AC Voltage Measurements up to 120 V with a Josephson Arbitrary Waveform Synthesizer and an Inductive Voltage Divider

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***Abstract* — We use a precision inductive voltage divider and a lock-in amplifier to extend the voltage range of a Josephson arbitrary waveform synthesizer with a maximum voltage of 250 mV rms to provide accurate voltage measurements up to 120 V. Experimental results show that the output of the JAWS can be extended to high voltages with uncertainties of a few microvolts per volt or less, depending on the voltage amplitude and frequency.**

***Index Terms* — Inductive voltage divider, Josephson junction array, measurement standards, measurement techniques, quantum voltage standards.**

I. INTRODUCTION

The Josephson arbitrary waveform synthesizer (JAWS) [1] has the potential to replace thermal voltage converters (TVCs) as a primary standard of alternating voltage with the ultimate accuracy of the quantum Josephson effect. However, the voltage range of JAWS technology is presently limited to 1 V rms per Josephson junction array.

At the National Measurement Institute Australia (NMIA) we have developed a 1000 V inductive voltage divider (IVD) of excellent ratio accuracy [2] that can potentially extend the voltage range of the JAWS up to a factor of 1000 without an appreciable increase in the uncertainty. In collaboration with the National Institute of Standards and Technology (NIST), we have been developing such a standard [3]. This paper presents a continuation of this work. We combined a 250 mV NIST JAWS system with the NMIA IVD and a lock-in amplifier and demonstrate agreement with thermal converters at voltages up to 120 V and frequencies up to 1 kHz within the uncertainties of the thermal converters.

II. SYSTEM OPERATION

Fig. 1 shows a simplified diagram of the system. A stable ac voltage from a semiconductor-based source is applied to an ac measurement standard (the unit under test) and to the input of the IVD. The ac measurement standard is traceable to primary TVCs. The ac source is synchronized with the JAWS using an arbitrary waveform generator referenced to the same 10 MHz clock as the JAWS. This 10 MHz clock is derived from the cesium primary standard that is designated as the Australian national frequency standard. The phase difference between the output voltages of the IVD and the JAWS can be adjusted within 0.001°, and the difference between these voltages is applied to the lock-in amplifier, which is set to measure the in-phase component of the difference voltage.

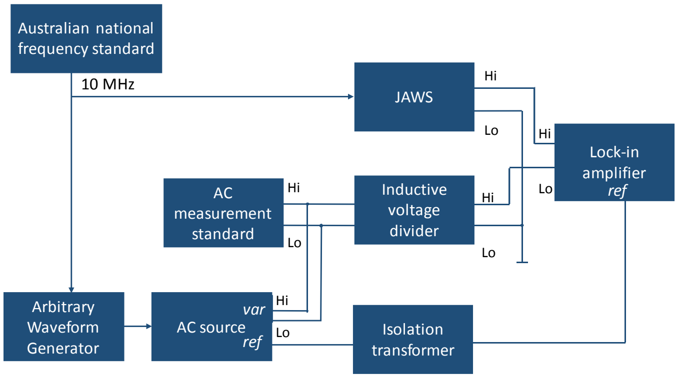

Fig. 1. Block diagram of the measurement system setup

The difference voltage is formed using coaxial cables and a modified tee connector and is applied to a single input of the lock-in amplifier. This is the main improvement from [3] where a differential summation function of the lock-in amplifier was relied upon.

The JAWS system is described in [4] and uses NIST Josephson junctions and microwave circuit designs [5]. The ratio uncertainties of the IVD range from 1×10^{-9} to 7×10^{-7} at frequencies from 40 Hz to 1 kHz. The ac source is a Clarke-Hess[§] 5500 phase standard modified to accept an external reference clock whose frequency can be adjusted within a small range to enable synchronization.

Two essential factors for achieving quantized operation of the JAWS are carefully laid out connections and an absence of ground loops. The circuit measurement ground is connected to the mains safety conductor (Earth) at the low potential output of the IVD only. The cases of the ac source and the lock-in amplifier are disconnected from the mains safety conductor to mitigate the effects of common-mode input voltage with respect to the mains safety conductor. The guard of the ac measurement standard is connected to the measurement ground but disconnected from its internal ground terminal. To avoid ground loops through the GPIB computer interface, the lock-in

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

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amplifier is connected to the control computer through an optically isolated GPIB extender.

The system operation depends on the adjustment of (a) the phase of the voltage between the ac source and the JAWS and (b) the reference phase setting of the lock-in amplifier with respect to its input. To adjust these phases we use the following procedure. First the cable is disconnected from the IVD output which is then shorted at the plug. Then the reference of the lock-in amplifier is adjusted to minimize the quadrature component of the lock-in amplifier reading. Finally the cable is reconnected to the output of the IVD and the phase of the ac source adjusted by, again, minimizing the quadrature component of the lock-in amplifier reading.

III. EXPERIMENTAL RESULTS

The precision evaluation of the JAWS system at voltages greater than 10 V is limited by the increasing uncertainty of the thermal ac-dc transfer standards. For this reason, we first evaluated our JAWS-based system at 7 V rms using a TVC with a low uncertainty (2 µV/V), and then proceeded to 70 V and 120 V. We used the same IVD for both experiments, which, given the very high voltage linearity of the IVD [2], gives us confidence that the type B uncertainty of the system is independent of the voltage amplitude.

In the first experiment, we calibrated a Keysight 3458A configured as a digital sampling voltmeter [6] at 7 V rms and at frequencies from 60 Hz to 1000 Hz using the JAWS and the NMIA conventional TVC-based ac-dc transfer calibration system. The ratio of the IVD was 0.01 and the output voltages of the JAWS and the IVD were 70 mV. The results are shown in Fig. 2. In a second experiment we calibrated a Fluke 5790A ac measurement standard at 70 V and 120 V, and at 60 Hz using the JAWS and the TVC-based ac-dc calibration system (Fig. 3). The IVD ratio in these measurements was 0.001.

IV. CONCLUSION

In both experiments, the JAWS-based system agreed with the NMIA conventional ac-dc transfer standards within their uncertainties. At low voltage (7 V), the largest difference was 1.3 µV/V, and at high voltage the largest difference was 4 µV/V at 120 V. Further experimental results will be presented at the conference (including different excitation voltages at different frequencies, different output voltages of the IVD for the same excitation voltage obtained with different ratios of the IVD). The uncertainty components will also be discussed in detail.

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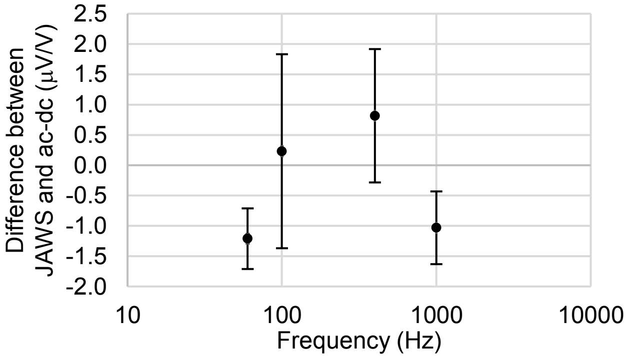

Fig. 2 Difference between the ac-dc difference of a digital sampling voltmeter measured using a TVC and the JAWS-based system at 7 V rms. The error bars show the standard deviation of the JAWS. measurement.

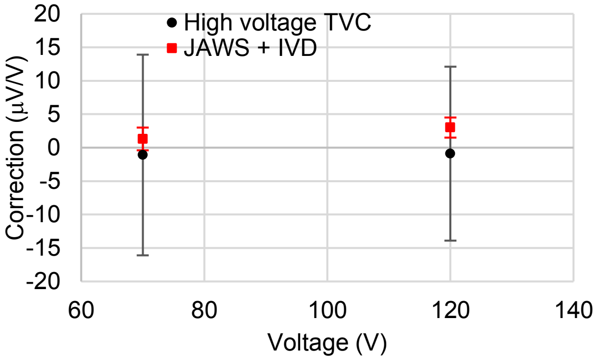

Fig. 3 Ac-dc difference of an ac measurement standard (Fluke 5790A) at 70 V rms and 120 V rms measured with a high voltage TVC and the JAWS-based system. The error bars show the TVC measurement uncertainty and the standard deviation of the JAWS measurement, respectively.