PRECISION DIFFERENTIAL SAMPLING MEASUREMENTS OF LOW FREQUENCY VOLTAGES SYNTHESIZED WITH AN AC PROGRAMMABLE JOSEPHSON VOLTAGE STANDARD

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Abstract

Sampling is a promising technique for comparing the stepwise-approximated sine waves synthesized by an AC Programmable Josephson Voltage Standard to the sinusoidal voltages of a secondary source at low frequencies (a few hundred hertz or less). This paper describes a differential method that uses an integrating sampling voltmeter to precisely determine the amplitude and phase of high purity sine wave voltages by comparing them to quantum-accurate waveforms.

Introduction

Recent progress in AC Programmable Josephson Voltage Standards (ACPJVS) [1-3] and in sampling measurements using such systems [4, 5] has opened new possibilities for the accurate measurement of low-frequency ac voltage waveforms. This technology is particularly interesting for electric power applications, for which NIST is developing a "Quantum-Watt" system. The method described here, which will be used in the NIST system, combines an ACPJVS with a secondary sinusoidal reference in a differential sampling configuration (Fig. 1). A sampling voltmeter is used as a null detector in order to minimize the effects of gain variation and other nonlinearities of the measurement.

Preliminary tests of the differential sampling method using two ACPJVS systems provided important information regarding the capabilities and limitations of the sampling technique [5]. This method can be used to determine the amplitude, phase, and harmonic content of any ac-voltage waveform. However, in order to achieve better results than those of conventional sampling techniques and take full advantage of the differential configuration, ac-sources with excellent amplitude stability, phase stability, and spectral purity are required. For the results presented in this paper, a Fluke 5720A calibrator was used as the ac source.[†]

Differential Sampling Technique

The amplitude of a staircase-approximated sine wave generated by the ACPJVS was chosen to closely match the amplitude of the sinusoidal source. Before each measurement sequence the sampling window was carefully aligned to the center of each constant-voltage step of the ACPJVS. Because the ACPJVS waveform is only strictly valid on the constant-voltage steps, the contributions from the transients must be removed. This is done by sampling the differential waveform twice on each step of the ACPJVS waveform [5], and the half of the data points containing the transients is discarded. The remaining measurements contain the integrated values of the voltage difference between the constant-voltage steps and the sinusoidal reference. With these data, we reconstruct the original sine wave and extract its amplitude and phase.

Before acquiring data, the phases of the two sine waves were matched in order to minimize the differential voltage so as to take advantage of the null detector configuration. In order to extract the contributions coming from the power line cycle frequency (PLC), the waveform was sampled over multiple waveform periods. We applied a fitting algorithm on the multi-period reconstructed waveforms to determine the amplitude and phase of the first 20 harmonics. Finally, the resulting amplitude was corrected by a mathematical factor to account for the finite aperture (integration) time of the sampler.

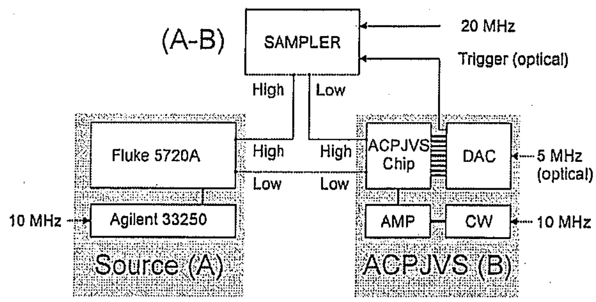

Figure 1. Schematic diagram showing the differential (A-B) measurement setup. The reference signal (a square wave at the same frequency of the ACPJVS waveform) for the phase and frequency locking of the 5720A is provided by an arbitrary waveform generator. All clock signals are locked to the same reference. For details on ACPJVS and PJVS setups see [6].

Results

Precision comparisons were performed between the ACPJVS and the Fluke sine wave with various numbers of samples and phase configurations. Both sources generated a 1.2 V rms, 50 Hz signal. Fig. 2 shows a typical measurement with the sampling voltmeter of the resulting differential (A-B) waveform. Fig. 2(a) shows all the integrated samples of the first four cycles of a typical measurement, where the solid circles represent "on step" samples and open circles, the transients. Plotting the "on-step" samples for all 32 cycles in Fig. 2(b), we observe that the differential amplitude is slightly modulated. This "jitter effect" is most likely caused by phase-drift of the calibrator, as discussed below.

The sampler acquired 100 individual traces, each consisting of 32 cycles of 50 Hz. For each of these traces, we fit the amplitude and phase of the sine wave and the first few harmonics. The results are shown in Fig. 3, where both the amplitude and phase of the fundamental exhibit good short-term stability. Over the duration of the measurement (about 150 s for all 100 traces), we calculated average values. Averaged over all 100 traces, the rms amplitude of the fundamental was 1.200 003 34 V with a corresponding standard deviation of the mean ($k = 2$) of 0.35 μV. Additionally, the fitting procedure gave rms amplitudes for the 2^{nd} and 3^{rd} harmonics of 17.1 μV (-96.9 dBc) and 7.5 μV (-104.1 dBc) respectively, and a 5.4 μV (zero to peak) amplitude for 60 Hz pickup. The fit results provide important confirmation of both the spectral purity of the sine wave

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[†]Commercial instruments are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by NIST, nor does it imply that the equipment identified are necessarily the best available for the purpose.

(harmonics well below our part in 10^7 target), and the measurement and analysis methods.

This analysis shows that the amplitude of the 5720A source is very stable. Nevertheless, as observed in Fig. 3(b), the phase and frequency locking function of the calibrator introduces a phase noise that affects the inferred amplitude. Fortunately, this effect is considerably reduced by averaging over many traces.

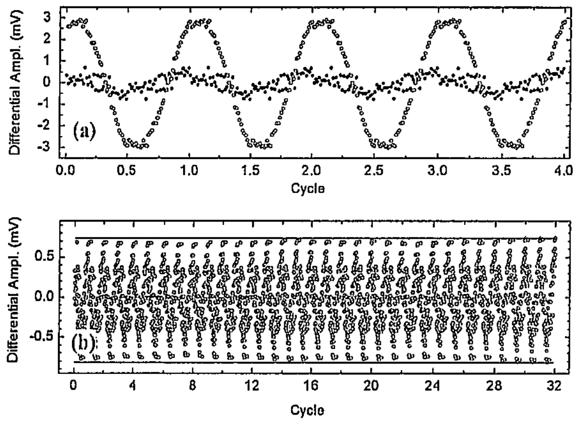

Figure 2. Differential amplitude measured by the sampling voltmeter using a 1.2 V rms ACPJVS stepwise-approximated 50 Hz sine wave with 80 steps. (a) On-step samples (solid circles) and transients (open circles) for the first four cycles of a single trace (#64). (b) Measured amplitudes of the on-step samples for all 32 cycles of the same trace. The two horizontal lines indicate the maximum amplitudes measured, and emphasize a small amplitude modulation.

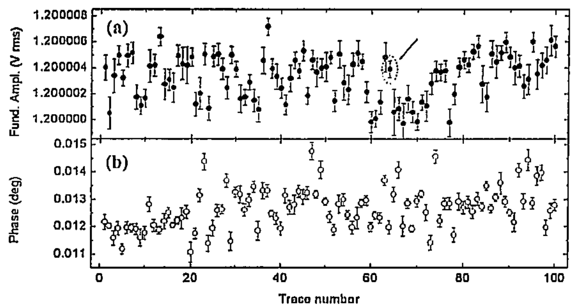

Figure 3. Inferred precision values of the 5720A amplitude and phase (nominally 1.2 V rms) at 50 Hz as measured with an 80-sample ACPJVS waveform. (a) Mean amplitude of the fundamental for each of the 100 traces. (b) Mean phase relative to the sampling window for the same sampled data. Error bars represent the standard deviation of the mean *(k = 2)* for each 32-cycle trace. The arrow indicates the mean value of trace #64, which is described in detail in Fig 2.

Figure 4 presents results of two important tests that are essential for determining potential sources of error in the differential sampling method. The measured values must be independent of both (a) the phase alignment, and (b) the number of samples in the ACPJVS waveform. This assumption remains valid as long as the resulting differential voltage is on the lowest (100 mV) range of the sampling voltmeter. In order to obtain consistent results, the output voltage of the 5720A must be constant over the duration of the test. To check the overall stability, we measured each setting at least twice.

In Fig. 4(a), the phase was adjusted over ±1 ° (ACPJVS waveform of 80 samples, 50 Hz). In Fig. 4(b), the number of samples in the 50 Hz sine wave was varied from 32 to 100. Other than the expected variations due to measurement noise, the inferred amplitude was independent of both phase alignment and number of ACPJVS samples. It is important to note that the sampling voltmeter's aperture time decreases with increasing number of samples and that this significant change did not affect the measured amplitude. Therefore, over the tested range, the results show that the aperture time used to rescale the data is well controlled. Note that the choice of the number of steps per ACPJVS waveform is a compromise between small differential voltages (requiring a high number of steps per ACPJVS waveform) and large aperture time (requiring a small number steps per ACPJVS waveform to reduce the noise contribution of the sampler [5]).

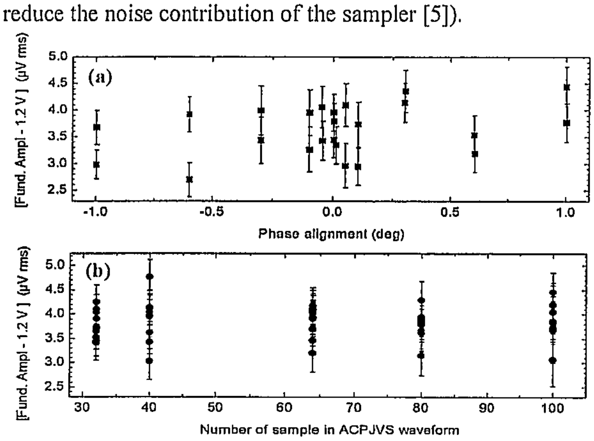

Figure 4. Demonstration that the differential sampling method produces consistent results with regard to (a) phase misalignment, and (b) number of samples in the ACPJVS waveform.

Summary and Conclusion

A differential sampling technique has been successfully demonstrated in which the ACPJVS provided a precision, quantum-accurate voltage (and phase) reference for accurately measuring the amplitude and phase of a high-purity 50 Hz sine wave produced by a Fluke 5720A calibrator. The results appear independent of phase alignment and number of samples. Nevertheless, the inferred amplitude was limited by the phase jitter from the 5720A, which introduced noise in the reconstructed amplitude. Fortunately, this jitter does not significantly affect rms measurements with the 5720A, which is its intended application. NIST is constructing a custom source for the Quantum-Watt system, which will have the necessary phase stability for these sampling measurements. The differential sampling technique avoids direct contributions from the ACPJVS transients and may enable new applications in the field of low frequency AC electric metrology, such as thermal voltage converter (TVC) calibrations, impedance measurements, and power applications.

References

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