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Design and implementation of differential AC voltage sampling system based on PJVS

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ABSTRACT

First, a differential sampling measurement principle is introduced. Based on this principle, we have developed a precision differential sampling system to measure AC voltage with the use of a quantum-accurate AC Programmable Josephson Voltage Standard. The differential sampling system design adopts switching measurement technology. By analysing the error source of the differential sampling system, a mathematical model is established, and the error transfer function is derived. We have performed a variety of measurements to evaluate this differential sampling system. First, the transition is analysed, and the selection scheme of the sampling window is described. After averaging, the uncertainty obtained in the determination of Fluke 5720A 1 V RMS amplitude sine wave at 60 Hz is 0.3 μV/V (type A); the uncertainty obtained in the determination of PJVS 1 V RMS amplitude sine wave at 60 Hz is 0.05 μV/V (type A).

1. Introduction

The most widely used method which trace the AC power frequency sine to AC Programmable Josephson Voltage Standard (ACPJVS) are the lock-in amplifier (LIA) [1–3] and the sampling technique [4–10]. LIA measures the difference between sine waveform and the fundamental frequency of stepwise-approximated sinewave (SASW) synthesized by ACPJVS. The precise measurement ensured ACPJVS as a reference signal. In this measurement, the uncertainty could reach 0.5 μV/V with voltage amplitude less than 0.75 V and frequency less than 40 Hz [2]. However, the harmonic content of the SASW could affect the reading of the LIA. Furthermore, PJVS is not quantized in the transients between the successive voltage levels of the SASW [7,11], during which the PJVS is not quantized, causing the root mean square (RMS) value of the SASW and its fundamental frequency to deviate from their ideal values related to fundamental physical constants.

An AC voltage precision measurement program, based on the Full-Scale Sampling method, usually uses a single sampling voltmeter such as Agilent 3458A [4–13]. The sine waveform and ACPJVS are alternately connected to the sampling voltmeter by means of a signal switch. Using the algorithm could reduce the dominant uncertainty contribution from 1 μV/V to 0.38 μV/V (both $k = 1$) [6].

Differential sampling is a technique for comparing the stepwise-approximated sine wave synthesized by ACPJVS to the sine voltages of a secondary source, by using the sampling digital voltmeter (DVM) and making sure the input signal of the DVM is as small as possible by adjusting the phase of the two sources. The measured sine wave can be reconstructed by using the known quantum voltage waveform and integral of the difference signal, thereby obtaining accurate amplitude of the measured sine waveform. The National Institute of Standards and Technology (NIST) has developed a differential sampling method that compares the voltage of an AC source with that of an ACPJVS [4]. The ACPJVS provides a precision quantum-accurate voltage reference to accurately measure the amplitude of a high-purity 50 Hz sine wave produced by a Fluke 5720A calibrator. The uncertainty obtained in the determination of the amplitude of a 1.2 V sine wave is 0.3 μV/V (type A).

In this paper, we design a differential sampling system that is used to measure the amplitude of a sine waveform (B) using an ACPJVS reference (A). The differential sampling system is designed by using a commercial ADC chip and a switching measurement technology. Transfer function of voltage amplitude error was deduced by analysing the errors of the differential sampling system. We prove that a switching measurement can effectively reduce the influence of gain errors by using the differential sampling system when measuring the amplitude of Fluke 5720A. In this paper, we also investigate the judgement criterion of the transition size, the discretization of reconstructed sine waveform within the sampling window, and an experiment that measures PJVS against PJVS.

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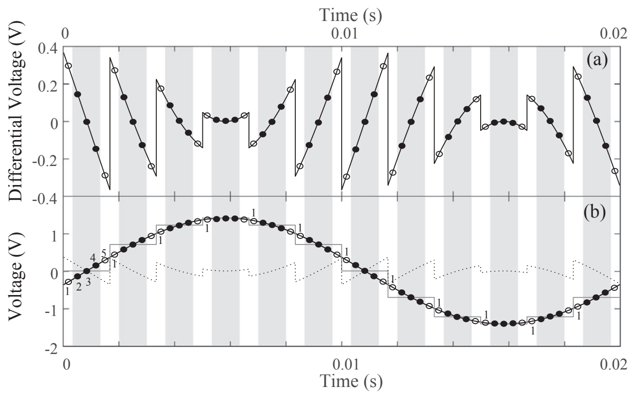

Fig. 1. (a) Zoom of the differential waveform. The circles show the sampling points of the differential waveform. Free of transients, the solid circle samples are used for sine waveform reconstruction. The open circle samples that contain the transients are discarded. The gray and white stripes correspond to the different sampling windows in signal processing. (b) Ideal simulated ACPJVS staircase-approximated sine wave with 12 samples and reconstructed sine wave (both with 1 V RMS amplitude and zero relative phase). The differential waveform is represented by the dotted line.

2. System description

2.1. Differential sampling measurement principle

A paper [14–16] has presented a new reconstruction method of sine waveforms: first DFT and then averaging. With this method, sine waveform can be reconstructed by using ACPJVS and differential signal, as shown in Fig. 1.

For simplicity, we have chosen in this example an ACPJVS waveform with 12 samples, and the differential waveform with 60 sampling point in one cycle. Both stepwise and sine waveform have 1 V RMS amplitude. The stepwise divides the sine wave into equal parts of step N (N = 12), and the sampling points of reconstructed sine waveform in the same position have the same identification number (such as number 1 in Fig. 1(b)). Then all number 1 positions will reconstruct a sine waveform, and numbers 2–5 will do the same. Because the ACPJVS waveform is only accurate on each constant-voltage step, the contributions from the transients must be removed, as represented with open circle samples in Fig. 1(b) (numbers 1 and 5). Therefore, the retaining points, numbers 2–4, could reconstruct three sine waveforms, and obtain three RMS amplitudes using an FFT algorithm. Then the final RMS amplitude could be acquired calculating the mean of those three RMS amplitudes. The relative Fourier coefficients of the reconstructed sine waveform concerned be calculated as Eqs. (1) and (2):

$$a_1(m) = \frac{2}{N}\sum_{n=0}^{N-1} x_{n,m}\cos(n,m), \quad a_1 = \frac{1}{t-s+1}\sum_{m=s}^{t} a_1(m) \tag{1}$$

$$b_1(m) = \frac{2}{N}\sum_{n=0}^{N-1} x_{n,m}\sin(n,m), \quad b_1 = \frac{1}{t-s+1}\sum_{m=s}^{t} b_1(m) \tag{2}$$

where s is the beginning of the sampling window, t is the terminal point, m is the number of selected points in the sampling window, and $m = t - s + 1$.

2.2. Measurement scheme of differential sampling system

Fig. 2 shows the measurement configuration for the differential sampling method, which mainly consists of three components: a sine waveform voltage source of high spectral purity and stability, an ACPJVS system that provides a reference voltage waveform, and a sampling system.

The PJVS system was developed by NIST. The ACPJVS chip enables

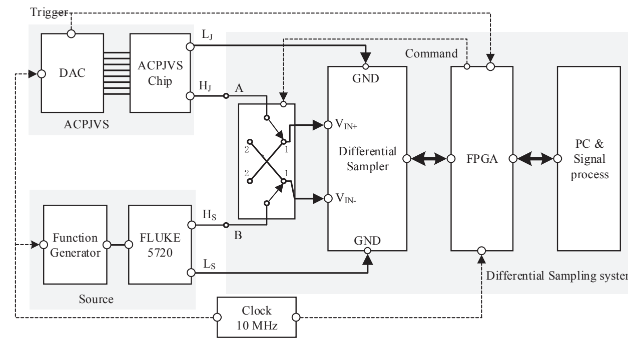

Fig. 2. An ac signal measurement system block diagram based on PJVS.

a maximum output of 2.25 V for 17.8 GHz microwave input. For some of the measurements reported in this paper, a Fluke 5720A was used as the sine waveform source. The reference signal for the phase and frequency locking of the Fluke 5720A is provided by an arbitrary waveform function generator. The differential sampling system is designed by ourselves, as shown in Fig. 2. We only describe one differential sampler in this paper, although two differential samplers in the sampling system have the purpose of power measurement. Detailed differential sampler design will be described below.

3. Switching measurement and error transfer function

3.1. Switching measurement

In the differential sampling system development, we used an LTC2378-20 analog-to-digital conversion (ADC) chip. The principle block diagram of the differential sampling system is shown in Fig. 3.

The differential sampling system consists of a reversing switch, voltage follower, adder, differential drive circuit, low pass filter, ADC, host computer, and FPGA timing control circuit. The reversing switch is photoMOS, with the purpose of A-B and B-A switching. In this method, we could acquire two RMS amplitudes by measuring sine wave minus stepwise and stepwise minus sine wave, then calculate the mean of the two amplitudes. The voltage follower can increase the input impedance of the differential sampling system. Signal conditioning fulfils the requirements for common voltage input of the differential driver amplifier. The LTC2378-20 is a 20-bit successive approximation analog-to-digital conversion chip with an integral non-linearity error of ± 0.5 ppm, quantization error of 2 ppm, maximum sampling rate of 1 MHz, and input differential voltage range of ± 5 V.

3.2. Error transfer function

The main error sources of the differential sampling system include gain error and offset error respectively in positive input and negative input, the gain error and offset error in the differential driver circuit, and the reference error and sampling error in the ADC. As a result of FFT analysis of the sine wave, we only consider the fundamental RMS, thus only the effects of gain errors, reference error, and sampling error on voltage amplitude measurement are analysed.

We assume the sine waveform is $V_s(n)$, the stepwise signal is $V_j(n)$, the differential signal is $V_d(n)$, the positive and negative gain error of the signal conditioning circuit are $E_p(n)$ and $E_n(n)$ respectively. Differential drive circuit error, reference error, and sampling error as a combined unit are denoted by $E_d(n)$. Thus, the differential signal before and after the switching measurement can be expressed by Eqs. (3) and (4).

$$V_{d1}(n) = [V_s(n)(1+E_p(n)) - V_j(n)(1+E_n(n))]\cdot(1+E_d(n)) \tag{3}$$

$$V_{d2}(n) = [V_j(n)(1+E_p(n)) - V_s(n)(1+E_n(n))]\cdot(1+E_d(n)) \tag{4}$$

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