# An International Comparison of 50/60 Hz Power (1996–1999)

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*Abstract*—**An international comparison of 50/60 Hz power is described. The traveling standard was an electronic power transducer that was tested at 120 V, 5 A, 53 Hz, at five power factors (1.0, 0.5, and 0.0). Fifteen National Metrology Institutes (NMIs) from six metrology regions participated in the comparison.**

## I. Introduction

INTERNATIONAL comparisons of units of measurement are often conducted informally between two or more National Metrology Institutes (NMIs). These comparisons are generally done to resolve technical problems or to evaluate new standards or technologies. Large-scale, formal comparisons, within and between the world's metrology regions, are critical elements in facilitating international trade through mutual recognition agreements [1]. The latter requires a pilot laboratory to run the comparison, schedule testing at each participating NMI, and select and coordinate transportation of the traveling standard. In 1987, the National Research Council (NRC) in Canada served as the pilot laboratory for one of the first international comparisons of electric power [2].

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In 1994, the National Institute of Standards and Technology (NIST) agreed to serve as the pilot laboratory for another such comparison. The international comparison of 50/60 Hz power began in June 1996. At about the same time, local power comparisons were beginning in the European Metrology Region EUROMET, coordinated by Rainer Bergeest of the Physikalisch-Technische Bundesanstalt (PTB) in Germany, and the North American Metrology Region NORAMET, coordinated by Eddy So at NRC [3]. Dr. Bergeest and Dr. So, experts in the field of power measurements, provided valuable assistance for the comparison described in this paper, which will eventually be linked to the EUROMET and NORAMET comparisons.

## II. Traveling Standard

After consultation with PTB, NRC, and other NMIs, it was decided to perform the comparison at 53 Hz—close to the power frequency of most countries, but far enough away to avoid annoying beat frequency problems. Five points were selected to test the amplitude and phase measuring capabilities of the power standards at each NMI: 120 V and 5 A at power factors 1.0, 0.5 lead, 0.5 lag, 0.0 lead, and 0.0 lag (where lead/lag indicates that the current waveform leads/lags the voltage waveform).

The traveling standard selected is a commercial electronic ac-power-to-dc-voltage converter based on the time-division-multiplier operating principle [4]. It is powered at 120 V, at mains frequencies between 50 Hz and 400 Hz. It has front-panel binding post/banana plug input terminals, with two voltage ranges (120 V and 240 V) and two current ranges (1 A and 5 A). With full-scale voltage and current applied at 1.0 power factor, the nominal output of the converter is 10 V dc, which is available at terminals on the front panel. It also has auxiliary monitor terminals for its +7 V and −7 V dc references.

The traveling standard selected was the more stable of two such instruments monitored in the NIST power laboratory for several years prior to the comparison. Participants were asked to record several test parameters that could influence the results. These include frequency, voltage, current, power factor, temperature, humidity, the zero offset, and the ±dc reference voltages of the traveling standard.

## III. NMI Power Standards

Brief descriptions of the power standards used to calibrate the traveling standard at the NMIs that participated in the comparison are given below. In addition to the operating principle, critical components of each system are identified, and the range of estimated combined standard uncertainties ($k = 1$) are given in microwatts/watt ($\mu$W/W) of the apparent power (VA).

*Argentina:* At the Instituto Nacional de Tecnología Industrial (INTI), measurements were made using a thermal power comparator, which uses the method of the mean squared value of the sum and the difference of two voltages [5]. One voltage is derived from the test voltage by means of a two-stage voltage transformer and the other from the test current by means of a two-stage current transformer with magnetic feedback and a precision resistor. With this system the ac power is compared with an equivalent dc power using a thin-film thermal converter. Combined standard uncertainties of this system range from 10 to 19 $\mu$W/W.

*Australia:* The National Measurement Laboratory (NML) standard of power comprises compensated current and voltage transformers and a double-bridge power comparator [6] and [9]. AC and dc power are applied simultaneously to the two bridge circuits which are based on two dual-heater multijunction thermal converters with outputs connected in series opposition. Differences between the bridges and asymmetries between bridge arms are cancelled by interchanging the ac and dc quantities and by reversing the power in both. This requires a total of four measurements, the mean of which gives true ac power in terms of applied dc power. Combined standard uncertainties range from 6 to 8 $\mu$W/W.

*Brazil:* In the Instituto Nacional de Metrología (INMETRO) Power Bridge [7], a reference current proportional to the test voltage is compared to the test current using a current comparator. At balance, the active, reactive, and apparent power are derived from the ac voltage, the impedance of standards used to generate the reference currents, and the current comparator ratio. This bridge is still under development and present combined standard uncertainties range from 25 to 30 $\mu$W/W.

*Canada:* In the NRC Power Bridge [8], reference currents proportional to the test voltage are compared to the test current using a current comparator. At balance, active power is derived from the ac voltage, the impedance of standards used to generate the reference currents, and the ratio of the current comparator. Combined standard uncertainties range from 6 to 8 $\mu$W/W.

*China:* In the National Institute of Metrology (NIM) Double-Bridge Power Comparator [9], the ac voltage and current are scaled to low-level signals using voltage and current transformers. These signals are compared to a known dc power using the bridge, which is based on a multijunction thermal converter. The output emf of the converter represents the difference between the ac and dc power. Combined standard uncertainties range from 4 to 6 $\mu$W/W. *In January 2000, NIM discovered several sources of error in this bridge and has requested a follow-up bilateral comparison.*

*Germany:* The first set of measurements at PTB was made using the PTB Thermal Wattmeter [10]. The follow-up measurements were performed using the recently developed PTB Sampling Wattmeter [11], in which the test voltage is measured using a thermal voltage converter and the test current is converted to a voltage using a current transformer and resistor. The ratio and phase of the voltage and current are measured using a sampling digital voltmeter, calibrated using an inductive voltage divider. High precision is obtained by driving the digitally synthesized source and the voltmeter from the same clock. Combined standard uncertainties range from 2.5 to 8 $\mu$W/W, depending on the system.

*Italy:* In the Istituto Elettrotecnico Nazionale (IEN) Digital Sampling Wattmeter [12], the test voltage is applied directly to a sampling digital voltmeter. The test current is converted to a low-level voltage using a current transformer and resistor before it is applied to a second sampling digital voltmeter. The waveforms are simultaneously sampled for a given time and active power is computed using a least squares sine fit algorithm. Combined standard uncertainty is 15 $\mu$W/W.

*Mexico:* In the Centro Nacional de Metrología (CENAM) Power Bridge [8], reference currents proportional to the test voltage are compared to the test current using a current comparator. At balance, active power is derived from the ac voltage, the impedance of the standards used to generate the reference currents, and the ratio of the current comparator. Combined standard uncertainties range from 17 to 27 $\mu$W/W.

*New Zealand:* In the Measurement Standards Laboratory (MSL) Power Standard [13], the test voltage is divided with a resistive divider to about 1 V, and a power bridge compares this voltage with the voltage across a current shunt passing the test current. The power bridge comprises two inductive voltage dividers, two precision resistors, and a precision capacitor. The unity power factor uncertainty of 19 $\mu$W/W is dominated by the uncertainty in the ac volt, which is being upgraded. Zero power factor uncertainty is 22 $\mu$W/W. *The laboratory's performance in the comparison was compromised by a breakdown in equipment maintaining the ac volt.*

*Russia:* In the D.I. Mendeleyev Institute for Metrology (VNIIM) Differential Thermal Wattmeter [14], ac power is compared to its dc equivalent using a VNIIM-designed Thermal Comparator based on dual-heater multijunction thermal converters. Its unity power factor ac/dc uncertainty is less than 8 $\mu$W/W. The test voltage and current (up to 400 V and 10 A) are converted by resistive voltage dividers and current shunts to 1.0 V with angular uncertainty no more than 6 $\mu$rad at frequencies between 45 Hz and 65 Hz. Combined standard uncertainties range from 9 to 14 $\mu$W/W.

*Singapore:* At the National Measurement Centre (NMC) of Singapore Productivity and Standards Board (PSB), the Automated Reference Power Calibration System consists of a stable power source and a reference watt converter. The system can provide traceable calibration of power and energy for voltage and current up to 600 V and 20 A, respectively, and for any power factor from zero lag through unity to zero lead with measurement uncertainty of 25 $\mu$W/W. *This uncertainty is to be improved when a new current comparator bridge system is introduced in mid 2000.*

*South Africa:* In the National Metrology Laboratory (NML) of the Division of Production Technology (CSIR) Power Bridge [8], reference currents proportional to the test voltage are compared to the test current using a current comparator. At balance, active power is derived from the ac voltage, the impedance of standards used to generate the reference currents, and the ratio of the current comparator. The combined standard uncertainties range from 20 to 40 $\mu$W/W. *Errors in the ac voltage measure-*

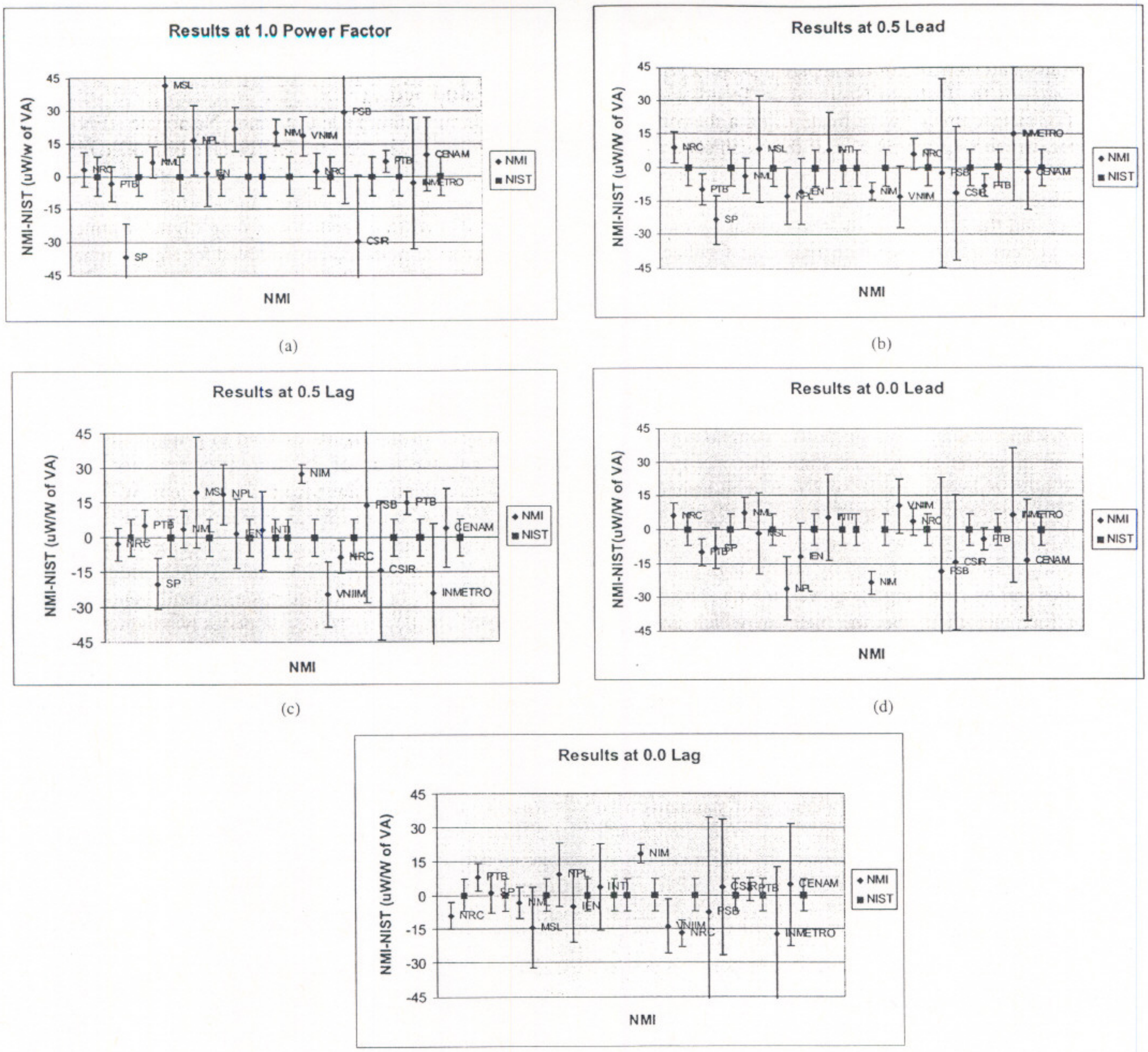


Fig. 1. Plots of the differences between NMIs, normalized to measurements at NIST before and after measurements at each NMI. NMIs (diamonds) from left to right: NRC, PTB, SP, CSIRO/NML, MSL, NPL, IEN, INTI, NIM, VNIIM, NRC, PSB, CSIR/NML, PTB, INMETRO, and CENAM. NIST values (squares) are along the zero line. Error bars represent the NMI combined standard uncertainty ($k = 1$).

*ment were encountered during the comparison and a follow-up bilateral comparison has been requested.*

*Sweden:* In the Swedish National Testing and Research Institute (SP) Digital Sampling Wattmeter [15], the active power is measured as the mean of the product of simultaneously sampled pairs of values of the voltage and the current (for sinusoidal signals). Due to the wattmeter design, the measured active power is also a function of the ratio of the inductive voltage divider used to scale the test voltage, the impedance of the shunt resistor used to scale and transform the test current into a voltage, the scale-factor of the two multimeters used to sample the scaled voltage and the voltage of the current shunt, and the trigger delay-time difference of the two multimeters. Best case combined standard uncertainties are from 8 $\mu$W/W to 15 $\mu$W/W, depending on the power factor. Errors in the waveform magnitudes were discovered after the comparison. *Data taken during the EUROMET power comparison may ultimately be substituted for the data presented in this paper.*

*United Kingdom:* At the National Physical Laboratory (NPL), power measurements are carried out by sampling the voltage and current waveforms using two isolated analog to digital converters (ADCs) of NPL design. Power is calculated by multiplying the sample pairs and using a summation to find the average power [16]. The waveforms are transformed to 1 V rms levels and applied to the ADCs. For the voltage channel, an inductive voltage divider was used. An electronically compensated current transformer and shunt resistor were used for the current channel. The gains of the ADCs are measured using a 1 V rms signal traceable to dc voltage via ac/dc transfer. Standard uncertainties are from 13 $\mu$W/W to 16 $\mu$W/W, depending on the power factor.

*United States:* In the NIST Power Bridge [17], reference currents proportional to the test voltage are compared to the test current using a current comparator. At balance, active and reactive power are derived from the ac voltage, the ratio of the inductive voltage dividers and the impedance of standards used to generate the reference currents, and the ratio of the current comparator. Standard uncertainties range from 6 to 9 $\mu$W/W.

## IV. Comparison

The original intent was to complete the comparison within three years. With 15 interested NMIs, it was decided to cycle the traveling standard back to NIST for intermediate tests after tests at two NMIs, rather than performing tests at the pilot laboratory before and after each NMI test. It is estimated that this procedure reduced the comparison time by about six months.

Several minor problems were encountered during shipment of the traveling standard, the worst of which resulted in a two-month delay in delivering the standard to one of the NMIs. The most reliable method of shipment was a direct flight, where the NMI customs agents handled the standard at each end. A Carnet traveled with the standard to simplify its passage through customs.

The traveling standard was selected because of its excellent stability and its apparent insensitivity to environmental factors. Temperature and humidity coefficients, within normal laboratory operating ranges, were negligible. While these parameters were measured at each NMI, corrections were not applied.

The internal dc references of the traveling standard, nominally $\pm 7$ V, were measured at each NMI. A change in the value of these references directly influences the transfer function of the standard. Measurements at NIST and at most NMIs indicate that the change in magnitude of the reference voltages during the three-year comparison was within 3 $\mu$V/V. Considering the stability of the reference voltages and the standard uncertainties of the measurements at each NMI, it was decided not to apply corrections for the reference voltages for the results given in this paper.

The output offset voltage of the traveling standard (with no power applied) was measured at most NMIs. With three exceptions, the offset voltages were within 2 $\mu$V/V of the mean offset measured at NIST. Again, it was decided not to apply corrections for this parameter for the results in this paper.

Two NMIs withdrew from the comparison after making measurements. Two additional NMIs asked to be included near the end of the third year, requiring the test period to be extended. Measurements were completed in October 1999.

## V. Results

The traveling standard, which had been quite stable during the first year of the comparison, began drifting in the second year. By the end of the third year, the 1.0 power factor errors had changed by 15 $\mu$W/W, with smaller changes observed at other power factors. To remove the influence of these drifts, the results have been normalized to the NIST values. Fig. 1 shows the plotted differences between the NMI measured values and the mean of the nearest before and after NIST values for the five test points. Error bars represent combined standard uncertainties for $k = 1$.

Measurements at PTB and NRC were performed at the beginning and near the end of the comparison to provide a better link to the EUROMET and NORAMET power comparisons. Data from both tests are shown on the plots.

## VI. Conclusions

With 15 NMIs contributing from six metrology regions, this was truly a global international comparison and one of the largest in electric power to date. Additional NMIs in Europe will ultimately be linked to this comparison through the EUROMET comparison.

While the state-of-the-art uncertainty for this derived electrical quantity is about 5 $\mu$W/W, the band within which most of the measured values fall is closer to 50 $\mu$W/W. While this is two orders of magnitude smaller than the uncertainty of the best revenue electricity meters, there is an increasing demand by meter and transformer manufacturers to provide calibration uncertainties approaching 10 $\mu$W/W.

At the NMIs that derive the ac watt from the volt, the ohm, and ac–dc transfer standards, classical thermal and bridge methods are yielding to waveform sampling techniques, which have improved significantly in the past decade. While the most accurate sampling systems still utilize sinusoidal test signals, they provide a means to analyze the complex waveforms that are common in today's power systems.

## References


[1] "Key comparisons and mutual recognition arrangement,", Bureau International des Poids et Mesures website, http://www.bipm.fr/enus/8_Key_Comparisons/key_comparisons.html, Apr. 2000.

[2] W. J. M. Moore, E. So, N. M. Oldam, P. N. Miljanic, and R. Bergeest, "An international comparison of power meter calibrations conducted in 1987," *IEEE Trans. Instrum. Meas.*, vol. 38, pp. 395–401, Apr. 1989.

[3] E. So, D. Angelo, T. Nelson, and L. Snider, "NRC - NIST intercomparison of power meter calibrations at 60 Hz and ranges up to 600 V, 100 A," in *Dig, CPEM 2000*, Sydney, Australia, May 2000, p. 664.

[4] P. Miljanic, B. Stojanovic, and P. Bosnjakovic, "The development of a high precision time-division power meter," in *Dig., CPEM 84*, Delft, The Netherlands, Aug. 1984, pp. 67–68.

[5] H. Laiz and R. García, "A power comparator with high accuracy simple and inexpensive," *IEEE Trans. Instrum. Meas.*, vol. 46, pp. 420–422, Apr. 1997.

[6] E. Z. Shapiro, Y. T. Park, I. F. Budovsky, and A. M. Gibbes, "A new power transfer standard, its investigation and intercomparison," *IEEE Trans. Instrum. Meas.*, vol. 46, pp. 412–415, Apr. 1997.

[7] G. Kyriazis, "Calibration of electrical power and energy standards with a capacitance bridge and a digital generator," in II SEMETRO, Curitiba, Paraná, Brazil, Sept. 24–26, 1996.

[8] W. J. M. Moore and E. So, "A current-comparator-based system for calibrating active/reactive power and energy meters," *IEEE Trans. Instrum. Meas.*, vol. IM-32, pp. 147–149, Mar. 1983.

[9] D. Zhang, Y. Jia, G. Zhang, Y. Zhang, and F. Guo, "A new power standard for audio-frequency measurements," *IEEE Trans. Instrum. Meas.*, vol. 39, pp. 545–547, June 1990.

[10] G. Schuster, "Thermal instrument for measurement of voltage, current, power and energy at power frequencies," *IEEE Trans. Instrum. Meas.*, vol. IM-29, pp. 153–157, Sept. 1980.

[11] G. Ramm, H. Moser, and A. Braun, "A new scheme for generating and measuring active, reactive, and apparent power at power frequencies with uncertainties of $2.5 \times 10^{-6}$," *IEEE Trans. Instrum. Meas.*, vol. 48, pp. 422–426, Apr. 1999.

[12] U. Pogliano, "High precision measurement of electrical power by means of synchronization of integrative analog to digital converters," in *Dig., 8th Symp. TC-4 IMEKO*, Budapest, Sept. 1996, pp. 33–36.

[13] A. C. Corney, "A traceable mains-frequency power standard," *IEEE Trans. Instrum. Meas.*, vol. 48, pp. 418–421, Apr. 1999.

[14] E. Shapiro and I. Budovsky, "Thermal watt-transfer standard," *IEEE Trans. Instrum. Meas.*, vol. 44, pp. 399–402, Apr. 1995.

[15] S. Svensson and K.-E. Rydler, "A measuring system for the calibration of power analyzers," *IEEE Trans. Instrum. Meas*, vol. 44, pp. 316–317, Apr. 1995.

[16] F. Clark and J. Stockton, "Principles and theory of wattmeters operating on the basis of regularly spaced sample pairs," *J. Phys. E, Sci. Instrum.*, vol. 15, pp. 645–652, 1982.

[17] N. Oldham and O. Petersons, "Calibration of standard wattmeters using a capacitance bridge and a digital generator," *EEE Trans. Instrum. Meas.*, vol. IM-34, pp. 521–524, Dec. 1985.