

EMERGING NEW REQUIREMENTS FOR ELECTRIC POWER AND ENERGY MEASUREMENTS

J. D. Ramboz, and O. Petersons
Electrosystems Division
National Bureau of Standards
Gaithersburg, Maryland 20899

Abstract

Advances in electronic instrumentation technology have brought greater stability and precision to transducers that are utilized for measuring electric power and energy. An advantage of instruments based on electronic transducers is that they can be readily adapted to the measurement of other quantities such as current, voltage, reactive and apparent power, power factor, demand, time-of-day readings, etc. The increases in the cost of energy during the past decade have stimulated the acceptance of new instrument technology by the users associated with the electric power industry. The electronic instruments have especially found acceptance in metering installations for large loads and at interchange points between utilities. Modern instruments, because of their accuracy capabilities, are also advantageous in those applications where the efficiency of large equipment such as generators and transformers has to be measured. A large number of the instruments used as physical standards by the industry and submitted recently to the National Bureau of Standards (NBS) for calibration have been of the electronic type. The calibration accuracies requested from NBS for power and energy measurements have increased at least fivefold (uncertainty reduction from $\pm 0.05\%$ to $\pm 0.01\%$) within the past several years. Calibrations for different quantities and values are being requested. These changing calibration requirements and the response of NBS to meet the requests of its calibration clientele are discussed.

Introduction

Shortly before the turn of the 20th century, the rotating, eddy-current driven disk watt-hour meter was developed and put into widespread service. For more than a century, this relatively simple, rugged, and dependable type of meter has been the mainstay of the electric utility business in performing measurements of electric energy. Built to operate for a period of thirty to forty years, experiencing the worst extremes of weather, and subjected to violent overloads due to lightning strikes, the rotating-disk watt-hour meter typically will continue to measure with errors of less than two percent. Considering that this type of single-phase meter presently costs about \$30, it is truly a remarkable instrument and a tribute to technical refinement for many years.

During the past decade, the cost of generating and distributing electric energy has risen dramatically. The "electric bill" for the U.S. in 1984 was \$135 billion (about 4% of the Gross National Product) [1]. This, coupled with increased consumption, has stimulated the acceptance of new instrument

technology by the users associated with the electric power industry, both the utilities and the manufacturers of meters, generators, transformers, and other electrical equipment. In the late 1960's and early 1970's, advances in electronic instrumentation technology brought greater stability and precision to electronic transducers that are utilized for measuring electric power and energy. Wattmeters and watthour meters of the time-division-multiplier type came into existence. Meters of the electronic type are becoming widespread in applications where accurate electric power and energy measurements have to be made.

Electronic meters are used today in many applications for making accurate measurements, not only of power and energy, but also of other important quantities such as voltage, current, power factor, apparent power (VA), and reactive power (VAR). They can be made to provide time-of-day and demand readings. Sometimes they are even equipped with communication interfaces so that they can be remotely set or read. In 1974, NBS calibrated an electronic watthour meter for a customer for the first time. Today, just over 10 years later, electronic-type wattmeters and watthour meters make up about two-thirds of the NBS calibration workload. The growth of the calibration of electronic "transducers" as standards is shown in figure 1. It is expected that this trend will continue with electronic standards comprising about 90% of the total workload by 1990.

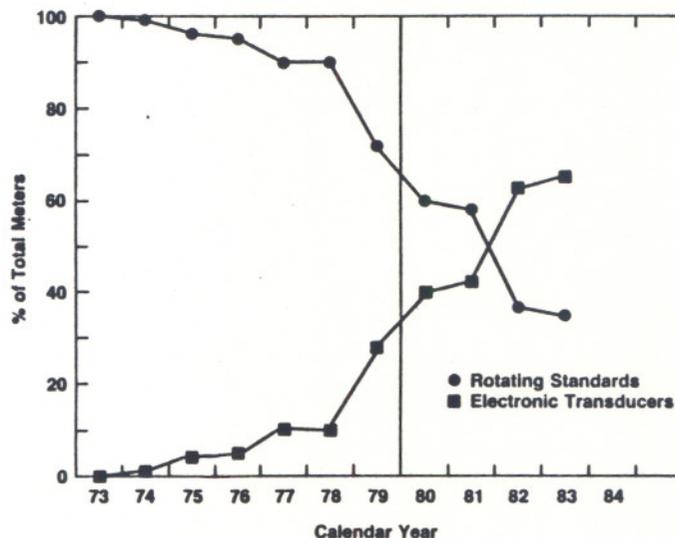


FIGURE 1 The number of rotating watthour meters and electronic transducers shown as a percentage of all meters calibrated for a 10 year period.

Traceability to basic standards over the years has undergone evolutionary changes to be able to meet the more stringent demands for accuracy in the measuring process. In the very early days at the National Bureau of Standards, an electrostatic wattmeter, capable of being used on dc as well as ac, served as a "primary" standard. The Park-Lewis standard electrodynamic wattmeter, an ac-dc transfer instrument, was incorporated into the calibration service in 1940 and represented one of the few improvements of the calibration capability for many years [2]. In 1954, special watthour standards took over the role as working standards and were traceable to fundamental standards through an ac-dc transfer using an electrodynamic meter [3]. At about the same time, the ac-dc thermal converter came into its own, providing an

improved method of establishing the ac voltage in terms of the dc reference volt [4]. AC current could be established in terms of the ac volt and resistance. In 1974, the current comparator power bridge was completed and used to establish the unit of electrical energy [5]. Today, it remains one of the most accurate means of determining electric power and energy in terms of the basic units of voltage, resistance, and time. It is possible to establish ac power with an uncertainty of better than $\pm 0.003\%$. In addition to the power bridge technique, a highly accurate thermal instrument was developed in the early 1970's by the Physikalisch-Technische Bundesanstalt (PTB) [6].

The current-comparator power bridge, the PTB thermal standard, and a bank of four precision watt-hour standards comprise the system of instruments that support the present NBS calibration service for electric power and energy. Presently being developed is a precision, dual-channel, current and voltage source based on digital synthesis techniques and incorporating a current-comparator power bridge.

Measurement Accuracy Requirements

Physical standards for electric energy measurement are needed to ensure equity in the billing for electric energy consumed and are used primarily by utility companies, meter manufacturers and state regulatory commissions. At the present time, the accuracy requirements for in-service watt-hour meters range from $\pm 0.5\%$ to $\pm 2.0\%$. (Most state regulatory commissions require the utility companies to maintain total measurement uncertainty to better than $\pm 2.0\%$; it is common practice, however, for the utilities to maintain this uncertainty below $\pm 1.0\%$.) To further improve equity in billings, utilities are beginning to meter large loads, such as those of certain industrial customers, with watt-hour meters that have uncertainties of the order of $\pm 0.1\%$. Similar measurement uncertainties of $\pm 0.1\%$ are being specified at utility interchange points on the power grid. (In the latter instance, a tenth of one percent measurement error can amount to hundreds of thousands of dollars per year for a single interchange point.)

The demands for high accuracy measurements and calibration support come primarily from three sectors: 1) manufacturers of large electrical equipment such as generators and transformers; 2) the technical community committed to maintaining and improving the accuracy of electrical power and energy metering; and 3) the instrumentation industry which develops and provides precision meters.

The most pressing and critical need for very accurate power measurements is that of the manufacturers of large electrical equipment. High accuracy is required to measure the power losses of equipment that is inherently very efficient, or operates at very low power factors. For example, if it is desired to measure the losses of a device that is 99% efficient with an uncertainty of $\pm 1\%$ by measuring the input and output power, both measurements must be performed with better than $\pm 0.01\%$ uncertainty. Similarly, if conductor losses of a transformer have to be measured with $\pm 1\%$ uncertainty and if the resultant load has a power factor of 0.01, the real power has to be measured with an instrument the uncertainty of which is $\pm 0.01\%$ of the apparent power. Many sales contracts contain penalty clauses related to the efficiency of the generator or transformer; these penalties amount to tens of thousands of dollars. Over the operating lifetime of the device, a very small

inefficiency can amount to large energy losses. The capability of making highly accurate power measurements is critical to the competitive posture of U.S. manufacturers for both domestic and foreign sales.

There is a small but rapidly growing industry that develops and markets electronic wattmeters and watthour meters. The uncertainties quoted by the manufacturers for the electronic type meters range from $\pm 0.1\%$ to $\pm 0.035\%$. Because of the very low uncertainties achieved in commercial areas and demands for higher calibration accuracy, new and better calibration approaches and hardware are being developed at NBS to support the changing calibration requirements.

Present NBS Calibration Services

The Electrosystems Division of the National Bureau of Standards is responsible for the derivation, maintenance, and dissemination of the units for the measurement of electric power and energy. These units are derived directly from the NBS as-maintained units of voltage, impedance, and time. At NBS, the unit of electric power is derived with an uncertainty of less than $\pm 0.0035\%$, and the unit of energy with an uncertainty of less than $\pm 0.0056\%$. Both of these quantities are derived and maintained at "power frequencies" of 50 and 60 Hz. (Calibration of wattmeters at a somewhat reduced uncertainty is also available at a frequency of 400 Hz to support military and aerospace measurement requirements.) Figure 2 shows the derivation the units of power and energy diagrammatically and traces the steps that transfer the originally derived "watt" to various instruments employed to support the calibration service, and eventually to the customers' standard instruments [7].

Customers' meters, shown at the bottom of figure 2, are compared to the NBS reference standards, which in turn are compared to the PTB thermal power/energy standard. The thermal standard is compared to the current comparator power bridge. Between each step in figure 2 are two sets of numbers. The first number of each set refers to the power factor and is either 1.0, or 0.5 leading or lagging. The uncertainties in parts per million (ppm) are shown in parentheses, where the first number is the estimated systematic uncertainty and the second number is the observed random component of uncertainty. The systematic uncertainty for the following step is the sum of the systematic and random uncertainties. The overall uncertainty for routine calibrations of customers' watthour meters is less than 500 ppm.

The NBS reference standard also is used in the electric energy Measurement Assurance Program (MAP) [8] and is shown to the left of the reference standard in figure 2. The random components of uncertainty are shown only as typical values since, in reality, they are determined individually for each "MAP interchange" at the time that the series of measurements is made.

Special high-accuracy calibrations are provided by directly comparing the meter being calibrated with the thermal standard. The random uncertainties are shown as "X" and "Y", respectively, for unity and half power factors. These uncertainties are determined at the time of test and depend, in part, upon the performance of the meter being calibrated. When performing high-accuracy calibrations on quality instruments, the overall uncertainty will generally be between 100 to 200 ppm. These special high-accuracy calibrations

are time-consuming and thus expensive, and are only performed for the most critical applications.

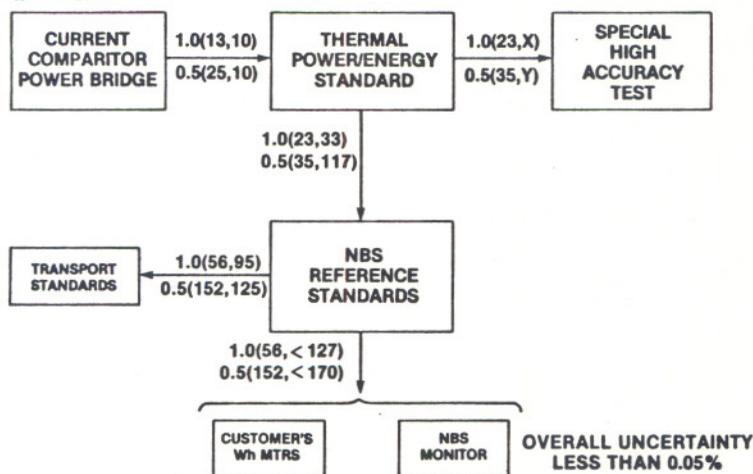


FIGURE 2 The major steps and uncertainties for the calibration "chain" for watt-hour meters at NBS. (See text for an explanation for the numerical data given.)

A simplified diagram of a current comparator power bridge is shown in figure 3. The voltage, V , of a sinusoidal generator is set to 120 volts by the use of an ac-dc thermal voltage convertor. This 120-volt ac signal is applied to the meter under test (MUT) and to a precision resistor, R , through the winding N_v of the current comparator. Steps are taken to ensure that the resistance of N_v is negligible in relation to R . The applied voltage and the precision resistance establish a known current, V/R , in N_v . A five-ampere current source, phase-locked with the voltage source, is connected to the current circuit of the MUT through the winding N_i of the current comparator. The number of turns and the polarities of the windings are such as to produce the ampere-turn balance and cancellation of the magnetizing force in the ferromagnetic core of the current comparator.

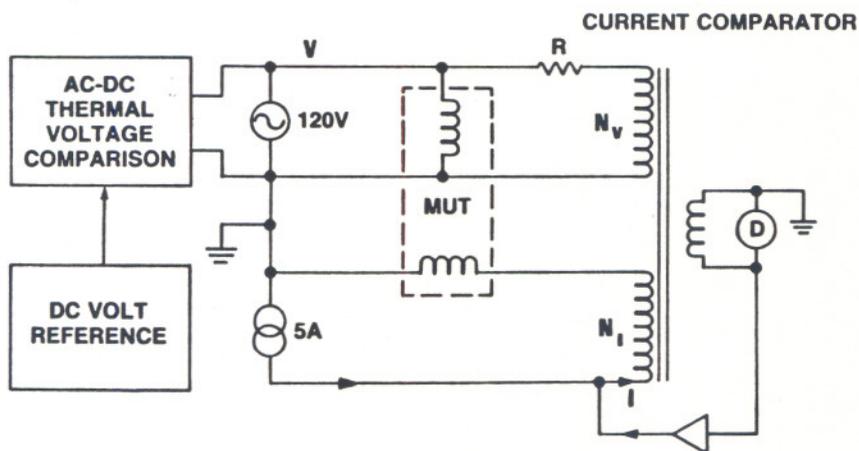


FIGURE 3 Simplified current comparator power bridge (for unity power factor as shown).

The current comparator is a special three-winding transformer in which the current ratio equals the reciprocal of the turns ratio to a high degree of accuracy, within a ppm or better. In practice, the amplitudes of and the phase angle between the two sources cannot be adjusted and maintained exactly at the desired values. Hence, a feedback amplifier is utilized for sensing and correcting the small ampere-turn imbalance. At the balance condition of the bridge with the detector (D) indicating negligible signal,

$$IN_I = (V/R)N_V, \text{ and}$$

$$I = (V/R)(N_V/N_I) .$$

The power (P) supplied to the MUT is given by

$$P = VI,$$

$$P = (V^2/R)(N_V/N_I) ,$$

which is the familiar expression for the power in a resistor modified by the ratio of the current comparator. Power factors other than unity are achieved by introducing precision capacitors in the circuit as discussed later.

The NBS reference (working) standards are four rotating watt-hour meters in a temperature-controlled enclosure. These meters have no registers, but rather provide an electrical pulse output of 500 pulses per revolution of the rotating disk. These meters are calibrated individually using the current-comparator power bridge, and only at 120 volts, 5 amperes, and at power factors of unity and 0.5, leading and lagging. Thereafter, these test conditions are maintained and are the only conditions under which the working standards are used. All ranging for other test voltages and currents are accomplished by the use of precision voltage and current transformers. When calibrating a customer's meter using the working standards, the sum of the outputs of the four meters is used.

The above-described system for calibrating wattmeters and watt-hour meters has been in use at NBS for about the past 10 years. Although its accuracy has been adequate for many of the calibrations requested, it is not sufficiently accurate for the critical requests presently being received. Problems of reliability are also of key concern, particularly when the present workload is large and "breakdowns" cannot be tolerated. High-accuracy tests can be done, as discussed above; however, they are not of a routine nature and are for some customers prohibitively expensive. In addition to requests for better accuracy, there is a very quickly growing demand for calibration of electronic meters that measure VAR's and VARh's (reactive power, and reactive energy, respectively). These requests are increasing because of the rapidly growing deployment of these types of meters. NBS has performed VAR/VARh calibrations for customers as special tests. For each special test, the thermal power standard and the NBS-developed phase-angle standard have been employed. These tests, however, are very tedious to perform and lengthy as well as costly.

New System Development

The new NBS power and energy calibration system presently being developed to permit higher accuracy measurements.

also expand the power factor range to include measurements at zero power factor and be capable of performing highly accurate measurements of other related parameters, such as VAR's and VARh's, on a routine basis. Calibrations will be performed, when needed, to an uncertainty of less than $\pm 0.01\%$ routinely. These measurements will be traceable through significantly fewer steps to the higher echelon standards.

The new system is based on a special NBS-developed, dual-channel, digitally-synthesized signal source having voltage and current channels [9]. The design and general approach are extensions of the technology that NBS attained while developing its present Phase Angle Standard [10]. The amplitudes and phase displacements of the two channels are very well known. The signal amplitudes are compared to a dc reference standard with a thermal voltage converter. The phase displacements are precisely controlled by digital techniques.

Figure 4 shows a block diagram of the digital generator. A high quality commercial controller having high speed data loading capability is used as the "intelligent" portion of the generator. It controls two random access memories (RAMs) which hold the digital codes for the desired waveform. Most of the time, sinusoidal waveforms are used, but the generator will have the capability of generating any arbitrary waveform. This adds greatly to its usefulness in evaluating instrument performance under distorted waveform conditions. The outputs of the two RAMs drive 18-bit multiplying digital-to-analog converters (MDACs) which construct the waveform. The voltage outputs of the MDACs, V_1 and V_2 , consist of as many as 2048 discrete amplitude steps per cycle and are sufficiently "smooth" so that no filtering is necessary. The dc reference for each MDAC is derived from individual 18-bit DACs which enables the output voltages from each MDAC to be adjusted in steps of 4 ppm of the full-scale output. The phase displacement between the two waveforms can be adjusted in $4\text{-}\mu\text{rad}$ steps.

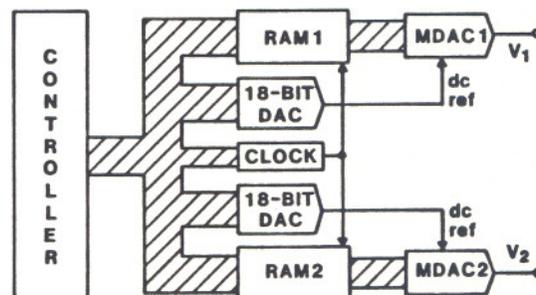


FIGURE 4 Fundamental block diagram of the digital generator.

The outputs, V_1 and V_2 , of the digital generator are relatively low-voltage signals and require amplification to the operational voltage and current magnitudes of 120 volts and 5 amperes required for the calibration of wattmeters and watt-hour meters. Figure 5 shows a diagram of the output of the digital generator providing signals for the calibration system. Voltages V_1 and V_2 feed amplifiers A and G, respectively, which amplify the voltage V to 120 volts and the current I to 5 amperes. These two amplifiers are ultra-stable and are specially designed for dc coupling and wide bandwidth to

maintain phase integrity [11]. The voltage V is applied simultaneously to the meter being calibrated (a wattmeter, WM, in this instance), the thermal voltage converter, TVC, and the current-comparator power bridge through inductive voltage dividers, IVD_1 and IVD_2 . The current I is applied through the meter WM, ranging transformer windings N_7-N_6 and N_5-N_4 , and the current comparator winding N_3 .

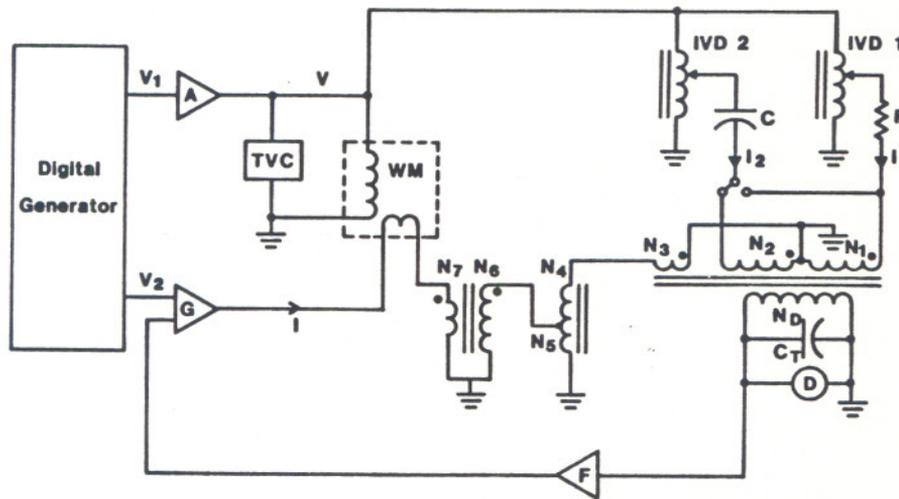


FIGURE 5 Wattmeter, WM, being calibrated with the current-comparator power bridge and being excited by the digital generator.

The voltage V is set by the generator to 120 volts as determined by the TVC. (The TVC uses a dc reference voltage which, for simplicity, is not shown.) The values of resistance, R , and capacitance, C , are selected, and the ratios of IVD_1 and IVD_2 are set to provide currents I_1 and I_2 to the comparator windings N_1 and/or N_2 (depending on the switch setting for I_2). The current I is then set to bring the ampere-turn balance to zero as indicated by the detector D . The turns ratios have been selected such that when the voltage V is exactly 120 volts, the current comparator will balance when I is exactly 5 amperes (to within very small experimental error.) Balances can be achieved to within 1 ppm. Feedback amplifier, F , is used to provide an autobalance feature which adds to the overall stability of the operation [12]. The current-comparator power bridge will be used in conjunction with the generator for the most accurate work (50 to 200 ppm measurements). The generator will be used alone for calibrations of 200 to 500 ppm ($\pm 0.02\%$ to $\pm 0.05\%$) uncertainty. In either instance, measurements can be made in a straightforward manner.

At the present time, two digital generators have been constructed and tested. Initial tests with a current comparator power bridge indicated short term stabilities (during approximately 15 minute periods) of the entire circuit to be better than 10 ppm. Work is continuing to complete the system which will be capable of calibrating several meters at the same time over a range of test voltages, currents, and any power factor. A range of frequencies will also be available. This will then provide NBS with the capability to meet the new

calibration demands of higher accuracy and economically provide a service for the much needed parameters of VAR's and VARh's.

Conclusions

The calibration system presently being employed at NBS has been in use for about 10 years providing an uncertainty of $\pm 0.05\%$. The new system under development will provide calibrations at $\pm 0.01\%$ or better. This system will be in operation by late 1986 and capitalizes on the latest technology in digital electronics. Almost totally automated, its computer controlled operation will make $\pm 0.01\%$ measurements a routine matter. In addition to providing the wattmeter and watthour meter calibration services presently available, it will with equal ease provide the economical capability of calibrating VAR and VARh meters at comparable uncertainties.

Acknowledgements

The authors wish to express appreciation to Mr. N. M. Oldham who is principally responsible for developing the new digital calibration system, to Mr. N. B. Belecki who gave many useful comments, and especially to Mrs. R. Cummings for preparing this manuscript.

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