POWER AND ENERGY MEASUREMENTS AT NIST

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Abstract

The NIST calibration service that provides electric energy traceability for the U.S. utility industry is described. Electronic watthour meters, submitted for test, are measured using the NIST Power Bridge, in which complex ac power is defined in terms of the more basic units of voltage, resistance, and capacitance. By integrating power over a known time period, the unit of energy is defined. Calibrations are performed using a synthetic loading technique at power levels between 0 and 60 kW. The basic uncertainty of the NIST Power Bridge is about 15 ppm at 120 V, 5 A, 0 to 1.0 power factor, at 60 Hz. However, calibration uncertainties depend on the power level and the instrument type. Typical uncertainties (k=2) are between 50 and 500 parts per million. A Measurement Assurance Program for 60 Hz energy is also available.

Introduction

Over 3000 electric utilities generate an estimated 3000 billion kilowatthours (kWh) of energy annually in the U.S. In 1996, the sale of electric energy exceeded $206 billion. This cost was shared by users as shown in Table 1.

[1] Electricity Division, Electronics and Electrical Engineering Laboratory, Technology Administration, U.S. Department of Commerce. Official contribution of the National Institute of Standards and Technology; not subject to copyright in the United States.

Table 1. User-share of electric power in the U.S.

Users	Energy (in billions of kWh)	Total Cost (in billions of dollars)	Cost/kWh (in cents per kWh)
Industrial	1030	47	4.60
Commercial	887	68	7.64
Residential	1082	91	8.36

The various types of devices that measure this energy are collectively known as electricity meters. They measure active power and energy (watt/watthour meters), reactive power and energy (var/varhour meters), peak power (demand meters), power factor (phase meters), and apparent power (voltmeters and ammeters). Electric utilities ordinarily charge customers only for the energy consumed by resistive loads (active power x time, e.g., kWh). However some industrial customers are charged for reactive energy because they produce low power factors that place unusual constraints on the electricity distribution system. Other customers, who use large quantities of energy intermittently, are charged at the rate of their peak energy consumption.

Until recently, electric utilities were essentially 'local monopolies' regulated by the state public utility commissions. With deregulation of the industry, it may soon be possible to shop for the most economical source of electricity. In theory, a consumer on the east coast will be able to buy power from a generation plant on the west coast. Transmission lines will be made available to all generators, but the final distribution and metering will be done by the local utility. To remain competitive, each company will be forced to optimize production. This means that flat rate metering may be replaced by time-of-use metering. Even residential watthour meters are being equipped with communication capability, and usage may be monitored every few minutes.

To maintain device compatibility and equitable billing of customers, national consensus standards are continually being developed to support the industry. One such standard, the American National Standard for Electricity Metering (ANSI C12) describes the electrical and mechanical performance of revenue meters [1]. A typical residential meter is required to perform with an uncertainty of ±2%. At first this may seem like a trivial metrology problem, however the 2% uncertainty must hold over the range of temperatures and humidities encountered across the country for long periods - the useful life of a modern watthour meter is over 30 years. With improvements in the past several decades, most watthour meters are now ten times more accurate than the C12 requirement. Meters that measure consumption at large industrial locations or at points of interchange between utilities, have uncertainties of 0.1% or lower. The equipment used to calibrate these meters is typically two or three measurement echelons away from national standards. Utilities would like a factor of ten improvement at each step, so only two steps lowers the uncertainty requirement at NIST to 10 ppm. This paper describes the techniques used to obtain this challenging level of uncertainty as well as the NIST calibration service for disseminating the units of power and energy.

Derivation of the SI Units of Electric Power and Energy

The NIST Power Bridge [2, 3] is used to derive complex ac power in terms of the basic electrical units of voltage, resistance, and capacitance. As shown in Fig. 1, the meter under test (MUT) is energized from a synthetic power source having separate voltage and current channels. Amplitude- and phase-adjustable test signals are generated by a dual-channel digital waveform generator which is followed by a voltage amplifier (A) to produce the test voltage (typically 120V) and a transconductance amplifier (G) to produce the test current (typically 5 A). The test voltage is measured to an uncertainty of approximately 5 ppm using a calibrated digital multimeter (DMM). By applying the test voltage to an adjustable resistor and/or capacitor, reference currents I_R and I_C are generated. These currents are compared to the test current I using a precise three-winding transformer known as a current comparator. Measurements at 1.0 power factor are made using only R. At zero power factor, only C is used. A combination of R and C is used to obtain any arbitrary lagging power factor. At ampere-turn balance the relationship between the currents is given by:

$$IN_3 = I_R N_1 - I_C N_2 \tag{1}$$

where N_1, N_2, and N_3 are the number of turns on various winding of the current comparator. By applying I_C to N_1, all leading power factors can be obtained.

The apparent power VI may be expressed in terms of the active power P and the reactive power Q by:

$$VI = P + jQ \tag{2}$$

where

$$P = (N_1/N_3)V^2/R \tag{3}$$
$$Q = (N_2/N_3)\,\omega C V^2 \tag{4}$$

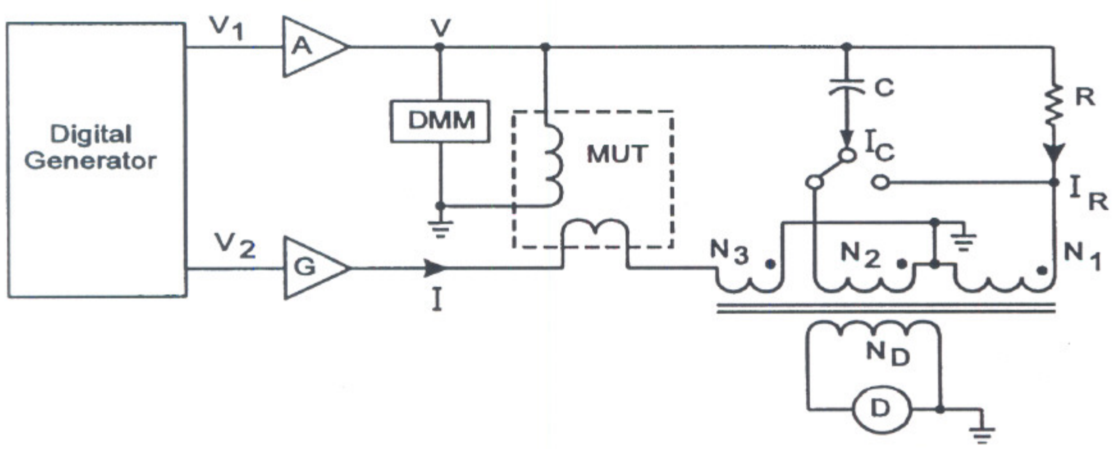

Fig. 1. Power Bridge

It is important to note that the active power applied to the MUT is only a function of V and R, the current comparator ratio errors, and the dissipation factor of C. Similarly, reactive power is only a function of V and C, the current comparator phase errors, and the phase angle of R.

Once the appropriate ratios are set on the current comparator, the bridge is balanced as follows: Using the DMM, the voltage applied to the MUT is adjusted to the desired test voltage by adjusting the gain of the voltage channel of the digital waveform generator. The amplitude and phase of the current are adjusted in a similar manner to achieve ampere-turn balance (where the output of the detection winding of the current comparator is minimized). At this point the active power applied to the MUT is given by Eq. 3. The Type B standard uncertainties and typical expanded uncertainties are given in Table 2 (in ppm of the apparent power).

Table 2. Type B standard uncertainties for NIST power and energy calibrations

Power Factor	Type B Standard Uncertainty	Expanded Uncertainty (k=2)
1.0	6	15
0.5 (lead and lag)	6	15
0.0 (lead and lag)	4	10

These are the best uncertainties obtainable using the NIST Power Bridge, requiring extensive characterization of the bridge components and numerous repeat measurements. They are normally applied only to measurements made for international comparisons between national laboratories.

NIST Calibration Services for Power and Energy

The NIST Power Bridge is the reference for 50 Hz to 400 Hz power and energy measurements at NIST. The NIST Calibration System is set up for electronic meters, but electromechanical meters can be calibrated with special setups. The NIST Power Bridge was designed for 120 V, 5 A operation, therefore additional voltage dividers and current transformers are necessary to provide calibrations over the range of 120-600 V, and 0.2-100 A. The uncertainties added by these devices is less than 50 ppm. Typical uncertainties range from 50 ppm to 500 ppm for the calibrations performed on watthour meters using this calibration system. These values vary with the instrument type and the applied power.

NIST offers an in-house calibration service for customer's watthour meters and a Measurement Assurance Program (MAP). For the in-house service, the customer must schedule the calibration in advance and the turn-around time is typically between 4 to 8 weeks. (We have recently introduced a streamlined service with limited test points with a two-week turn-around time that is outside the scope of this paper.) The MAP takes about twice as long. Test fees are available in the latest NIST Special Publication SP250 [4].

For all in-house calibrations, the customer requests the test parameters (voltage, current, power factor, and frequency) within the limits of the NIST services. The meter is connected to the test bench and allowed to "warm-up" for at least one hour before testing begins. Most commercial standard wattmeters provide an analog output in the form of a dc voltage or current which is proportional to the measured power, this is measured using a precision DMM. Most watthour meters provide a pulse output whose frequency is proportional to the measured power. This allows the user to measure energy simply by counting the number of output pulses or by measuring the frequency of these pulses (if the source is sufficiently stable). The NIST Calibration System utilizes 6 frequency counters, allowing for the simultaneous measurement of 6 watthour meters. The DMM and the frequency counters are connected via the GPIB bus to a computer that collects data on each meter under test. These data are then compared to the expected output for that particular test parameter and the error is computed and printed out. The measurement is then repeated 4 more times. A spreadsheet program averages the data collected and computes the standard deviation, which is used to compute the uncertainty at each test point. A report of calibration is then printed that gives the test points and the results of the measurements and the uncertainty for each test point.

The MAP [5, 6] uses a NIST-owned watthour meter calibrated using the same calibration facility. The meter is calibrated at NIST and sent to the customer's standard laboratory where it is tested as though it were one of the customer's working standards. The meter is then returned to NIST where it is recalibrated. A test report is issued which assigns a correction and uncertainty to the customer's calibration system, based upon the difference between the data taken at NIST and the data taken at the customer's laboratory.

Conclusions

NIST supports electricity metering for the U.S. electric utility industry through a calibration service for wattmeters and watthour meters. The standard for 50 Hz to 400 Hz power and energy is the NIST Power Bridge, which is capable of uncertainties as low as 10 ppm for specific test points. Tests over the range of 120 V to 600 V, 0.2 A to 100 A, at any power factor for active and reactive power are available at uncertainties that range from 50 ppm to 500 ppm range. Two alternatives are available for power and energy measurements at NIST. The most popular is for customer-owned meters that are tested at NIST. A measurement assurance program is also available which used a NIST-owned meter to test the customer's calibration system.

Aknowledgments

The author wishes to express his gratitude to Nile Oldham for his contributions to this paper.

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