An improved current-comparator-based power standard with an uncertainty of 2.5 uW/VA (k=1)

So, Eddy; Arseneau, Rejean; Angelo, Dave

Publisher's version / Version de l'éditeur:

IEEE Transactions on Instrumentation and Measurement - Special Issue, 2012-07-06

An Improved Current-Comparator-Based Power Standard with an Uncertainty of 2.5 μW/VA ($k = 1$)

Eddy So, *Fellow, IEEE,* Rejean Arseneau, *Senior Member, IEEE,* and Dave Angelo

Abstract – **An improved power standard derived from a current comparator power bridge for calibrating active/reactive power and energy meters under sinusoidal conditions is described. Measurements can be made at any power factor from zero lag through unity to zero lead, positive or negative power, at 120 V, 5 A, and 50 or 60 Hz. The improved power standard has an estimated uncertainty of not more than 2.5 μW/VA at $k = 1$. Special high accuracy current and voltage range extenders have been incorporated to extend the current and voltage ranges up to 200 A and 1200 V, respectively.**

Index Terms **— Current-comparator, power bridge, power standard, uncertainty.**

I. INTRODUCTION

A unique standard for the unit of power does not exist. The measurement of power must rely on a reference that is derived from the standards of voltage and resistance. Various techniques have been developed for combining these two standards in such a way as to provide a practical and convenient power standard. The power bridge, based on the current comparator, is one way of achieving this objective.

The current comparator power bridge to establish a power standard at NRC was developed more than 35 years ago. Over the years the accuracy of the power bridge has been continuously improved and its uncertainty has been decreased to less than 10 μW/VA at $k = 1$ [1]. The uncertainty of the system is determined primarily by the uncertainty in establishing the ac voltage from the dc reference, the current comparator winding ratio errors, and the stability of the in-phase and quadrature current sources, that is, the reference resistor R and the reference capacitor C. Further improvement, mainly achieved through improvement in the main components and their error evaluations, including better measurement of the AC/DC transfer, in reducing the uncertainty of the current-comparator-based power standard to not more than 2.5 μW/VA at $k = 1$ is described in this paper. Although basically designed for calibration at the 120-V, 1-A level, 50 Hz or 60 Hz, at any power factor from zero lag through unity to zero lead, measurements at reduced and higher voltages and currents can also be made, typically from 69 V to 1,200 V and from 0.01 A to 200 A.

Manuscript received June 27, 2012. The authors are with the Measurement Science and Standards Portfolio, National Research Council of Canada, Ottawa, ON, K1A-0R6, Canada. (e-mail: eddy.so@nrc.ca; rejean.arseneau@nrc.ca; dave.angelo@nrc.ca)

Therefore, in order to provide a better understanding on the overall improvement of the current-comparator-based power standard, an overview of the of the basic current comparator power bridge is provided, including its main components and means to extend the current and voltage ranges of the power bridge. A one-page summary paper on the main issues of the improved current-comparator-based power standard has been described [2].

II. IMPROVED CURRENT-COMPARATOR-BASED POWER STANDARD

A. Basic Power Bridge

The basic power bridge is shown schematically in Fig. 1. It divides the apparent power into two orthogonal components - the active power and the reactive power. Provided that the orthogonality is maintained, inaccuracy in one of the components does not affect the other. A reference resistor R and a reference capacitor C are used to derive the in-phase and quadrature currents to the power bridge. When used in a calibration system the current comparator can be connected in a feedback arrangement to control the magnitude and phase of the test current in accordance with the bridge settings N_X, N_R, and N_C. This, together with the voltage, establishes the measurement conditions and makes possible the calibration of watt/watt-hour, var/var-hour, volt-ampere-hour, ampere-squared-hour and other similar types of metering instruments.

The current comparator is designed for operation with a current rating of 1 ampere-turn for the current comparator windings. In the actual bridge, the equivalent of six-digit resolution is obtained in the N_R and N_C windings with each winding having a total of 100 turns [1]. With a current rating of 1 ampere-turn for the current comparator windings, the bridge can be operated at 120 volts, 1 ampere, using resistive and capacitive impedances of 12 000 ohms at 50 Hz and 60 Hz. The N_X winding is configured for ratio multiplication, having taps at 1, 2, 5, 10, 20, 50 and 100 turns, allowing current operations at 1 A, 0.5 A, 0.2 A, 0.1 A, 0.05 A, 0.02 A, and 0.01 A, respectively.

High accuracy current and voltage range extenders have been designed/constructed to allow the power bridge to be operated at extended currents from 5 A up to 200 A, and voltages from 69 V up to 1200 V.

Means are provided for accessing pertinent data from the system and the meter-under-test to enable processing in a computer.

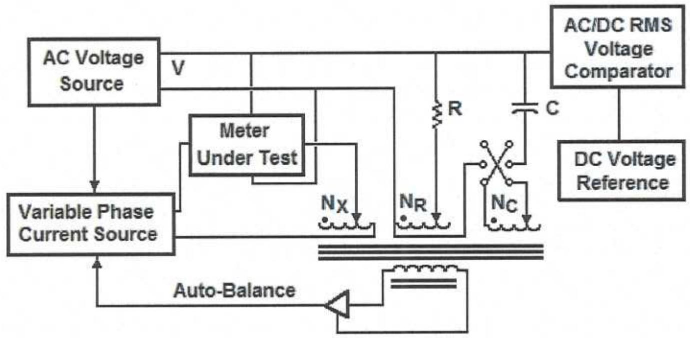

Fig.1. Basic current comparator power bridge

B. Reference Resistor

The in-phase or active power component of the wattmeter current is scaled by the current comparator against the 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 the 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

$$VI = (1/N_X)\,(N_R\, V^2/R + jN_c\, V^2\omega C). \qquad (1)$$

The power reference is the power dissipated in the reference resistor V^2/R. Thus both the voltage V and reference 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. The reference resistor R was selected for its low, ac-dc transfer-error characteristic. Its nominal value is 12 kΩ with magnitude and phase angle error stability of better than 1 μΩ/Ω and 1 μrad. It consists of twelve 1000-Ω card-wound bifilar type resistors on a low thermal expansion substrate connected in series. These are assembled and enclosed in a brass shield with flow-through ventilation. This bridge reference resistor is calibrated under actual operating condition of 120 V, after its condition is stabilized due to heating effects and power coefficient. A known calibrated reference standard resistor [3] is used against which the bridge reference resistor is being measured. It is a 10-kΩ oil-filled resistor with a temperature sensor. It has a temperature coefficient of less than 0.1 ppm/^{0}C and a power coefficient of less than 1 ppm/W. When 120 V is applied to this resistor for 2 minutes, the temperature sensor indicates a change of 0.01%. As per its specifications, a change of 0.01% in the temperature sensor would indicate a change of 0.2 ppm in the reference standard resistor. The calibration/measurement procedure of the bridge reference resistor R is done within approximately 30 seconds. Thus, the reference standard resistor change due to the time of 30 seconds it takes to perform the power bridge resistor measurement can be considered negligible.

C. Reference Capacitor

The reference capacitor, which is solid-dielectric, is automatically compensated for its instability and loss by comparing it with a low-loss gas-dielectric capacitor and adjusting for its differences accordingly [4]. The circuit (Fig. 2) is basically a self-balancing current-comparator-based capacitance bridge providing a stable and pure quadrature current to the load. The stability and purity of the quadrature current are determined by the reference capacitor C_s and the gain of the feedback circuit. Capacitors C_s and C are, respectively, a gas-dielectric low-loss reference standard capacitor made with Invar [5] and a polystyrene solid-dielectric capacitor which has a dissipation factor of about 0.0002 at power frequencies, and a temperature coefficient of about 100 ppm/^{0}C.

At ampere-turn balance condition, the reference quadrature current equation is

$$I_L = +j\,\frac{N_S}{N}\,V\omega C_S \qquad (2)$$

Two active reference capacitors have been developed. One for operation at a frequency of 50 Hz, and the other for 60 Hz operation.. The capacitance values and current comparator winding ratio have been chosen to provide a quadrature current reference of l0 mA at an applied voltage of 120 V and at a frequency of 50 Hz and 60 Hz, respectively. The stability and loss angle of the quadrature current thus obtained are estimated to be better than 1 μF/F and 1 μrad, respectively.

A special 1000-pF reference standard capacitor made of stainless steel parallel plates, which has a loss angle characteristic of less than 1 μrad at power frequencies is used as an "absolute" loss angle standard (dissipation factor standard) [6] to measure the magnitude and loss angle of the active reference capacitors, using a high voltage capacitance bridge [7].

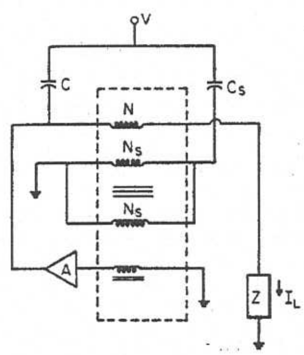

Fig. 2. Current-comparator-based reference capacitor

D. Current Range Extender

For current operation of 5 A and higher up to 200 A, an enhanced wide-band three-stage current transformer with three cores (C_1, C_2, and C_3) is used as a special current range extender, as shown in Fig. 3 [8]. Windings N_{DD}, N_{CC}, N_D, and Nc have 100 turns each. N_P and N_S are the primary and secondary windings with 40 turns and 200 turns, respectively. The 40-turn primary winding N_P has taps at 20 turns, 10 turns, 5 turns, 4 turns, 2 turns, and 1 turn, to allow the power bridge current extension to 5 A, 10 A, 20 A, 40 A, 50 A, 100 A, and 200 A, respectively. At power frequencies of 50 Hz and 60 Hz, the ratio errors, including stability, are less than 1 x 10^{-6} for both the in-phase and quadrature components. The output of the current range extender is connected to the N_X winding.

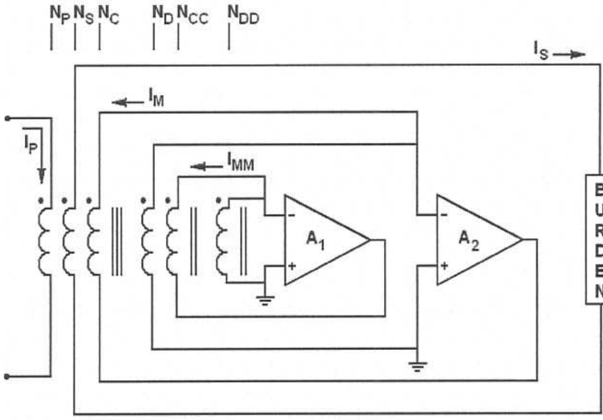

Fig. 3. Enhanced wide-band three-stage current range extender

E. Voltage Range Extender

For voltage operation of higher than 120 V up to 1200 V, a current-comparator-based high voltage divider is used as a voltage range extender. The divider is basically a capacitive voltage divider, as shown in Fig. 4. Capacitors C_H and C_L are high and low voltage low-loss gas-dielectric standard capacitors, respectively. They are the same type of gas-dielectric capacitor made with invar as that used in the bridge reference capacitor (see Section IIC). Both have a voltage rating of 750 V, loss angle of less than 10 µrad, and a temperature coefficient of less than 2 ppm/^{0}C. The current comparator is used in a feedback loop to correct the magnitude and phase of the output voltage E_L to an accuracy value of better than 10 × 10^{-6} and 10 μrad, respectively [9], with a stability of better than 1 ppm for both magnitude and phase error. The active voltage divider has seven gain settings of 1, 2, 5, 10, 20, 50, and 100, corresponding to ranges of 100%, 50%, 20%, 10%, 5%, 2%, and 1% of the rated primary high voltage. At each range, the rated output voltage is 120 Vrms.

Capacitor C_L will be subjected to a rated output voltage of only 120 V, while capacitor C_H will be subjected to an input voltage range of 120 V up to 1,200 V. Therefore, C_H should have a low voltage dependency which is less than 1 µF/F up to its rated voltage 750 V. This was verified by comparing it with another gas-dielectric standard capacitor of 100 pF which has a much higher voltage rating of 100,000 V, using a high voltage capacitance bridge. For an input voltage of higher than 750 V up to 1200 V of the voltage divider, then the 100 pF, 100,000-V gas-dielectric standard capacitor is used as C_H. It has negligible voltage dependency at 1200 V and less.

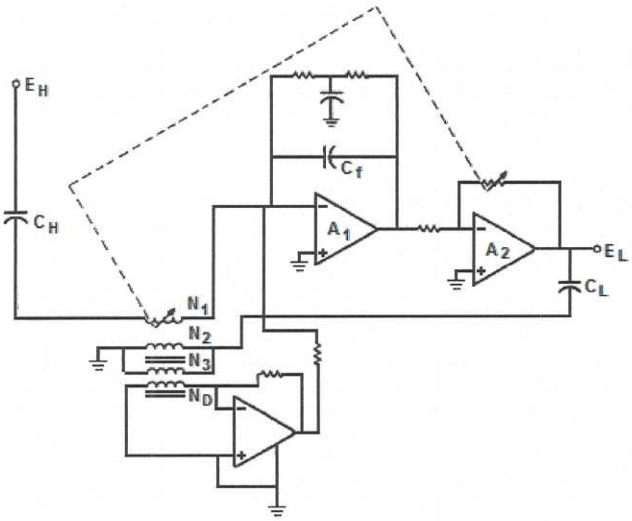

Fig. 4. Current-comparator-based voltage divider

The magnitude and phase errors of the output voltage E_L are corrected by the feedback circuit to provide an ampere-turn balance in the current comparator. From the ampere-turn balance equation of the current comparator, the output voltage E_L of the divider is given by

$$E_L = \frac{C_H}{(C_L(N_2/N_1)} E_H \quad (3)$$

Thus, the divider output is determined only by the capacitance ratio of the high-voltage gas-dielectric capacitor and the low-voltage gas-dielectric capacitor, and the current comparator winding ratio. The switches changing the winding ratio and the gain of amplifier A2 are mechanically coupled to keep *(N2/N1) x (G)* constant, where G is the gain settings of the divider. The capacitance ratio and the current comparator ratio (gain settings) can be chosen to provide selected voltage ranges of 69 V, 240 V, 360 V, 480 V, 600 V, 720 V, and 1200 V. For the power bridge operation at voltages higher than 120 V, the input voltage of the voltage divider is connected to the input voltage of the meter-under-test, while the 120 V output of the voltage divider is connected to the input voltage of the power bridge. For operation at 69 V, the input voltage of the voltage divider is connected in parallel with the input voltage of the power bridge, while the output voltage of the voltage divider is connected to the input voltage of the meter-under-test. The voltage divider is calibrated using a current-comparator-based capacitance bridge.

III. UNCERTAINTIES

The overall uncertainty of the power standard is determined primarily by the uncertainty in establishing the ac voltage from the dc reference, the current comparator winding ratio errors, and the stability of the reference resistor and reference capacitor. The known measured errors of these components can be accounted for, leaving only the measurement uncertainties of the calibration of these components. The calibration measurements of these components are done by taking the average of at least 5 sets of measurements on different days. Each set of measurements is in turn the average of at least a series of 5 to 10 measurements. Due to the excellent stability and repeatability characteristics of the bridge components, the resulting Type A uncertainties of these components are usually about 0.1 ppm or less. Therefore, the resulting total estimated uncertainties, which encompass the Type A and Type B uncertainties, is determined primarily by the Type B uncertainties of the calibration methods. The establishment of the ac voltage from the dc voltage is done at the 1 volt level, since the ac/dc transfer standard at the 1 volt level has the lowest estimated uncertainty at power frequencies of 1 μV/V [10]. The transfer standard is a commercially available instrument. The corresponding 1-volt dc voltage is provided by a commercial dc voltage source, which has a stability/uncertainty of 0.2 μV/V at 1 volt. An inductive voltage divider (IVD) is used to reduce its 120-volt operating voltage of the power bridge to the 1 volt level. The 120V/1V ratio of the IVD is measured/calibrated using a current-comparator-based capacitance bridge. This capacitance bridge is in turn calibrated using a scale of gas-dielectric capacitors with substitution and build-up techniques. To minimize/eliminate the effects of leads and winding impedances of the current comparator, all the capacitors are provided with proper unloading circuits [7]. The uncertainty of the capacitance bridge ratio and corresponding IVD ratio at 120V/1V at power frequencies is estimated to be 0.3×10^{-6} for both the in-phase and quadrature components. The winding ratios of the 1-ampere current comparator is also calibrated using the substitution and build-up techniques of gas-dielectric capacitors with proper unloading circuits to minimize the effects of leads and winding impedances of the current comparator. Its winding ratio errors are estimated to be not more than 0.3×10^{-6} for both the in-phase and quadrature components at power frequencies. The bridge reference resistor is calibrated using an ac current-comparator-based resistance bridge [11, 12] and its magnitude and phase angle errors are measured against a calculable Gibbing's resistor [13] through a known 10 kΩ reference standard resistor (See Section II). Since the winding ratio errors of the 1-ampere current comparator of the power bridge are known, it is used as the current comparator component in the ac resistance bridge. The bridge reference resistor magnitude and phase angle error stability are better than 1 μΩ/Ω and 1 μrad, respectively. The two reference capacitors for 50 Hz and 60 Hz operations, respectively, are calibrated using the current-comparator-based capacitance bridge. The uncertainty of their resulting quadrature current reference is estimated to be less than 0.5×10^{-6} for both the in-phase and quadrature components. The current and voltage range extenders are calibrated using current-comparator-based high-frequency CT test set [14] and current-comparator-based capacitance bridge, respectively. The uncertainty of their corresponding ratio errors are less than 0.5×10^{-6} for both the in-phase and quadrature components, respectively.

Estimates of the effects of possible total uncertainties which encompass the Type and Type B uncertainties at $k = 1$ for power bridge operation at 120 V/5 A are listed in Table I for active power and reactive power measurement at unity and zero power factor, respectively. Table II shows the total estimated uncertainty (square root sum of squares - RSS) of the system for both active power and reactive power measurements at unity, half, and zero power factors. The residual uncertainty at zero power factor for active power measurement and unity power factor for reactive power measurement is caused by the uncertainty in the measurement of the phase defect of the reference capacitor and reference resistor, respectively.

Table I

SOURCES OF TOTAL ESTIMATED UNCERTAINTIES ($k = 1$)

Uncertainty	Active Power	Reactive Power
AC Voltage		
IVD : 0.3×10^{-6}		
DC reference: 0.2×10^{-6}		
AC/DC: 1×10^{-6}		
Total voltage (2 x RSS)	2.1×10^{-6}	2.1×10^{-6}
Reference Resistor		
Magnitude: 0.5×10^{-6}	0.5×10^{-6}	
Phase: 0.5×10^{-6}		0.5×10^{-6}
Reference Capacitor		
Magnitude: 0.5×10^{-6}		0.5×10^{-6}
Phase: 0.5×10^{-6}	0.5×10^{-6}	
Current Comparator		
In-phase: 0.3×10^{-6}	0.3×10^{-6}	
Quadrature: 0.3×10^{-6}		0.3×10^{-6}
Range Extender 5A/1A		
In-phase: 0.5×10^{-6}	0.5×10^{-6}	
Quadrature: 0.5×10^{-6}		0.5×10^{-6}
Total Uncertainty RSS	2.3×10^{-6}	2.3×10^{-6}

Table II

TOTAL ESTIMATED UNCERTAINTIES VS POWER FACTOR ($k = 1$)

	Power Factor					
	Active Power			Reactive Power		
	1	0.5	0	0	0.5	1
Uncertainty	2.3	2.3	2.3	2.3	2.3	2.2

For operation at extended currents up to 200 A and voltages up to 1200 V, the uncertainty of the power standard could basically be maintained due to the high accuracy range extenders. See sections *(D)* and *(E)*.

Based on the stability and repeatability characteristics of the calibrations of the power bridge components, such as, DC 120 V supply, thermal transfer standard, bridge resistor, bridge capacitor, etc., it is estimated that the overall repeatability (Type A uncertainty at $k = 1$) of the NRC Power Standard would be better/less than 0.5 μW/VA.

With the development of the new improved NRC current-comparator-based power standard, it would be useful in the interests of improving and maintaining the accuracy of such power standards to make inter-comparisons between these systems whenever suitable opportunities arise. NIST has developed a new and more accurate power standard based on a Programmable Josephson Voltage Standard [15]. Therefore, a bilateral comparison was arranged between NRC current-comparator-based Power standard and NIST quantum-based power standard. The comparison was implemented using a transfer standard consisting of a highly stable commercial sampling-type power/energy meter of better than 2 μW/VA. The measurements were made at 120 V, 5 A, 50 Hz and 60 Hz, at power factors of 1.0, 0.5 lead and lag, and 0.0 lead and lag. The results of the comparison indicate agreement to within the stated uncertainties of the participants [16]. The agreements of the results provide confidence in the accuracy and reliability of the developments of the two power standards with different measuring principles.

IV. CONCLUSION

An improved current-comparator-based power standard derived from the current comparator power bridge for calibrating active and reactive power and energy meters under sinusoidal conditions at 120 V/5 A, 50 Hz – 60 Hz, is now available for use at NRC. The improvements to reduce its overall uncertainty to not more than 2.5 μW/VA at $k = 1$, including the design/construction of high accuracy current and voltage range extenders to allow the power bridge to be operated at extended currents from 5 A up to 200 A, and voltages from 69 V up to 1200 V, respectively, was presented.

A bilateral comparison between the new improved NRC current-comparator-based power standard and NIST quantum-based power standard at 120 V, 5 A, 50-60 Hz indicate that the NRC and NIST measurement systems are in agreement within the uncertainty of the measurements.

ACKNOWLEDGMENT

The assistance of P. Filipski for providing calibration of the new thermal transfer standard and D. Bennett for the construction of the enhanced wideband three-stage current transformer range extender is greatly appreciated.

REFERENCES

[1] 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-32-1, pp. 147–149, Mar. 1983.

[2] E. So, R. Arseneau, and D. Angelo, "An improved current-comparator-based power standard at 120 V/5 A, 50 Hz – 60 Hz, with an uncertainty of 2.5 μW/VA ($k = 1$)," *CPEM2012 Conference Digest.*

[3] Transportable Resistance Standards (SR-102, SR-103, SR-104), "User and Service Manual", IET Labs, Inc.

[4] E. So and W. J. M. Moore, "A stable and accurate current-comparator-based quadrature-current reference for power frequencies," *IEEE Trans.Instrum. Meas.*, vol. IM-31, no. I, pp. 43-46, Mar. 1982.

[5] J.F. Hersh, "A highly stable reference standard capacitor," *General Radio Experimenter*, August 1963.

[6] E. So and J. Q. Shields, "Losses in electrode surface films in gas dielectric capacitors," *IEEE Trans. Instrum. Meas.*, vol. IM-28, no. 4, pp. 279-284, Dec. 1979.

[7] W. J. Moore and P. N. Miljanic, *The Current Comparator*, London, U.K.: Peter Peregrinus, 1988, vol. 4.

[8] E. So and D. Bennett, "Compact wideband high-current (≥ 1000 A) multistage current transformers for precise measurements of current harmonics," *IEEE Trans. Instrum. Meas.*, vol. IM-56, no. 2, pp. 43-46, pp. 584-587, April 2007.

[9] E. So, "The application of the current comparator in instrumentation for high voltage power measurements at very low power factors," *IEEE Trans. Power Delivery*, Vol. PWRD-I, pp. 98-104, Jan. 1986.

[10] M. Boeker and A.D. Inglis, "Calibration Report Fluke 792A AC-DC Transfer Standard *SIN 9836001*," NRC Report Number ES-2011-0050-01, July 11, 2011.

[11] E. So and W. J. Moore, "A direct reading ac current-comparator bridge for resistance measurements at power frequencies," *IEEE Trans. Instrum. Meas.*, vol. IM-29, pp. 364–366, Dec. 1980.

[12] E. So and B. Djokic, "A computer-controlled current-comparator-based four-terminal resistance bridge for power frequencies," *IEEE Trans. Instrum. Meas.*, vol. IM-50-2, pp. 272-274, April 2001.

[13] B. Wood and D. Inglis, "Calibration Report of a Standard AC Resistor S/N 1000," NRC Report Number ES-2010-0024-01, Jan. 31, 2011.

[14] N. L. Kusters and W. J. M. Moore, "The development and performance of current comparators for audio frequencies," *IEEE Trans. Instrum. Meas.*, vol. IM-14, no. 6, pp. 178–190, Dec. 1965.

[15] B.C. Waltrip, et al, "AC power standard using a programmable Josephson voltage standard," *IEEE Trans. Instrum.Meas.*, vol. 58-4, pp. 1041–1048, April 2009.

[16] B.C. Waltrip, T.L. Nelson, E. So, and D. Angelo, "A bilateral comparison between NIST quantum-based power standard and NRC current-comparator-based power standard," *CPEM2012 Conference Digest.*