NRC–NIST Intercomparison of Calibration Systems for Current Transducers With a Voltage Output at Power Frequencies

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***Abstract*—A number of international comparisons of current transformer calibrations at power frequencies were conducted in the past. However, all comparisons were done with a secondary current output of 5 A. This inter-comparison of current transformer calibration systems for power frequencies between the National Research Council of Canada and the National Institute of Standards and Technology, USA, was done with a primary current range of 100 A and a nonstandard secondary output signal of voltage range of 10 V. The comparison was implemented with a transfer standard consisting of a commercial current-comparator-based transimpedance amplifier, based on a development at the National Research Council of Canada modified to make the output voltage adjustable in magnitude and phase within a range of ± 1 percent. The results indicate that there are no significant differences in the overall accuracy of calibration systems for current transducers with a voltage output at power frequencies in each laboratory.**

***Index Terms*—Current transformer calibration, international comparison, transimpedance amplifier.**

I. Introduction

The measurement of electric power and energy at high currents requires a precise means for scaling those currents down to usable metering levels. For most practical purposes, this role has been adequately fulfilled by the inductive current transformer with a rated output of 5 A.

Recent developments in sampling techniques have enabled an accuracy of better than 50 parts per million of full scale to be achieved in digital meters. In order to use sampling techniques for the measurement of current to obtain power and energy, it requires that the output signal of the current transformer/transducer be converted to an ac voltage output through a transimpedance circuit, a current-to-voltage converter. For a rated primary current, the rated output voltage can be in the range of 10 mV to 10 V or higher. The calibration of such current transducers with a voltage output requires ratio standards and measurement techniques different than those used in the calibration of conventional current transformers.

National laboratories, in particular the National Research Council of Canada (NRC) and the National Institute of Standards and Technology (NIST), have received requests from the industry to provide calibrations of current transducers with an ac output voltage. Therefore, NRC and NIST have developed special current transformer calibration systems to address these requests. The comparison of the two systems at a power frequency of 60 Hz for calibrations of current transducers at a current range of 100 A with a corresponding output voltage range of 10 V is presented. The comparison is implemented using a commercial current-comparator-based transimpedance amplifier with a rated output voltage of 10 V, based on a development at NRC [1], as a transfer standard.

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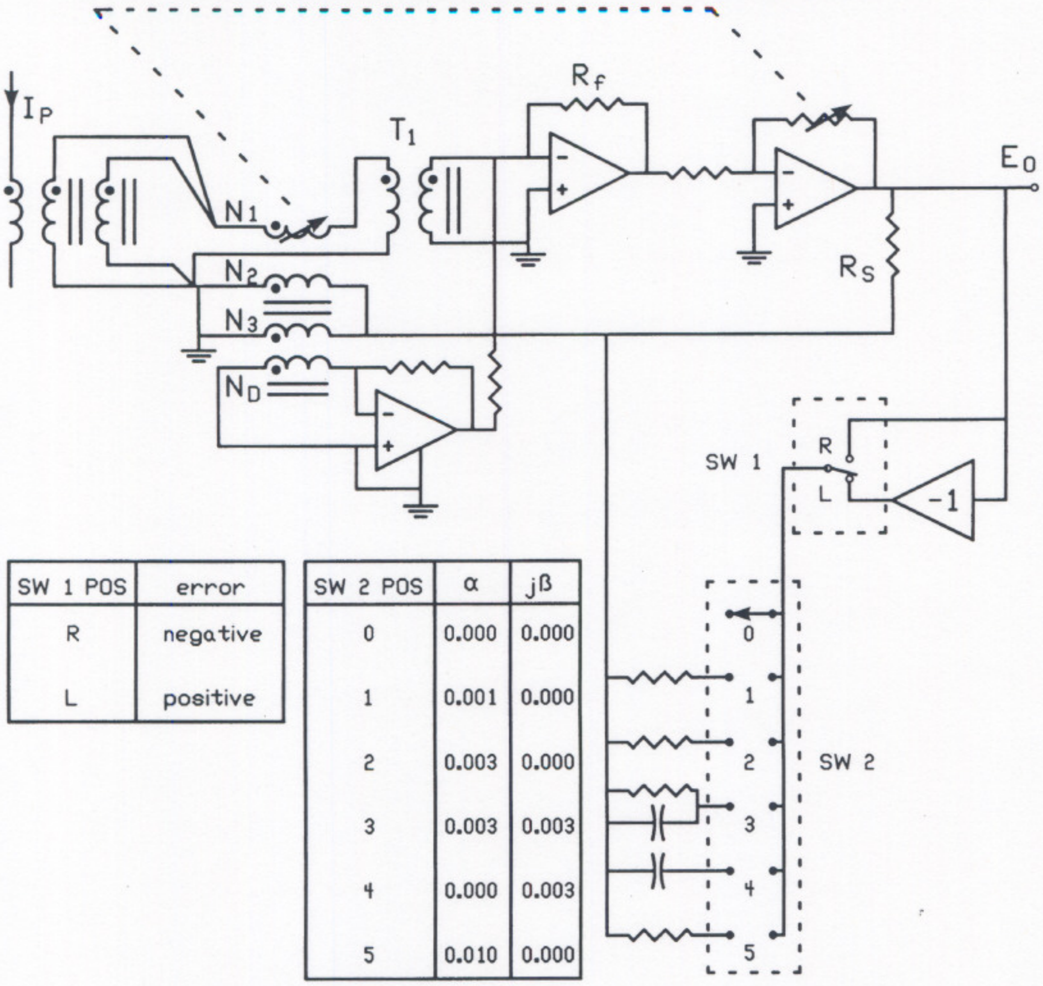
II. Transfer Standard

A transimpedance circuit is basically a current-to-voltage converter to obtain a voltage proportional to, and in phase, with the input current. The basic circuit of the transfer standard based on the current-comparator-based transimpedance amplifier is shown in Fig. 1. It consists of a two-stage current transformer coupled, through a current comparator, to an operational amplifier with a resistive feedback followed by a gain amplifier. The current comparator is used in a feedback mode to automatically correct the magnitude and phase errors without requiring adjustment controls. The transfer standard is a commercial current-comparator-based transimpedance amplifier, modified to include a feature of having known adjustable errors [1]. The output of a transimpedance amplifier is given by

$$E_0 = I_P \cdot R_T \cdot (1 + (\alpha + j\beta))$$

where α and β, respectively, are the in-phase and quadrature errors of the transimpedance R_T, and I_P is the primary current. The current comparator ensures that the relative in-phase and quadrature errors are less than 10×10^{-6}. For the transfer standard, a commercial current-comparator-based transimpedance amplifier was modified to allow the in-phase and quadrature errors to be adjustable in steps within a range of one percent. This was implemented using a switch with six nominal error settings: 1) zero in-phase ($\alpha = 0$) and zero quadrature ($\beta = 0$) errors; 2) 0.1% in-phase error ($\alpha = 0.001$); 3) 0.3% in-phase error ($\alpha = 0.003$); 4) 0.3% in-phase ($\alpha = 0.003$) and 0.3% quadrature ($\beta = 0.003$) errors; 5) 0.3% quadrature error ($\beta = 0.003$); 6) 1% in-phase error ($\alpha = 0.01$). For each nonzero error setting, the errors can be switched to either positive or negative errors. Thus, there are a total of eleven error settings. The range of error settings up to one percent is to simulate current trans-



SW 1 POS	error
R	negative
L	positive

SW 2 POS	α	jβ
0	0.000	0.000
1	0.001	0.000
2	0.003	0.000
3	0.003	0.003
4	0.000	0.003
5	0.010	0.000

Fig. 1. Transfer standard.

ducers with accuracy class as per IEEE Standard C57.13 [2]. The transfer standard has a rated input current of 100 A with a corresponding rated output voltage of 10 V. The uncertainty and stability of the equivalent transimpedance at all error settings are less than 10×10^{-6}. Its special feature of having different error settings allows the comparison of the NRC and NIST calibration systems for current transducers with an ac output voltage within an error range of one percent.

III. Calibration Systems

A. NRC Calibration System

The NRC calibration system is based on current comparator technology. It basically consists of two systems, an analog system and a digital system, as shown in Fig. 2. The analog system consists of a current-comparator-based resistance bridge with a two-stage current transformer as a current-range extender [3]. The in-phase and quadrature errors of the current transducer-under-test (transfer standard in Fig. 2) can be measured by comparing the current input I_P of the current transducer, using the current comparator, with currents derived from the output voltage of the transducer-under-test through a reference resistor R_S and a reference capacitor C_S. The uncertainty of the analog calibration system is determined primarily

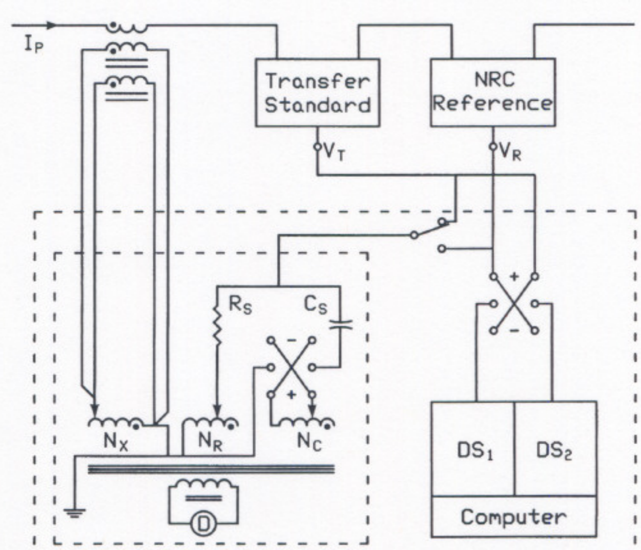


Fig. 2. NRC calibration system.

by the basic ratio uncertainty of the current-comparator-based resistance bridge, including the two-stage current-range extender, and the reference resistor and capacitor. The total

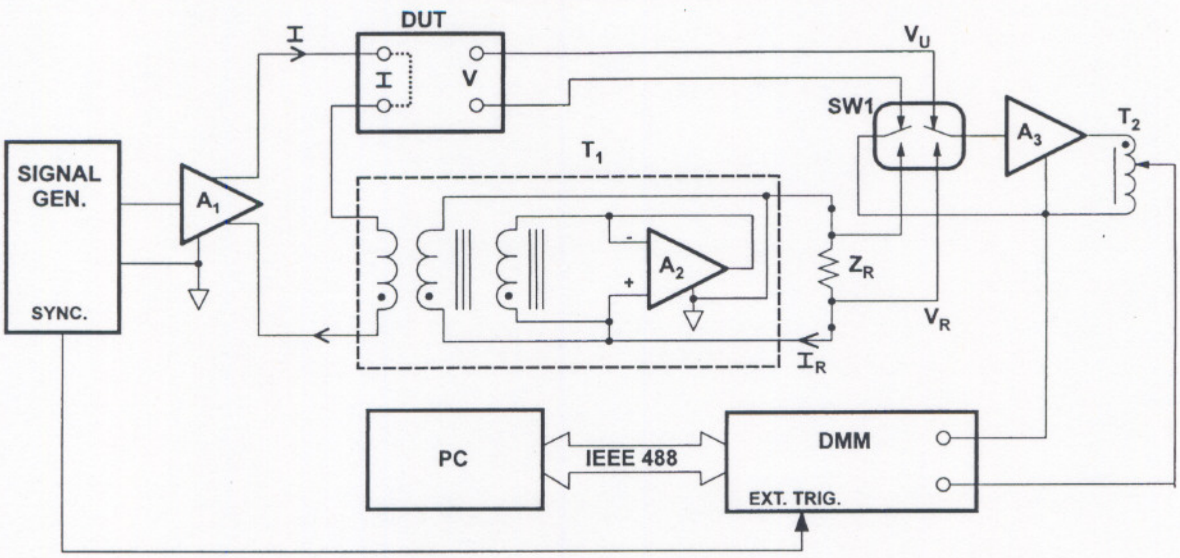


Fig. 3. NIST calibration system.

combined relative ratio uncertainty (2σ) at power frequencies is less than 10×10^{-6} for both magnitude and phase.

The digital system comprises a reference current-comparator-based transimpedance amplifier (NRC reference in Fig. 2) with a rated output voltage of 10 V, and two commercial sampling digital voltmeters DS_1 and DS_2 [4]. The voltmeters are set to digitize the input voltages in the dc mode. The sampling rate is fixed at 512 times the signal frequency. The voltmeters are only used on their 10-V range and mostly above 50% of the range, since input scaling is provided in a custom built voltage circuit. The reference current-comparator-based transimpedance amplifier has gain settings corresponding to ranges of 100%, 50%, 20%, 10%, 5%, 2%, and 1% of rated primary current. The voltage output of the current transducer-under-test and that of the reference current-comparator-based transimpedance amplifier are sampled by the voltmeters. The digital samples are transferred via an IEEE-488 bus to the computer for comparisons and analysis. The magnitude and phase differences between the current transducer-under-test and the reference current-comparator-based transimpedance amplifier are calculated from a fast-Fourier-transform (FFT) analysis of the digital sample data files. To minimize the effect of phase errors present in the front-ends of the voltmeters, means are provided for interchanging the connections of the device-under-test and the reference [4]. The total combined relative uncertainty (2σ) of the digital calibration system at power frequencies is estimated to be less than 20×10^{-6}.

B. NIST Calibration System

The NIST calibration system is shown in Fig. 3. It consists of a two-stage binary inductive divider, an amplifier-aided two-stage current transformer, a precision shunt, a wideband buffer, and a commercial sampling voltmeter DMM [5]. The reference voltage $V_R = I_R Z_R$ across the precision shunt Z_R, is compared to the output voltage V_U of the device-under-test DUT, using a commercial sampling multimeter DMM. A binary inductive voltage divider T_2 is used to equalize the amplitudes of the V_R and V_U signals sampled by the DMM. This equalization has the effect of minimizing any amplitude-dependent phase errors of the DMMs input circuitry. The sampled signal is then downloaded via an IEEE-488 bus to the system controller PC. Phase information between the sampled V_R and V_U signal records is maintained by triggering the DMM with the signal generator's external synchronization signal. The total combined relative uncertainty (2σ) of the NIST calibration system at power frequencies is estimated to be less than 20×10^{-6}.

IV. Measurement Results

The in-phase and quadrature errors of the transfer standard were measured at the eleven error settings providing errors within a range of 1%. Measurements at all these settings were done at a frequency of 63 Hz and primary currents of 100%, 50%, 10%, and 1% of rated primary current. Therefore, there are four sets of measurements. The measurement result for each set of measurements is the average of the results of at least four repeat measurements made over a period of several days. The standard deviations (2σ) of all repeat results for each test condition were less than 10×10^{-6} for both in-phase and quadrature. The NRC results using the analog calibration system were obtained from the average of two sets of measurements taken at the start and at the end of the comparison. These results are taken as the base values for the comparison and as the best values for the errors of the transfer standard. The NRC results using the digital calibration system were obtained only at the end of the comparison. For each test condition, the relative standard deviations (2σ) of all repeat results were less than 10×10^{-6} for both in-phase and quadrature.

The differences of the measurement results of the in-phase and quadrature errors at the eleven error settings are given at a frequency of 63 Hz and primary currents of 1%, 10%, 50%, and 100% of rated primary current. Table I shows the differences between the error measurement results of the transfer standard obtained using the NIST digital system and the NRC analog

TABLE I
NIST ERRORS–NRC ANALOG ERRORS (PARTS PER MILLION)

Ip	1%		10%		50%		100%	
Switch	In-Phase	Quad.	In-Phase	Quad.	In-Phase	Quad.	In-Phase	Quad.
0	1	5	-1	4	-3	2	-7	4
L1	1	7	1	4	-3	3	-4	5
L2	3	8	0	6	-4	5	-4	6
L3	1	6	3	4	-2	5	-6	4
L4	5	6	3	5	0	4	-3	4
L5	-1	4	0	4	-2	4	-5	1
R1	1	5	0	3	-2	3	-6	4
R2	2	7	-2	2	-5	2	-5	4
R3	5	11	1	2	-4	3	-5	2
R4	1	6	1	2	1	0	-4	4
R5	1	8	0	3	-2	3	-7	2

TABLE II
NRC DIGITAL ERRORS–NRC ANALOG ERRORS (PARTS PER MILLION)

Ip	1%		10%		50%		100%	
Switch	In-Phase	Quad.	In-Phase	Quad.	In-Phase	Quad.	In-Phase	Quad.
0	20	-40	-8	-13	3	-3	-6	-8
L1	20	-38	-5	1	-5	7	-9	5
L2	17	-38	-7	0	-8	10	-9	6
L3	18	-42	-7	-2	-7	3	-7	3
L4	23	-43	-7	-3	-6	3	-9	3
L5	20	-42	-6	-2	-8	7	-11	5
R1	15	-38	-6	0	-8	6	-10	4
R2	20	-36	-9	0	-6	6	-9	3
R3	20	-41	-5	6	-6	11	-7	4
R4	21	-42	-5	6	-6	6	-5	5
R5	22	-41	-5	2	-10	7	-10	4

system. Table II shows the differences between the error measurement results of the transfer standard obtained using the NRC digital system and the NRC analog system. The column under "Switch" corresponds to the six nominal error settings, as explained in Section II. L5 and R5 denote the highest error settings of 1% error, with L and R indicating positive and negative errors. The measured errors are in parts per million corresponding to in-phase and quadrature. For all test conditions, the differences in the measurement results between the NIST digital and NRC analog calibration systems were found to be less than 10×10^{-6} for in-phase and 15×10^{-6} for quadrature.

The differences between the error measurement results using the NRC digital and analog systems at primary currents of 10%, 50%, and 100% of rated primary current, were found to be within 15×10^{-6} for both in-phase and quadrature. At the test current of 1% of rated primary current, the differences in the error measurements were less than 25×10^{-6} for in-phase and 45×10^{-6} for quadrature. This increase in the differences of the measured in-phase and quadrature errors was found to be due to the effect of dc offsets in the interface voltage-gain amplifiers of the NRC digital system to allow the digital meters to operate at the 10-V range, regardless of the level of the input primary current. For this test condition, the gain of the voltage-gain amplifiers was at 100. Due to the voltmeters being set to digitize the input voltages in the dc mode, any dc offset introduces an equivalent systematic in-phase and quadrature error in the measurement results. This effect was estimated to cause an increase in the measured in-phase and quadrature errors by about 25×10^{-6}. Therefore, when corrected for the effect of dc offset in the voltage-gain amplifiers, the differences in the measured errors between the NRC digital and analog systems at 1% of rated primary current would be within 20×10^{-6}. The degree of agreement in the comparison is determined by the uncertainties in the results at each laboratory and the stability of the transfer standard. The stability of the transfer device at all test conditions, based on measurement results taken over a longer period of time at NRC, is better than 10×10^{-6} for both in-phase and quadrature errors. Therefore, based on the results shown in Tables I and II, it can be concluded that within the uncertainty of the measurements, there are no significant differences in the accuracy of the calibration systems for current transducers with an ac output voltage in each laboratory.

V. CONCLUSION

The test results indicate that the calibration systems of NRC and NIST at power frequencies for current transducers with an ac voltage output are in agreement within the uncertainty of the measurements. The interface voltage-gain amplifiers of the NRC digital system will be improved to minimize dc offsets at the high gain settings, which could effect the measured in-phase and quadrature errors of the current transducer-under-test.

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