High-Accuracy Sampling Wattmeter

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Abstract—A high-accuracy sampling wattmeter was deveoped at NIST (National Institute of Standards and Technology) to investigate the feasibility of using waveform sampling techniques for making very accurate power measurements at frequencies from 50 Hz to 1000 Hz. The prototype instrument was used to demonstrate the accuracy achievable with the sampling method. The goal of this study was to develop an instrument having measurement uncertainty of less than ±50 ppm over these frequencies. The new high-accuracy sampling wattmeter was built around a wideband instrument developed earlier at NIST. The new wattmeter uses 16-bit analog-to-digital (A/D) converters and includes a two-stage current transformer in one of the input modules. This wattmeter, as the previous wattmeter, operates with asynchronous sampling. The high accuracy is achieved by approximately synchronizing the interval over which samples are taken with the period of the input signal. Special care was taken to design input stages with a flat frequency response and low temperature sensitivity. The wattmeter has been calibrated using the NIST Audio-Frequency Power Bridge. The two instruments agreed to better than ±50 ppm of full scale over the 50 Hz to 1000 Hz frequency range at all power factors.

I. Introduction

As part of an ongoing program at NIST to increase the accuracy of electrical power measurements, a study of the problems associated with high-accuracy sampling wattmeters was undertaken. The measurement of power requires the synchronous measurement of voltage (V) and current (I). The method selected during this study uses dual-channel sampling of the V and I waveforms, arithmetic multiplication of the digitized values, and averaging of the products to obtain a power measurement. Other methods for making power measurements include time-division multipliers [1]–[4], analog multipliers [5], thermal [6], [7] and current-balance techniques [8]. Common to all of these methods is the requirement for conditioning the input signals for the respective power-conversion technique. The conversion circuitry generally requires signals in the range of a few volts. In power measurements the input signals are often voltages in the hundreds of volts and higher and currents ranging from a few milliamperes to many hundreds of amperes. This paper describes one part of the ongoing program, to develop a high-accuracy sampling wattmeter. The conversion circuitry that was developed for this instrument and its performance are described. Many of the problems encountered during this development are common to the other types of wattmeters.

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In developing the high-accuracy sampling wattmeter, the goal was to build an instrument capable of measuring typical power signals in the frequency range of 50 to 1000 Hz with an uncertainty of less than ±50 ppm of full-scale range. One reason for selecting the digital-sampling approach was the earlier success in developing the wideband sampling wattmeter [9]. Since the earlier instrument was modular, the development of the new wattmeter was simplified by utilizing elements from the previous wattmeter in the design. The signal-conditioning circuitry of the earlier wattmeter, which converted input voltages into 12-b digital signals, was built into plug-in modules. The new wattmeter was developed by designing two new modules that used 16-b converters. One module was designed for voltage levels up to 240 V, and the other was designed to accept currents from 1 to 5 A.

II. Principles of Operation

The principle of operation of the high-accuracy sampling wattmeter has been described in many papers [9]–[13]. These principles are reviewed briefly here. Periodic power signals with a voltage $v(t)$, and a current $i(t)$, having a period of T seconds, deliver an average power P of

$$P = \frac{1}{T}\int_0^T v(t)i(t)\,dt. \tag{1}$$

Sampling wattmeters calculate the average power by performing the integration numerically. The voltage and the current waveforms are sampled simultaneously, converted to digital values, and the product of their digital values, the instantaneous power, is calculated. The average power can then be computed by averaging many samples of instantaneous power. If the voltage at time t_k is denoted as $v(t_k)$ and the current as $i(t_k)$, then an estimate W of the average power can be calculated as

$$W = \frac{1}{n}\sum_{k=0}^{n-1} v(t_k)i(t_k) \tag{2}$$

where n is the number of samples used in the average. If the sampling is asynchronous, i.e., the sampling is not phase locked to be some multiple of the frequency being sampled, the power estimate W from (2) does not equal the average power P from (1). The difference is due to what is called truncation error. This type of error varies from measurement to measurement. It can be reduced by averaging over a large number of samples. The time interval over which these samples are averaged, t_1 to t_{n+1}, is called the summation interval. For sinusoidal power signals with a voltage amplitude of V, a current amplitude of I, and a frequency of less than one-fourth the sample

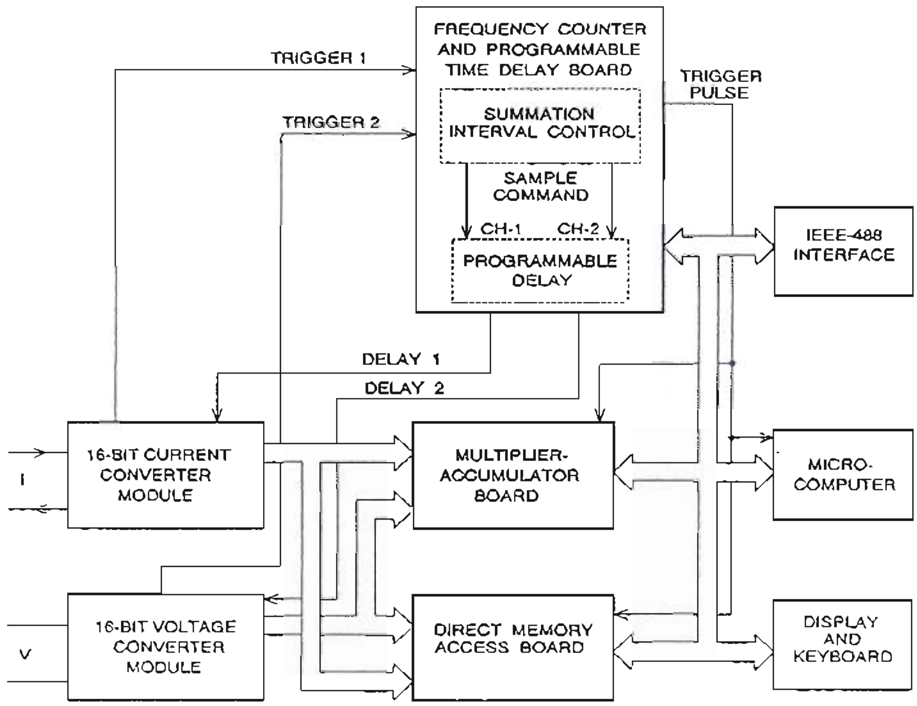

Fig. 1. Block diagram of the NIST high-accuracy sampling wattmeter.

rate, the magnitude of the maximum truncation error, $E_{\max}$, is given by [9]

$$|E_{\max}| = \frac{VI\gamma}{4\pi c|\sin\gamma|} \tag{3}$$

where c is the number of cycles of the input signal in the summation interval, and the angle γ is given in terms of the input signal frequency f as $\gamma = 2\pi f/f_s < \pi/2$, where f_s is the sample rate. For a frequency of 60 Hz, the summation interval must be greater than 208 s for this error to be less than 10 ppm. If the summation interval is approximately synchronized with the input frequency such that the difference between the summation interval and a complete number of cycles is less than one sample period, then the maximum truncation error is given by [9]

$$|E_{\max}| = \frac{VI}{2n}. \tag{4}$$

Thus, with approximate synchronization the truncation error is independent of the number of cycles of the input signal and is inversely proportional to the number of samples n in the summation interval. Using approximate synchronization and a sampling rate of 75 kHz, the truncation error for 60-Hz power measurements is less than 10 ppm for a summation interval greater than 1.4 s, compared to over 208 s for asynchronous sampling for the same error.

In addition to the errors due to the sampling process, quantization, and truncation, the major error in determining the power estimate W comes from the imperfections of the hardware used the make the measurements. The errors due to these effects are discussed in Section V. A brief description of the structure of the new wattmeter follows.

III. System Architecture

Fig. 1 is a simplified block diagram of the NIST high-accuracy sampling wattmeter. Each input module produces two output representations of the input signal. One is the digitized sample of the voltage or current, and the other is a scaled analog copy of the input signal. The digital samples are sent to the multiplier-accumulator circuit where the power calculations are carried out, and to the direct-memory access (DMA) circuit where segments of the input signal are stored. The summation interval control circuitry uses the isolated analog outputs, triggers 1 and 2, to control the summation intervals to be within one sample period of a complete number of cycles. The sample commands to the input modules are time shifted using programmable time delays to compensate for the differential time shifts of the analog portions of the two input modules. This differential time control assures accurate low power factor measurements for the wattmeter. A microcomputer is used to read the keyboard commands, estimate the voltage and current parameters from the DMA data, calculate the power from the multiplier-accumulator data, and determine the frequency from the summation control data. A display is provided for visual output as well as an IEEE 488 interface for access by an external computer. The 488 interface provides output of all calculated values and full control over the operation of the wattmeter.

IV. Hardware Changes

The primary hardware modifications that changed the earlier wide-band sampling wattmeter to the high-accuracy sampling wattmeter were those made to accommodate 16-b sampling versus 12-b sampling. Two new input modules were designed and constructed that use commer-

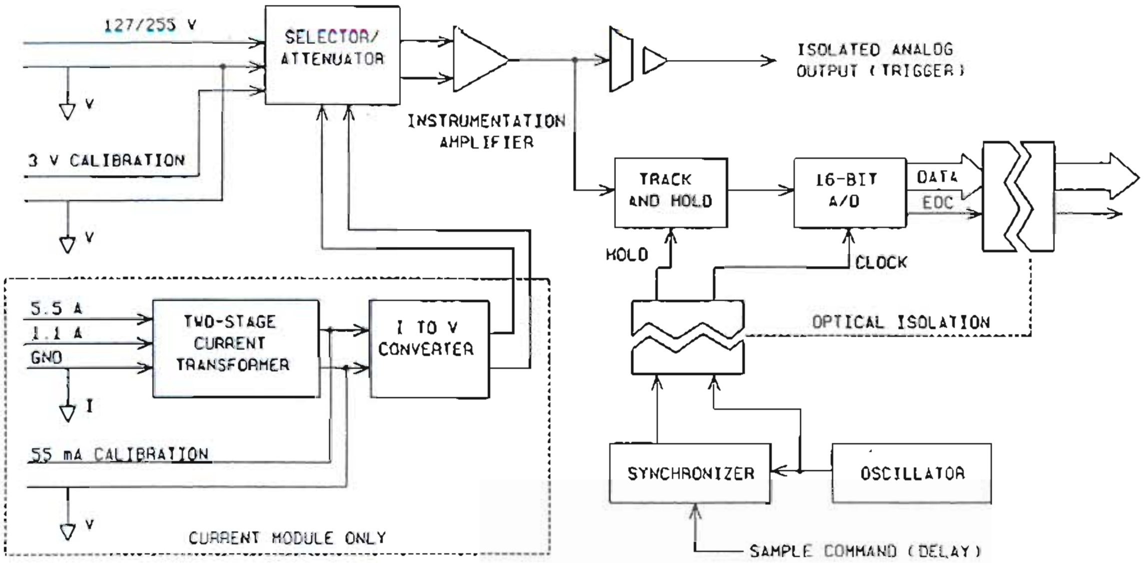

Fig. 2. Block diagram of the voltage and current input modules.

cial 16-b A/D converters. The additional bits required the development of a new multiplier-accumulator board. To aid in the calibration of the wattmeter, an IEEE 488 interface card was added.

One input module samples of the voltage of the power signal with input ranges of 127 V rms and 255 V rms and a calibration input of 3 V rms. Fig. 2 shows a block diagram of the input modules. The calibration input signal goes directly to an instrumentation amplifier used to buffer the input signal for the track-and-hold circuitry. The amplifier was selected because of its good temperature stability, low noise, low offsets, and good common-mode rejection. Even though the amplifier bandwidth is only 1 MHz, it is adequate for the design frequency range of 50 to 1000 Hz. While the calibration input has the input impedance of the instrumentation amplifier, 5 TΩ in parallel with 6 pF, the 127-V and 255-V inputs use an RC attenuator with an input impedance of 100 kΩ in parallel with 10 pF. The 3-V rms output of the attenuator is buffered by the instrumentation amplifier. The track-and-hold circuitry and 16-b A/D converter are both contained in a single commercial chip. Two different 16-b converter circuits were tested. One runs with a sampling rate of 37.5 kHz and the other at 75 kHz. The results for both were comparable. The measurements described in this paper have been made using the faster converter.

The second module samples the current of the power signal. This module uses a two-stage transformer to convert full-scale ranges of 5.5-A rms and 1.1-A rms input currents to 55 mA rms. Based on theoretical design calculations, this transformer has a scaling error of less than 1 ppm over the frequency range of 50 to 1000 Hz. A compound operational amplifier circuit is used to convert the 55-mA current to a 3-V rms signal. The remainder of the current module, as shown in Fig. 2, is the same design as the voltage module. Thus both modules have the same voltage measurement capability.

For both of these modules, significant design features were incorporated to reduce the coupling of noise between the digital and analog portions of the circuit. Among these features is the use of optical coupling between the input modules and the rest of the wattmeter circuitry. Even the oscillator that drives the A/D converter chip is powered by the system power and optically coupled to the converter circuitry. This arrangement reduces the amount of circuitry running at the clock frequency on the same power supply as the converter. Separate power supplies are used for the digital and analog portions of each module. The commons of these supplies are tied together at the analog portions of each module. The commons of these supplies are tied together at the analog ground of the converter chip. Finally, the radiation of digital signals in the modules is reduced by using four-layer, printed circuit boards (PCB's). The use of four-layer PCB's allows almost all of the digital traces to be placed next to a ground plane.

V. Performance

The critical factors that are of interest for the wattmeter are the noise level, frequency response, and temperature coefficients of the input circuitry. The noise levels of the input circuitry were measured by applying a constant dc signal or a short circuit to the voltage and current modules and then recording the range of digital codes generated by the modules. The final design achieved an approximate noise level of plus/minus one code width. The data showed about 60% of the output at one code, 15% to 25% at each of the adjacent codes, and 1%–2% at plus and minus two codes. Fig. 3 shows a typical distribution of codes for 100 samples of the voltage module with the input shorted. Similar results were observed for the current module.

The frequency response of the two modules was compared with standard commercial calibrators, and an ac/dc comparator was used to measure the amplitude of the test signals. Fig. 4 shows the frequency response of the current module. Fig. 5 shows the frequency response of the

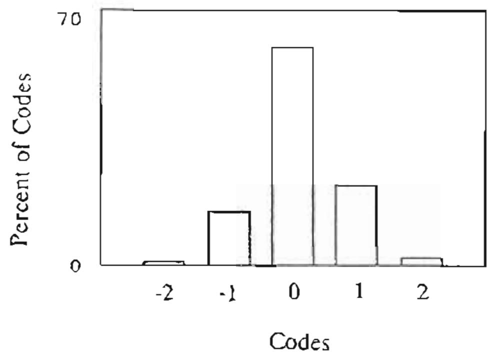

Fig. 3. Typical distribution of voltage codes for shorted input.

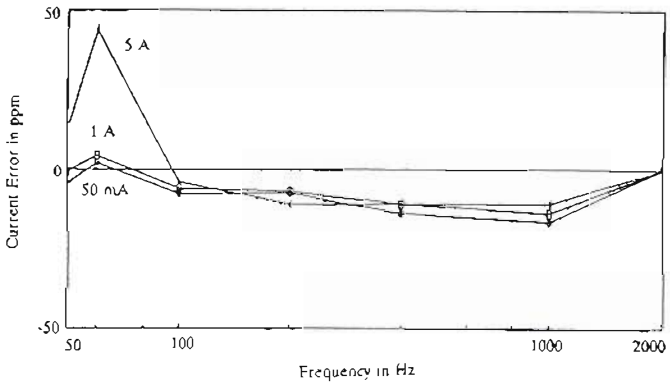

Fig. 4. Frequency response of current module.

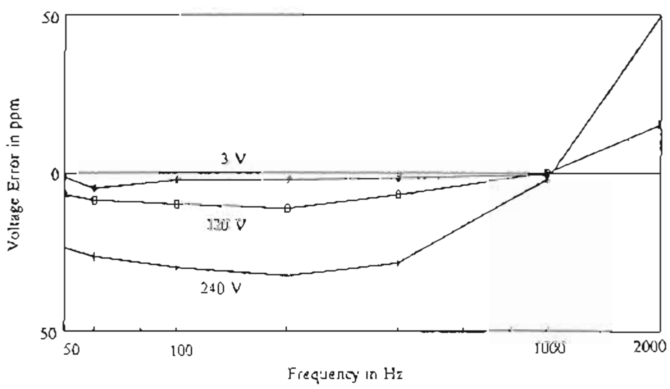

Fig. 5. Frequency response of voltage module

voltage module. The frequency response of the 255 V range is marginal for the project goal. Attempts will be made to reduce the errors for this input range by redesigning the attenuator for this range. The other ranges have errors that are well within the ±50 ppm uncertainty goal.

The power frequency response was measured using the NIST audiofrequency power bridge [8]. Fig. 6 shows the typical results of calibration of the wattmeter for power measurements. This graph shows the power errors for unity and zero power-factor lead and lag signals with voltage and current amplitudes of 120 V and 1 A. These results show that the power uncertainty goal of less than ±50 ppm of full-scale range was achieved.

The temperature sensitivities of the two input modules were measured for a temperature change of about 25°C, from 10°C to 35°C. Table I shows the results of these tests. The first three rows are the results obtained for the voltage module, and the last two rows show the results obtained for the current module. The temperature sensitivities range up to 2.6 ppm/°C for the voltage module and up to 3.6 ppm/°C for the current module. Based on this data, the expected power temperature sensitivity would be about 5 ppm/°C. However, each of the module sensitivities was measured independently, so no information was obtained to determine the temperature sensitivity of the phase of each module. Thus, the power sensitivity may be significantly larger, particularly for low power factor signals.

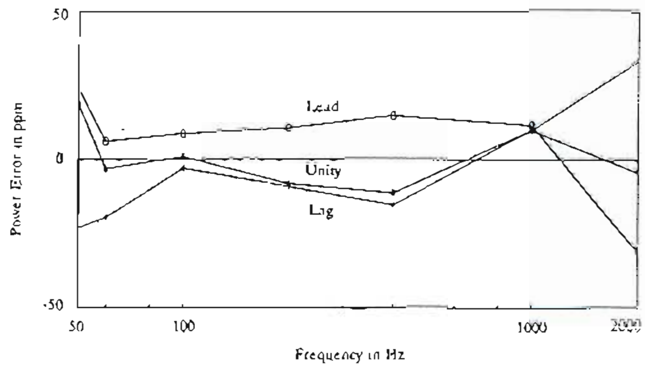

Fig. 6. Frequency response of power measurements.

TABLE I

TEMPERATURE SENSITIVITIES FOR THE INPUT MODULES IN ppm/°C

Range	50 Hz	400 Hz	1 kHz
3 V	0.9	2.6	2.6
120 V	2.1	2.3	−1.3
240 V	0.4	1.1	1.6
1 A	2.5	2.5	2.9
5 A	3.6	3.2	2.9

VI. SUMMARY

The development at NIST of a high-accuracy sampling wattmeter shows that sampled power measurements can be made with an uncertainty of less than ±50 ppm of full-scale range. The process of upgrading an earlier wideband sampling wattmeter (12-b A/D converters to 16-b A/D converters, etc.) required careful attention to noise considerations. The use of optical coupling between the analog sampling circuitry and the rest of the system is common to both of these systems. This feature is believed to be very significant to achieving the low-noise performance. The other feature that was found to be very significant was the use of four-layer, printed circuit boards. An earlier design of the new modules that use only two layers had a significantly higher noise level.

A two-stage transformer provided the current scaling with a very flat frequency response over the frequency range of interest. The use of an RC attenuator for the voltage scaling has proved to be marginal in frequency response for the 255 V range. Further circuit refinements will be attempted in order to achieve a flat frequency-voltage response.

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