantum locking range and linear fit showing the AC-DC difference obtained using the JAWS at 0.6 V and 1 kHz as a function of percentage of dither of all bias parameters, including the amplitude and phase of the microwave channels, the mixer amplitude, and the low-frequency bias currents.

To facilitate the margins optimization for the DC patterns, a 1 kHz tone with an amplitude 80 dB below the DC signal is added. The output voltage is directly proportional to the TTS rms input voltage; therefore, assuming a uniform distribution, the uncertainty component due to this added tone is 0.0029 µV/V. We also take into account the uncertainty from the frequency signal, estimated at 0.042 nV/V. Small AC and DC pattern offsets originating mostly from the finite number of Josephson junctions are taken into account based on the resolution of the offset correction applied to get the AC-DC difference. This uncertainty is 0.029 nV/V. For a given cable at frequencies >10 kHz, lead corrections are empirically quadratic in frequency and set by assuming perfect agreement at 500 kHz. The uncertainty for the lead corrections is obtained by scaling the uncertainty from the comparison to the other TTS at 500 kHz. The uncertainty budget for the data taken at 0.6 V is shown in Table 1. It combines to an expanded uncertainty ($k = 2$) of 0.27 µV/V up to 10 kHz.

Table 1. Uncertainty budget for the AC-DC difference of the TTS at 0.6 V in the 700 mV range measured against the JAWS. f is the frequency in hertz.

Standard uncertainty component (µV/V)					
Type A	Dither	1 kHz tone	Freq. offset	Pattern offsets	Lead Correction ($f > 10^4$ Hz)
0.13	0.027	0.0029	4.2×10^{-5}	2.9×10^{-5}	$2.9\times10^{-11}f^{2}$

V. CONCLUSION

We measured the AC-DC difference of a commercial thermal transfer standard using the JAWS at 0.6 V and found excellent agreement with the results obtained using conventional references. An uncertainty budget for the method involving the JAWS achieved a combined expanded uncertainty ($k = 2$) of 0.27 µV/V at 10 kHz and below. Lead correction uncertainties have been estimated for frequencies of 20 kHz–500 kHz. We expect the JAWS to replace aging thermal converters as the primary source of AC-DC difference traceability in the near future.

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