HIGH-ACCURACY SAMPLING WATTMETER

Gerard N. Stenbakken and Amos Dolev
National Institute of Standards and Technology[1]
Gaithersburg, MD 20899

Abstract - A high-accuracy sampling wattmeter was developed 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 is not portable but was used to demonstrate the accuracy achievable with the sampling method. The goal of this development was to build an instrument with an uncertainty of less than ±50 ppm over these frequencies. The new high-accuracy sampling wattmeter was built around a previous wideband instrument developed earlier at NIST.

The new wattmeter uses 16-bit converters and includes a two-stage current transformer in one of the 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.

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 measurement of voltage (V), current (I), and the phase angle between these two quantities. In addition to dual-channel sampling of the V and I waveforms and the multiplying required to obtain power, as described in this paper, 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 amperes to many hundreds of amperes. This paper describes one part of the ongoing program, the development of

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.

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 Hz to 1000 Hz with an uncertainty of less than ±50 ppm. 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-bit digital signals was built into plug-in modules. The new wattmeter was developed by designing two new modules which used 16-bit 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. Thus, the new wattmeter does not require an external current shunt as did the earlier wattmeter.

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

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

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

$$|E_{max}| = \frac{V I}{2 n} \ . \qquad (4)$$

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, then 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 period 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 and a current amplitude of I, the magnitude of the maximum truncation error, E_{max}, is given by [9]

$$|E_{max}| = \frac{V I \gamma}{4\pi c |\sin \gamma|} \ , \qquad (3)$$

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 $\gamma = 2\pi f/f_s$, where f_s is the sampling frequency. For a frequency of 60 Hz, the summation interval must be greater than 265 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, γ, then the maximum truncation error is given by [9]

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 265 s for asynchronous sampling.

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 to make the measurements. The errors due to these effects are discussed under the section on performance below. A brief description of the structure of the new wattmeter follows.

System Architecture

Figure 1 is a simplified block diagram of the 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 circuit where segments of the input signal are stored. The summation control
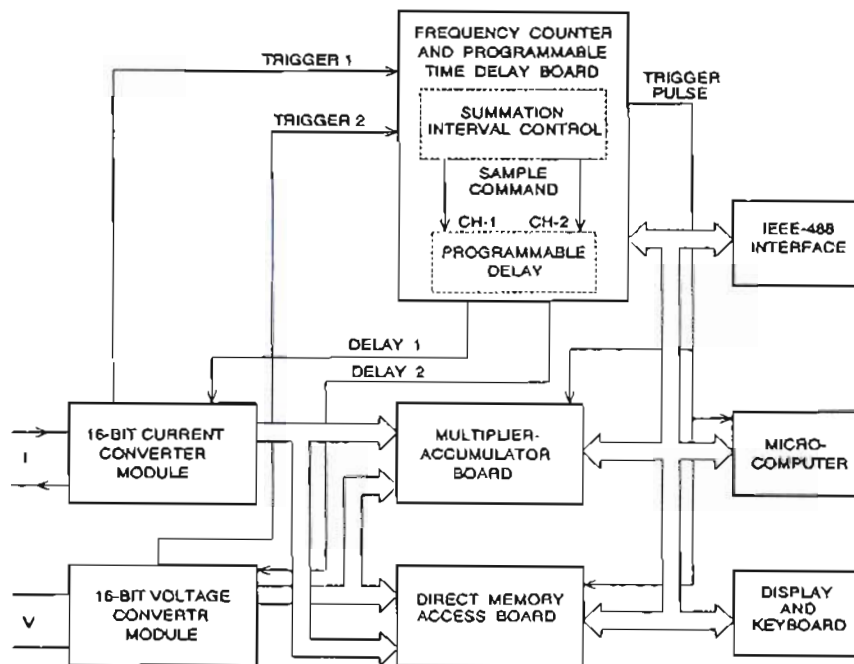

Figure 1 -   Block Diagram of the High-Accuracy Sampling Wattmeter.

circuitry uses the isolated analog outputs, trigger 1 and trigger 2, to control the summation intervals to within one sample period of a complete number of cycles. The sample commands to the input modules are time shifted 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 and an IEEE 488 interface for access by a computer. The 488 interface provides output of all calculated values and full control over the operation of the wattmeter.

Hardware Changes

The primary hardware modifications that changed the wideband sampling wattmeter to the high-accuracy sampling wattmeter were those made to accommodate 16-bit sampling versus 12-bit sampling. Two new input modules were built that use commercial 16-bit analog-to-digital (A/D) converters. The additional bits also required a new multiplier-accumulator board. To aid in the calibration of the wattmeter, the IEEE 488 interface card was added.

One input module samples 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. 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 its bandwidth is only 1 MHz, it is adequate for the design frequency range of 50 Hz 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-bit A/D converter are both contained in a single commercial chip. Two different 16-bit converters circuits were built and tested. One runs with a sampling rate of 37.5 kHz and the other at 75 kHz. The results for both were comparable. The final measurements described in this paper have been made using the faster converter.

70

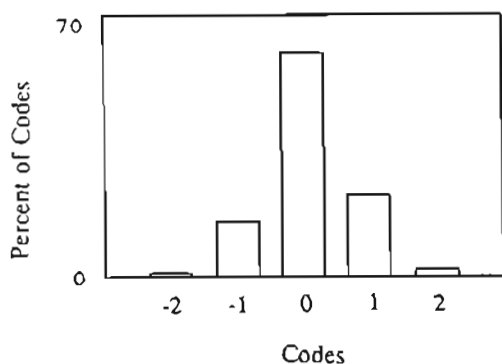Percent of Codes

0

-2   -1   0   1   2

Codes

Figure 2 -   Typical Distribution of Voltage Codes for Shorted Input.

The second module samples the current of the power signal. This module uses a two-stage transformer to convert full scale 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 Hz 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, the instrumentation amplifier and 16-bit analog-to-digital converter, is the same design as the voltage module.

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 ground of the converter chip. Finally, the radiation of digital signals in the modules is reduced by using four-layer, printed circuit boards (PCBs). The use of four-layer PCBs allows almost all of the digital traces to be placed next to a ground plane.

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 first two factors have been measured; the temperature coefficient tests have not yet been performed.

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 percent of the output at one code, 15 to 25 percent at each of the adjacent codes, and one to two percent at plus and minus two codes. Figure 2 shows a typical distribution of codes for 100 samples of the voltage module with the input shorted.

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. Figure 3 shows the frequency response of the current module. Figure 4 shows the frequency response of the voltage module. The frequency response of the 240 V range is marginal for the project goal. Attempts will be made to reduce the errors for this input. The others errors are within the ±50 ppm uncertainty goal.

The power frequency response was measured using the NIST Audio-Frequency Power Bridge [8]. Figures 5 and 6 shows the typical results of calibration of the wattmeter for power measurements. These graphs are for input signals of 120 V and 1 A. Figure 5 shows the unity power factor results and figure 6 shows the results for zero power factor lead and lag. These results show that the goal of ±50 ppm uncertainty for power measurements was achieved.
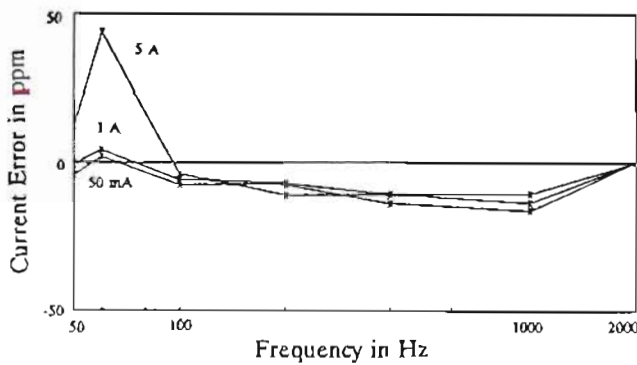
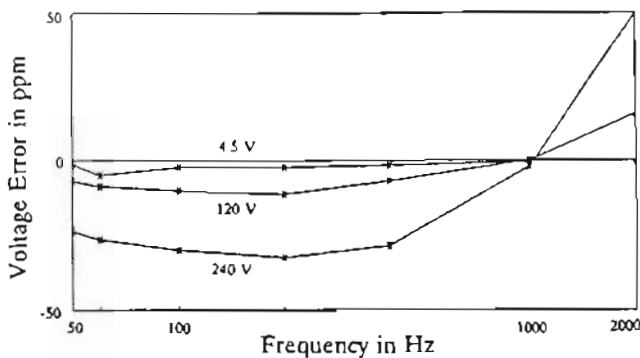Figure 3 - Frequency Response of Current Module.

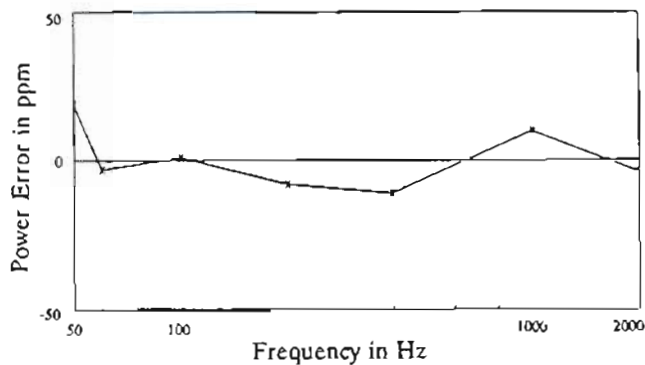Figure 4 - Frequency Response of Voltage Module.

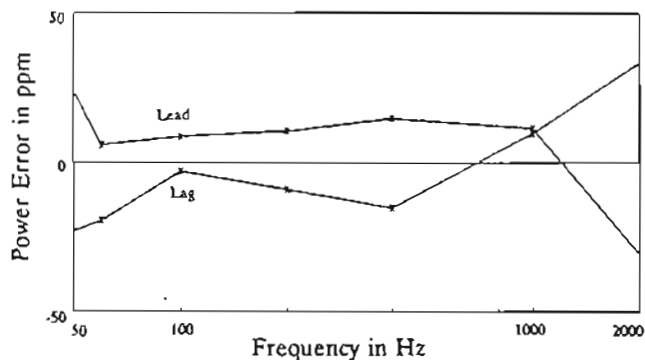Figure 5 - Frequency Response of Unity Power-Factor Power Measurements.

Figure 6 - Frequency Response of Zero Power-Factor Lead and Lag Measurements.

Conclusions

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. The process of upgrading an earlier wideband sampling wattmeter (12-bit converters to 16-bit 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 with 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 240 V range. Further circuit refinement will be tried to get a flat frequency-voltage response.

Acknowledgements

References

[1]   M. Tomota, T. Sugiyama, and K. Yamaguchi, "An Electronic Multiplier for Accurate Power Measurements," *IEEE Trans. Instrum. Meas.*, IM-17, pp. 245-251, Dec. 1968.

[2]   R. Bergeest and P. Seyfried, "Evaluation of the Response of Time-Division Multipliers to AC and DC Input Signals," *IEEE Trans. Instrum. Meas.*, IM-24, pp. 296-299, Dec. 1975.

[3]   G. J. Johnson, "Analysis of the Modified Tomota-Sugiyama-Yamaguchi Multiplier," *IEEE Trans. Instrum. Meas.*, IM-33, pp. 11-16, Mar. 1984.

[4]   P. S. Filipski *et al.*, "A TDM wattmeter with 0.5 MHz carrier frequency," *IEEE Trans. Instrum. Meas.*, IM-39, pp. 15-18, Feb. 1990.

[5]   B. Gilbert, "A Precise Four Quadrant Multiplier with Subnanosecond Response," *IEEE Journal of Solid State Circuits*, SC-3, pp. 365-373, Dec. 1968.

[6]   G. Schuster, "Thermal Measurement of AC Power in Comparison with the Electrodynamic Method," *IEEE Trans. Instrum. Meas.*, IM-25, pp. 529-533, Dec. 1976.

[7]   L. C. Cox and N. L. Kusters, "A Differential Thermal Wattmeter for the AC/DC Transfer of Power," *IEEE Trans. Instrum. Meas.*, IM-25, pp. 553-557, Dec. 1976.

[8]   B.C. Waltrip and N.M. Oldham, "Performance Evaluation of a New Audio-Frequency Power Bridge," *IEEE Trans. Instrum. Meas.*, IM-40, pp. 380-383, Apr. 91.

[9]   G.N. Stenbakken, "A Wideband Sampling Wattmeter," *IEEE Trans. Power Appar. Syst.*, PAS-103, pp. 2919-2926, Oct. 1984.

[10]   Raymond S. Turgel, "Digital Wattmeter Using a Sampling Method," *IEEE Trans. Instrum. Meas.*, IM-23, Dec. 1974.

[11]   Michael F. Matouka, "A Wide-Range Digital, Power/Energy Meter for Systems With Nonsinusoidal Waveforms," *IEEE Trans. on Industrial Electronics*, IE-29, pp. 18-31, Feb. 1982.

[12]   John J. Hill and W. E. Alderson, "Design of a Microprocessor-Based Digital Wattmeter," *IEEE Trans. on Industrial Electronics and Control Instrumentation*, IECI-28, Aug. 1981.

[13]   F. J. J. Clark and J. R. Stockton, "Principles and Theory of Wattmeters Operating on the Basis of Regularly Spaced Sample Pairs," *Jour. of Physics E: Scientific Instruments*, Vol. 15, No. 6, pp. 645-652, June 1982.

[14]   T.M. Souders, "A Wide Range Two-Stage Current Transformer of High Accuracy," *IEEE Trans. Instrum. Meas.*, IM-21, pp. 340-345, Nov. 1972.