

An International Comparison of Power Measurements at 120 V, 5 A, and 60 Hz

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Abstract—An international comparison of ac power measurements between metrology laboratories at the Physikalisch-Technische Bundesanstalt—Institut Berlin, (PTB(IB)), the Electrosystems Division of the National Bureau of Standards (NBS), and the Division of Electrical Engineering at the National Research Council of Canada (NRC(EE)) is described. The three calibration systems, each of different design and developed independently, are discussed, and estimates of the systematic uncertainties are given. The transfer standard was a recently developed thermal wattmeter of high stability. No laboratory differed by more than ± 15 parts per million (ppm) from the average, with reference to apparent power at unity and 0.5 power factors, lead, and lag. This is consistent with the error limits estimated by each of the participants.

I. INTRODUCTION

COMPARISON measurements of electrical quantities using different and independently developed calibration systems are highly relevant to the establishment and maintenance of the basic standards and associated measurement procedures at the national metrology laboratories. Such comparisons not only inspire confidence in the assignment of a value to a standard but through the investigation of residual discrepancies lead to overall improvement. Since the expenses for developing several calibration systems are prohibitive for any institution alone, international comparisons are regularly made between many metrology laboratories. These comparisons also ensure international consistency of measurements and contribute to the establishment of a generally acknowledged level of attainable measurement certainty. In addition, they usually demonstrate the actual state of the art in calibrating the involved transfer devices.

International comparisons are frequently made with respect to the units of dc voltage and resistance. Other quantities, for example, capacitances and transformer ratios, are compared from time to time whenever a suitable opportunity arises, such as the development of improved transfer devices. There have been few comparisons made, however, in the measurement of ac power at the normal transmission

frequencies, 50–60 Hz, although this has been always highly desirable in view of the somewhat complicated nature of the measurements. Since ac power is a derived quantity, involving the basic standards of dc voltage and resistance as well as an ac–dc transfer process, a reference standard embodied in a single device does not exist. Instead, the standard of ac power is represented by an entire calibration system incorporating the basic standards. The error of such a system cannot be determined from a direct measurement; it can be estimated only from the error contributions of the components. In order to check this error estimation, it would be necessary to compare different calibration systems supplied with the same input power directly. This, however, is not feasible in practice since it would require that a considerable number of sensitive calibrated instruments be transported from one laboratory to another without degradation of accuracy.

This situation has been altered recently by the development of a sufficiently accurate, stable, transportable, thermal wattmeter at the PTB(IB). During the summer of 1976, this wattmeter was calibrated by the NBS, the NRC(EE), and the PTB(IB) with reference to the local standards. In this paper, a description of the equipment and procedures used by the three laboratories is given, and the results of the calibrations are reported and compared. Supplementary measurements between two of the laboratories (NBS and NRC(EE)) using some commercial time-division multiplier (TDM)-type wattmeters are also included.

II. THE PTB(IB) THERMAL WATTMETER

The instrument is based on a thermal ac–dc transfer principle that has recently been described [1]. It has been designed for the measurement of ac voltage, current, power, and energy at power frequencies. An ac current, derived from the input quantity to be measured, is automatically balanced by the equivalent dc current at the heater of a multijunction thermal converter. An integrating-type analog-to-digital converter makes it possible to perform further processing of the measured dc value with a digital arithmetic unit which calculates linear (for rms voltage and current) and square-law (for power) time-average values as well as time-integrated quantities (for energy). The result is suitably scaled and indicated in the correct units on a digital display.

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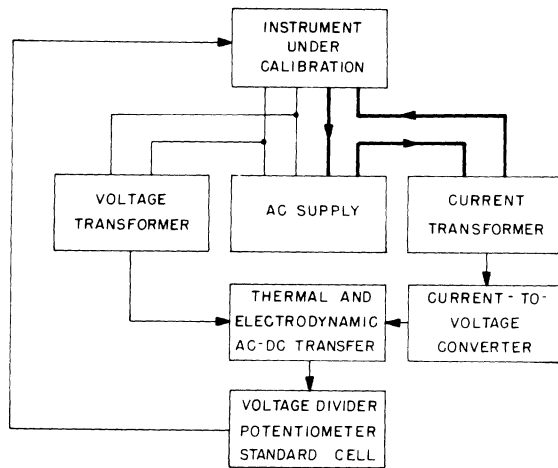


Fig. 1. PTB calibration system.

The resolution of the instrument depends on the averaging time interval and is of the order of 1 ppm for a period of 100 s. Its accuracy depends mainly on the stability of the internal voltage and resistance references and the input transformer and matched resistive divider ratios. The voltage reference including the divider ratio can be checked *in situ* by dc calibration.

III. CALIBRATION PROCEDURES

A. At PTB(IB)

The configuration of the PTB equipment is shown in Fig. 1. This system, which has been described elsewhere in detail [1], can be used to make calibrations of ac voltage, current, and power. The instrument under calibration is connected to the system in the usual manner with voltage circuits in parallel and current circuits in series. The ac supply enables an independent setting of voltage and current amplitudes, their relative phase angle, and the operating frequency.

The input to the calibration system consists of matching transformers for voltage and current. The secondary current of the current transformer is also converted to a voltage by means of a resistor. The ac-dc transfer of voltage (for rms values) or voltage product (for power) can be made alternatively by electrodynamic and thermal methods. Both transfer instruments deliver dc voltages equivalent to the input ac voltages. Their values are determined with reference to the standard cell by means of a resistive voltage divider and a potentiometer. There is an independent option for calibrating the instrument under test with reference to the dc standard. This provides a check of its functions and the opportunity for correction of the drifts of its internal voltage reference.

The systematic uncertainties can be classified for the system components as shown in Fig. 1. The uncertainties consist of contributions due to the voltage and current transformers, the resistor used for current-to-voltage conversion, the ac-dc transfer, the scaling of the dc voltage by the divider and the potentiometer, and, finally, the voltage standard itself. Except for the ac-dc transfer, all uncertainties are due to the calibration of the individual

TABLE I
UNCERTAINTIES OF PTB-IB CALIBRATIONS
(IN PPM OF APPARENT POWER OR OF NOMINAL)

| Systematic uncertainty: contributing source | POWER AT POWER FACTOR | | | VOLTAGE | CURRENT |
|--|-----------------------|-----|-------------|---------|---------|
| | -0.5 (lag) | 1.0 | +0.5 (lead) | | |
| Voltage transformer | 1 | 1 | 1 | 1 | - |
| Current transformer | 3 | 2 | 3 | - | 2 |
| Current-to-voltage Converter (resistor) | 1 | 2 | 1 | - | 2 |
| ac-dc transfer | 2 | 2 | 2 | 1 | 1 |
| Voltage divider | 2 | 2 | 2 | 1 | 1 |
| Potentiometer | 2 | 2 | 2 | 1 | 1 |
| Standard cell | 1 | 2 | 1 | 1 | 1 |
| Total systematic uncertainty (rss) | 5 | 5 | 5 | 2 | 3 |

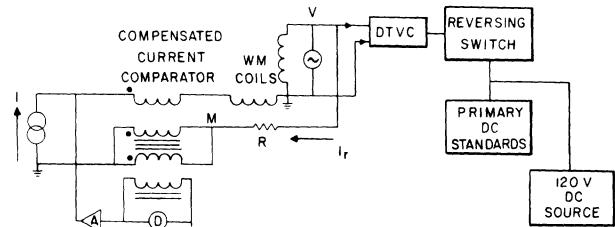


Fig. 2. NBS calibration circuit for unity power factor.

components in terms of the primary standards of PTB. Their numerical values under the conditions of the comparison measurements are compiled in Table I, properly weighted for the different electrical quantities. The difference between the equivalent dc quantities provided by the thermal and electrodynamic systems has been considered in the assignment of the value for the ac-dc transfer error. Since the two systems rely on different principles and have been developed independently, an error leading to a common offset is not very likely. The total systematic uncertainty has been derived from these components as the root of the sum of squares (rss).

B. At NBS

The NBS used the recently completed current comparator energy system to calibrate the PTB wattmeter. The basic principle of operation is a constant power-time interval method which has been completely described in an earlier paper [2]. Although the approach to the measurement is similar to the NRC method, this by no means detracts from the independence of the reported values. The systems were developed independently in the two laboratories, and the approaches for establishing the ac voltage and the phase relationship are essentially different techniques. In addition, the currents are scaled to the working level by different methods. Therefore, it is highly unlikely that the sources of systematic error would be the same.

In the NBS method, the ac voltage and current are precisely maintained and measured in terms of the primary dc standards using conventional potentiometric techniques and an ac-dc transfer standard. A simplified circuit diagram of the system, connected for unity power factor operation, is shown in Fig. 2 along with the instrumentation used to establish the ac voltage. Fig. 3 is the modified voltage circuit for the 0.5-power-factor lag connection of the system. At

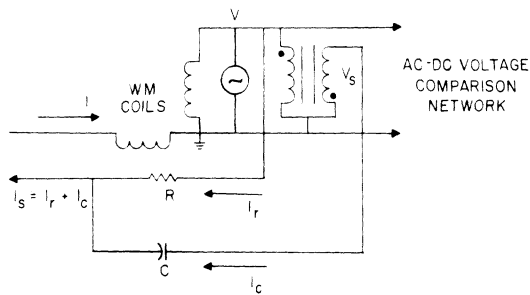


Fig. 3. Modifications to NBS circuit for 0.5-power-factor lag.

balance the dc and ac voltage at the differential thermal voltage comparator (DTVC) are equal. The ac voltage across resistor R establishes a known reference current in the secondary of the compensated current comparator which is transformed up to the current level of the primary and by means of the feedback circuit is held in adjustment to maintain the ampere-turn balance. At balance the expression for the power applied is given by

$$P_a = \frac{NV_{dc}^2}{R} (1 + C_{wa})$$

where P_a is the applied power in watts, N is the nominal turns ratio of the current comparator, V_{dc} is the corrected dc voltage at the DTVC input, R is the nominal dc value of the resistor, and C_{wa} is the sum of the corrections associated with each of the components used for the measurement. The combined uncertainties for the dc-voltage measurement system and the DTVC used to establish the ac-voltage amount to 8 ppm. The uncertainties attributed to the components used to maintain the current level are 6.4 ppm for the resistor and 1.1 ppm for the current comparator. The rss systematic uncertainty assigned to unity power factor is 10 ppm. At 0.5 power factor, the magnitude of uncertainty for the additional contributing components is 5.3 ppm for the phase-shifting voltage transformer and 19.6 ppm for the capacitor conductance. This gives the rss estimate of the systematic uncertainties of 0.5 power factor as 23 ppm of applied power or 12 ppm of apparent power. A detailed explanation of these uncertainties for the NBS system is given in [2].

The values for the PTB instrument first measured at NBS in July 1976, differed from the PTB results by more than the combined uncertainties of both test systems. Although the difference was less than 100 ppm, it was significant and not to be tolerated. The situation created a measurement challenge that required both time and effort to resolve the discrepancy. In late August, the investigation disclosed that the power supply in the feedback circuit of the current comparator had become defective and was introducing an error signal which offset the ampere-turn balance. The results reported in Table II in this paper are those taken after the trouble was disclosed and corrected. This shows the value of comparisons of this type to evaluate the error analysis of basic measurement techniques.

An additional benefit of this comparison was the disclosure that the NBS electrodynamic wattmeter method, on

TABLE II
CALIBRATIONS OF THE PTB WATTMETER
(IN PPM OF APPARENT POWER AT 120 V, 5 A, AND 60 Hz)

| LABORATORY | ERRORS* | | | RANDOM UNCERTAINTY LIMITS (3σ) | | | NUMBER OF MEASUREMENTS | | |
|------------|-----------|---------|------------|--------------------------------|-----|-----|------------------------|-----|-----|
| | -0.5(lag) | 1.0 | +0.5(lead) | -0.5 | 1.0 | 0.5 | -0.5 | 1.0 | 0.5 |
| PTB(IB)-1 | + 7(8) | + 5(8) | + 7(8) | 3 | 3 | 3 | 7 | 7 | 7 |
| NBS | +20(16) | + 2(17) | +21(14) | 4 | 7 | 1 | 12 | 12 | 9 |
| NRC(EE) | +20(25) | +14(39) | +36(21) | 9 | 9 | 6 | 5 | 10 | 5 |
| PTB(IB)-2 | + 7(7) | - 1(7) | +14(7) | 2 | 2 | 2 | 9 | 9 | 9 |
| AVERAGE | +16 | + 6 | +22 | | | | | | |

Total uncertainty is shown in parenthesis after each error value.

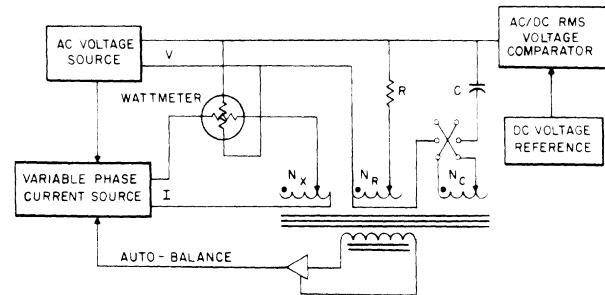


Fig. 4. NRC(EE) calibration circuit.

which all power and energy measurements in the United States were previously based, agreed with the current-comparator method to better than 30 ppm. Prior to this test no means were available to precisely compare the older NBS system with the new current-comparator system.

C. At NRC(EE)

The NRC(EE) calibration procedure employs a power bridge based on the current-comparator technique [3]. In this circuit, as shown in Fig. 4, the in-phase or active power component of the wattmeter current is scaled by the current comparator against a reference current derived by applying the wattmeter voltage to a reference resistor R . Similarly, the quadrature or reactive power component of the wattmeter current is scaled against the current from a reference capacitor C . The current comparator is maintained in ampere-turn balance by feedback to the current source. The balance equation of the bridge is

$$VI = \frac{1}{N_x} (N_R V^2/R + jN_C V^2\omega C).$$

The power reference is the power dissipated in the resistor— V^2/R . Thus both the voltage V and resistance R must be related to the dc standards. The ac voltage V is compared to a dc reference of the same nominal value using an ac-dc, rms voltage comparator (4). The resistor R was selected for its low, ac-dc transfer-error characteristic.

The most serious source of uncertainty in the NRC(EE) measurements arose in the establishment of the dc reference. Proper equipment such as a volt box and standard cell were not locally available at the time of the measurements. Instead, a scaling technique using a multirange differential voltmeter was employed, for which the overall uncertainty is estimated at 19 ppm. Inclusion of the wattmeter dc calibration feature in this process, however, reduces the uncertainty to 14 ppm. The ac-dc transfer at the bridge voltage level contributes a further 5 ppm to the voltage uncertainty. The

uncertainties in the current-comparator ratio and the resistor are each estimated to be of the order of 5 ppm. The resulting uncertainty in power at unity power factor thus becomes

$$\sqrt{(2 \times 14)^2 + (2 \times 5)^2 + (5)^2 + (5)^2} = 30 \text{ ppm.}$$

At 0.5 power factor, the uncertainty of the capacitor dissipation factor, estimated at 5 ppm, increases this to about 31 ppm.

IV. MEASUREMENT RESULTS

During the calibrations of the PTB wattmeter, its readings and those of the standard system were recorded over a period of several days. The average errors of the instrument as well as 3σ limits of the random uncertainty were calculated from these data. The results obtained by the three laboratories are given in Table II along with the total uncertainties. The listed quantities are defined as follows.

Errors:

$$(P_w - P_A)/S$$

where P_w is the active power indicated by the wattmeter, P_A is the active power applied to the wattmeter, and S is the apparent power.

Random Uncertainty Limit (3σ):

$$3 \cdot \sqrt{\frac{\sum (x_i - \bar{x})^2}{n(n-1)}}$$

where n is the number of measurements, x_i is the i th measurement, and \bar{x} is the average of n measurements.

Total Uncertainty: Systematic uncertainty plus random uncertainty limit.

A graphical illustration of the results presented in Table II is shown in Fig. 5. The calibrations PTB(IB)-1 are those made by PTB at the beginning of the comparison and PTB(IB)-2 at the end. In deriving the averages quoted, each of the PTB calibrations is given half weight. It is apparent from the two PTB values that the wattmeter calibration was relatively unaffected by either the transport conditions experienced between laboratories or the time period of 4 months taken to accomplish the intercomparison.

Comparisons of the voltage and current measuring functions of the wattmeter were also made. The errors given in Table III are in parts per million, being positive if the meter indication is larger than the actual quantity.

In assessing the results, the following factors should be taken into account.

1) The errors in power measurement are referred to apparent power. This is more favorable by a factor of two at the half-power factors than if they had been referred to the active power or output.

2) In the NRC(EE) measurements, the base voltage was the 7-V dc used to calibrate the PTB wattmeter. This voltage was not referred back to the Canadian National Standard.

At unity power factor, the NBS calibration agrees with the average of the two PTB(IB) calibrations while NRC(EE) deviates by 12 ppm. Also at PTB(IB) the voltage-current product obtained from the calibration of the wattmeter

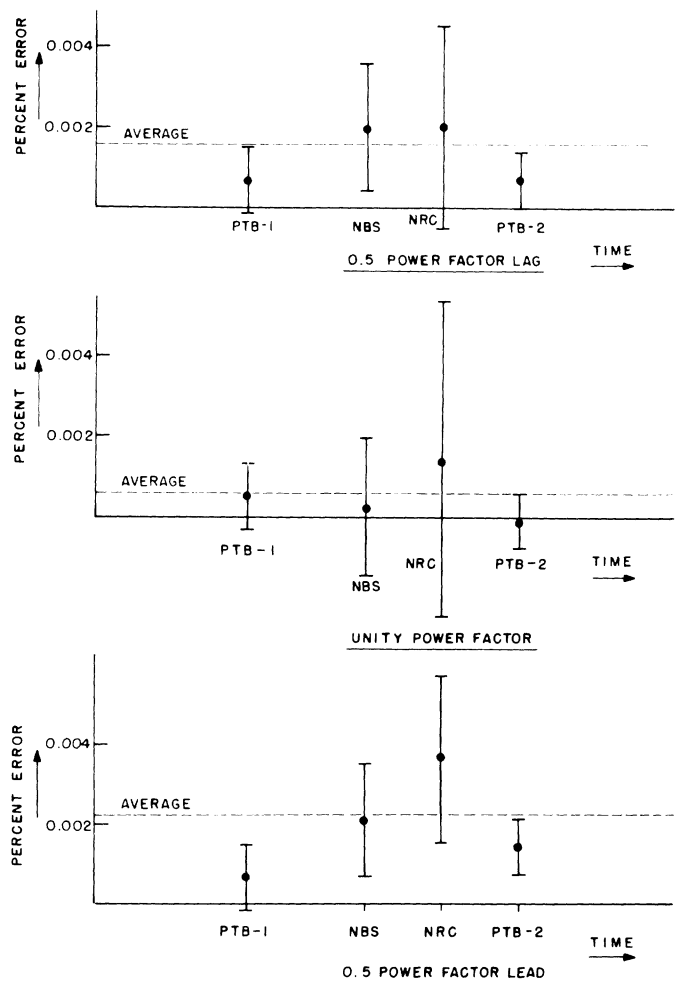


Fig. 5. Comparison of calibrations.

TABLE III
CALIBRATIONS OF THE
PTB WATTMETER VOLTAGE AND CURRENT FUNCTIONS
(IN PPM OF NOMINAL AT 120 V, 5 A, AND 60 Hz)

| LABORATORY | ERRORS | | RANDOM UNCERTAINTY LIMITS (3σ) | | NUMBER OF MEASUREMENTS | |
|------------|---------|---------|---|---------|------------------------|---------|
| | Voltage | Current | Voltage | Current | Voltage | Current |
| PTB(IB)-1 | -2 | +7 | 2 | 2 | 7 | 7 |
| NBS | -4 | - | 2 | - | 33 | - |
| NRC(EE) | n | +28 | 4 | 4 | 12 | 6 |
| PTB(IB)-2 | -4 | +3 | 2 | 1 | 9 | 9 |
| AVERAGE | -2 | +16 | | | | |

voltage and current functions agree with the power measurements. At NRC(EE) it is 14 ppm higher. However, the NRC(EE) voltage calibrations agree to within 3 ppm of the corresponding PTB(IB) values whereas there is a considerable discrepancy (23 ppm) in the current measurements. Since the NRC(EE) current measurements involve the current-comparator bridge and the resistor while the voltage measurement does not, the major portion of this discrepancy can thus be attributed to these components. The estimated uncertainties in the NRC(EE) voltage determination were therefore probably too pessimistic and those for the other components too optimistic.

At 0.5 power factors, the errors as measured by all three laboratories shift toward the positive, independent of

TABLE IV
NBS/NRC(EE) COMPARISON USING COMMERCIAL WATTMETERS
(IN PPM OF APPARENT POWER AT 120 V, 5 A, AND 60 Hz)

| WATTMETER | (NBS-NRC) AT POWER FACTOR | | |
|-----------|---------------------------|-----|------------|
| | -0.5(lag) | 1.0 | +0.5(lead) |
| 1 | +30 | - 5 | +16 |
| 2 | -31 | -40 | -58 |
| AVERAGE | 0 | -22 | -21 |

whether the phase is leading or lagging. Part of the shift, approximately 10 ppm, is due to a slight nonlinearity of the transfer wattmeter that has also been determined independently. The residual discrepancy appears as an offset of the PTB(IB) results compared to those of NBS and NRC(EE). This cannot be explained by the additional error sources considered at half power factor, since they should only cause phase shifts resulting in differences which are symmetrical to zero for leading and lagging phase angles. Self-consistency measurements conducted at PTB(IB) involving only the ratio of unity to half-power-factor values offered no clue to this problem, since the predicted deviations were less than 1 ppm. Thus the results suggest that any further comparison measurements should be specially directed toward clearing up the discrepancy at half power factors.

The results of a parallel comparison between NBS and NRC(EE) using two commercially available wattmeters of the TDM type are shown in Table IV. The reported difference is computed from the average value obtained by the base laboratory, at the beginning and end of the comparison period, and is compared with the value obtained at the other laboratory. The average value was used because instabilities of the order of 50 ppm were observed for both instruments during the exchange period. While the commercial meters were not as stable as the PTB(IB) instrument, the results are still very impressive. It is apparent that commercial power instruments are vastly improving and will soon warrant measurements of this higher accuracy.

V. CONCLUSION

The results of an international comparison of ac, sinusoidal power measurements at 120 V, 5 A, 60 Hz, and unity and 0.5 power factors (lead and lag) have been presented. The methods used by each of the three participants have been described, and an estimate of the uncertainties in each has been given.

There are several outstanding factors in this comparison test; however, the most important is that it is the first international comparison of an extremely accurate ac-power measurement. The close agreement achieved by the three independent laboratories using their standard test methods has taken away uncertainties that existed in the error estimations. It has been verified that the recently developed calibration systems have improved the measurement capabilities of the participating laboratories by an order of magnitude. In addition, a common level of accuracy has been established that makes it easier to investigate residual discrepancies.

The positive results were made possible by having a suitable wattmeter for a transfer device. The tests with commercial wattmeters indicate what can be achieved with transfer instruments of lesser stability. It is apparent, however, that such wattmeters are suitable only for comparisons of a factor of two to five less precise than those presented in this paper.

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