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# A New System for Traceable Calibrations of Weld Current Monitors at INTI Argentina

Marcos E. Bierzychudek, José Luis Casais, Axel Britos, Branislav Djokić, *Fellow, IEEE*, and Harold Parks

**Abstract**— This paper presents an improved system for traceable calibrations of weld current monitors/testers at short duration high pulsed currents developed recently at the Instituto Nacional de Tecnología Industrial (INTI) in Argentina. The calibration system has an increased capability of generating short duration high pulsed currents of up to 25 kA, and an improved uncertainty of 0.2 % of the calibration system for the measurement of their root-mean-square values. The performance evaluation of the improved calibration system conducted at INTI and also at the National Research Council (NRC) Canada is presented. Its use is intended for providing a traceable and IEC/ISO 17025 Standard compliant calibration service to the automotive industry in Argentina.

**Index Terms** — Calibration, measurement, measurement uncertainty, uncertainty calculation, Rogowski coil, resistance welding, weld tester, weld current monitor.

## I. INTRODUCTION

ROGOWSKI coils are widely used for measurements and monitoring of high AC steady-state and transient currents [1]-[2]. They have been studied for over one hundred years [3]-[6] and have many applications [7]-[9]. Rogowski coils are used in electric utilities for protective relaying and monitoring the operation of electric equipment (e.g. circuit breakers), in electric power industry for measuring high currents (e.g. of arc furnaces), in research (e.g. measuring currents in power electronic applications), in military applications (e.g. measuring currents in electric launchers), etc.

Calibration methods of Rogowski coils with and without integrators are also presented in the published literature [9]-[13]. As Rogowski coils have no magnetic cores and do not exhibit saturation, they have an excellent linearity vs. current [14]. Depending on their construction they can have a wide frequency bandwidth, from very low to very high frequencies, though many of their applications are at power frequencies. They allow the measurement of high currents with high harmonic frequency components. Their output (normally a voltage) is proportional to the input (primary) current first time-derivative, and consequently proportional to the frequency, it is

necessary to integrate the output to recover the current waveform. A number of integrator topologies have been studied and evaluated [3]-[5]. Among these, combining a passive and an active integrator offers some advantages [3].

An important class of applications is the use of Rogowski coils in the resistance welding in the automotive industry. Resistance welding is used in industry for joining metal parts permanently by heating the joints to the melting point by means of electrical current during a well-defined time interval. The current intensity, i.e. the root mean square (RMS) value of the welding current, and weld time affect the quality of welds and consequently of the final products. The AC current is measured/monitored by Rogowski coils, also known as current sensing coils, and their accompanying current meters, which provide the information about the measured current in various forms to the operator. The weld current meters (WCMS) used in resistance welding consist of a Rogowski current sensing coil and a microcontroller based instrument that provides a user interface, performs data processing, presents results of the measurements, and perform communication and other functions.

The WCMS can be configured to discard one or more cycles at the beginning and at the end of the train of pulses to mitigate the effects of transients on the measurements. They provide information about the number of cycles measured, RMS value of the current, per power line cycle and half-cycle, average, minimum and maximum RMS values, current peak values, conduction angle values for pulsed currents, etc.

Weld current monitors with current sensing coils need traceable calibrations to satisfy quality control requirements and to ensure the consistency of welding process [15]-[18]. Argentinian car companies periodically ask INTI, as the Argentinian National Measurement Institute, for the calibration of their weld testers used in the production process, to verify if their performance is within the required specifications.

This paper presents an improved system for traceable calibrations of weld current monitors/testers at short duration high pulsed currents developed recently at INTI with assistance of NRC. The initial work on this development was briefly

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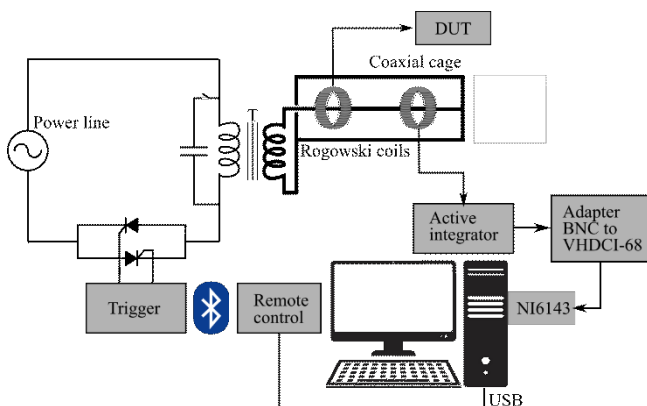
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introduced in [19]-[20]. More details about the calibration system design, its performance evaluation and its traceability are provided in the current paper. The novel system features a newly designed reference Rogowski coil and integrator, a hexagonal coaxial cage encompassing the reference and Rogowski coil under test, a new standalone wideband digital sampling board with high sampling rate, and a novel custom-developed software for configuring the instruments, collecting and processing measurement data, and reducing measurement errors originating from current source transients.

The calibration system has an increased capability of generating short duration high pulsed currents of up to 25 kA, and measurement of their root-mean-square values with an improved uncertainty of 0.2 %, which was not easy to achieve due to the variability of operational and test conditions. The initial simple test service evolved into a traceable calibration service with reduced uncertainties for the automotive industry in Argentina, at the INTI high-current lab. This new Calibration and Measurement Capability (CMC), compliant to the requirements of ISO/IEC 17025 Standard, is to be submitted for review to the Regional Metrology Organization SIM (Sistema Interamericano de Metrología).

## II. DESCRIPTION OF THE IMPROVED CALIBRATION SYSTEM

Fig. 1 presents a block diagram of the newly developed calibration system, which consists of a current source, a reference Rogowski coil with an active integrator, a digital sampling board and a personal computer. The current source was implemented with a current step-up transformer, T, powered from the power line by an autotransformer (not shown in Fig. 1) that can be adjusted so that a current with an RMS value of 4–25 kA can be generated in the current step-up transformer secondary, starting from which a current loop with test current is formed.



**Fig. 1.** A block diagram of the calibration system for weld current meters.

A set of switchable capacitors connected in parallel with the current step-up transformer primary are used to compensate for the inductive part of the load that the calibration system presents to the autotransformer and the power line. If necessary, the compensation capacitors can be disconnected to avoid

current transients produced during the thyristors turn-off time. The primary current of the step-up current transformer is controlled by a microcontroller and a pair of high current thyristors in antiparallel connection, driven by a zero-crossing trigger circuit. The microcontroller communicates with the computer using Bluetooth Low Energy (BLE) interface. The thyristors turn on and off the primary current for a set duration. The test current duration is limited to 150 power line cycles to prevent overheating of the current step-up transformer and conductors in its secondary circuit. This test current duration is more than sufficient for calibration purposes while it keeps low the temperature variation of the current step-up transformer, the hexagonal cage, and the device under test in the cage.

The current step-up transformer is operated at a near short-circuit condition using heavy solid-copper conductors and a hexagonal coaxial cage custom-made of heavy aluminum plates and center conductor. Inside the coaxial cage, the test current creates an approximation of the ideal symmetrical 1/R-type magnetic induction for the reference Rogowski coil and Rogowski coil under test [16]. Both coils are installed inside the cage around the test current carrying center conductor. The cage also provides a very low impedance path for test current. A photo of the calibration system current source including the coaxial cage is shown in Fig. 2.



**Fig. 2.** A photo of the calibration system with the hexagonal coaxial cage.

The larger maximum test current compared to that reported in [19] was achieved by introducing a switchable bank of compensation capacitors, and by shortening and improving the connections of the current step-up transformer and the coaxial cage. The impedance at the modified current step-up transformer secondary connections was found to be 0.17 mΩ, determined by applying a continuous AC test current of 5 kA and measuring the voltage across the transformer terminals. The real and imaginary components of the current loop impedance are determined from the simultaneous sampling of the voltage at the current step-up transformer secondary and the integrator output voltage representing the test current measured

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by the reference coil and integrator. The measured current loop impedance had a real component of 0.13 mΩ and imaginary component of 0.11 mΩ.

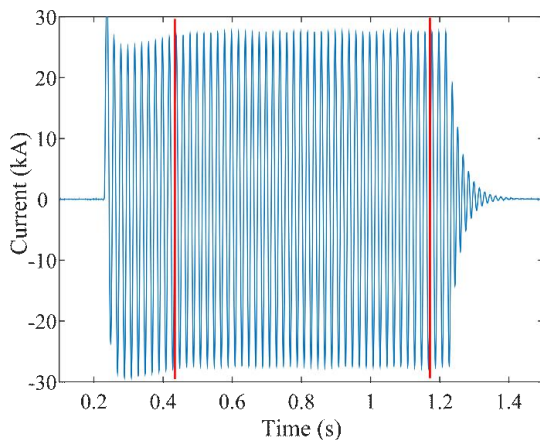
The test current represents the primary current both for the Rogowski coil of the weld current meter which is the device under test (DUT), and for the reference Rogowski coil.

The reference system is composed of a Rogowski coil, an active integrator, a data acquisition board, a special adaptor connecting the integrator and data acquisition board, and a custom-developed software running on a personal computer. The software controls the measurement process, collects and records the data, processes the data, presents them visually and stores the measurement results.

The reference Rogowski coil is wound on a thermally stable acrylic material with enameled copper wire in a single layer. Its calculated resistance and inductance were in good agreement with the measured values. An external resistor was connected to the coil terminals for improving its transient response [4]-[5]. The reference Rogowski coil output is connected to the active integrator input to recover the primary current waveform. They are connected by means of a coaxial cable with BNC connectors.

The active integrator was designed as a three-stage device to increase its frequency bandwidth. It consists of: a passive integrator, an active integrator and an output stage that allows automatic DC offset control and setting the gain to make the output voltage be within the data acquisition board input voltage range. The integrator was built using resistors with low temperature and voltage coefficients, and capacitors with low temperature coefficients and low dissipation factors to obtain a stable transfer function with time and temperature. The time constant of the active and passive integrator were matched by selecting components with matching measured values. The operational amplifiers were selected to have low offset voltages, low input currents, and wide frequency bandwidths. A bandwidth of 100 kHz was achieved.

The integrator output is sampled by a data acquisition board



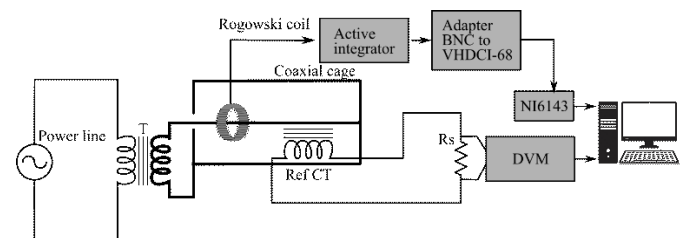
**Fig. 3.** Graph of a measured current. The red cursor line at the left indicates the cycle number 10 and the other red cursor line indicates the cycle number 47.

(NI-6143, 16-bit resolution, and ±5 V input voltage range). The transfer constant of the Rogowski coil and integrator as a group is selected to fit in the acquisition board input voltage range of ±5 V for a maximum current of 25 kA. Consequently, their nominal transfer constant was 7500 A/V, and its actual value was determined by calibration.

The calibration system is configured and controlled by a custom-developed software. During the configuration phase, a number of power line cycles for the measurement is set. When a measurement is run, the thyristors in the current source are triggered through the BLE interface. Then the data acquisition board samples the integrator output voltage. The data samples are transferred to the computer, and the recorded current waveform data are graphically presented, including two adjustable cursors. The RMS value of the measured current is calculated for an integer number of power line cycles between the cursors, as shown in Fig. 3. The cursor positions are adjusted in accordance with the configuration of the weld current meter under test. The cycles outside of the area between the cursors are discarded for the calculation of the current RMS value. (In Fig. 3, the first 10 cycles and those after the 47th cycle are to be discarded.)

### III. PERFORMANCE EVALUATION

The measurement part of the calibration system, which includes the reference Rogowski coil, active integrator, data acquisition board, and computer with the custom-developed software, is calibrated at steady-state AC currents in a setup shown in Fig. 4. The calibration is performed by a comparison of the integrator output voltage with a voltage across a reference AC shunt,  $R_s$ , in the secondary of a reference current transformer, Ref CT. The Rogowski coil and the reference current transformer share the same primary current. The integrator output voltage is digitized by the data acquisition board and processed by the custom developed software at the computer. The reference AC shunt voltage is measured by a reference digital voltmeter and the measurement data processed at the computer.



**Fig. 4.** Calibration of the measurement part of the reference calibration system at steady-state AC currents.

The 10 kA current transformer can be installed inside the hexagonal coaxial cage and in this way the reference Rogowski coil is calibrated in the same position where it is used for the calibration of other devices under test. A custom split wooden disk was manufactured to center the coil on the current carrying center conductor, and to keep the coil position fixed. With this, the influence of the Rogowski coil positional sensitivity is greatly

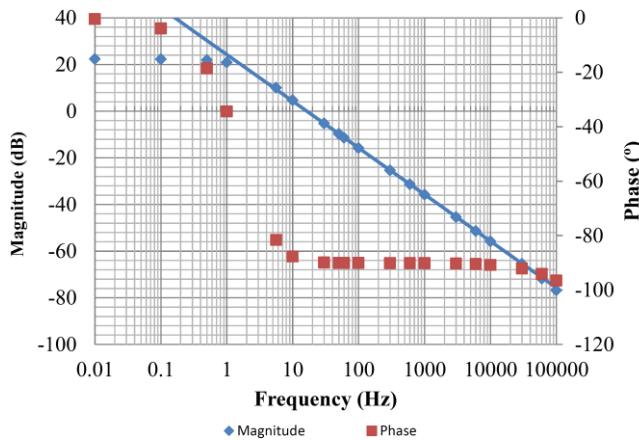
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diminished.

### A. Active Integrator

The frequency bandwidth of the active integrator was measured up to 100 kHz using a Stanford Research SR830 lock-in amplifier. The amplifier output was providing a sinusoidal voltage to the integrator input, and the integrator output voltage was measured with the amplifier. The magnitude and phase frequency response of the integrator is shown in Fig. 5. The integrator shows a linear behavior from 10 Hz up to 100 kHz, with a slope of -20 dB/decade. The phase displacement is  $-89.99^\circ$  at 50 Hz, and it is within  $0.84^\circ$  from 30 Hz up to 10 kHz.

The linearity of the integrator was evaluated varying its input voltage provided from a high accuracy AC voltage calibrator and measuring the integrator output with a high accuracy digital (sampling) voltmeter. The integrator input voltage was varied from 0.1 V to 25 V at frequencies of 50 and 60 Hz. The linearity was calculated as the relative deviation of the measured output voltage from the straight line fitted through all of the measured pairs of input and output voltage. The maximum deviation determined was less than 0.03 %.



**Fig. 5.** Measured frequency response of the active integrator. The blue line is the amplitude response of an ideal integrator.

### B. Data Acquisition Board

The Data Acquisition Board and the associated custom-developed software were evaluated using a multifunction calibrator Fluke 5700 calibrated against INTI reference thermal voltage converter standards. For sinusoidal AC voltages with peak values from 0.1 V to 5 V, at 60 Hz, the measured error was lower than 0.05 %. For DC voltages in the same span, the measured error was determined to be lower than 0.01 % for the gain and less than 85  $\mu$ V for the offset.

The custom-developed software for the calculation of voltage RMS value was evaluated comparing the measurement results obtained by means of it against the results obtained by another software developed in a calculation and programming platform. The algorithms in both take the measured data, apply 10 kHz low-pass digital FIR filters, remove DC mean values obtained this way, and calculate the RMS values of the AC

voltage. The difference between the two sets of results was found to be less than 0.003 %.

### C. Short Time Stability, Temperature Coefficient and Positional Error of the Reference Rogowski Coil

Several verification and characterization tests were performed on the reference calibration system consisting of the Rogowski coil, integrator, and data acquisition board. These tests were performed at the current of 3 kA of the power line frequency of 50 Hz.

The time stability was evaluated by comparing the reference calibration system repeatedly during four months against the standard current transformer, Ref CT, that was occasionally disconnected due to other calibration services performed in the lab for clients. The observed drift was 0.017% per month. This was taken into account as an uncertainty with rectangular distribution, making this uncertainty component 0.010%.

A temperature coefficient (TC) of the Rogowski coil and integrator as a group was evaluated by changing the temperature in the high current laboratory and allowing sufficient time for the coil and integrator to reach thermal equilibrium. The coil and integrator transfer constant, at the test current of 3 kA, 50 Hz, was measured at temperatures between 18 °C and 23 °C. The temperature coefficient of 0.0075 %/°C was determined.

The Rogowski coil positional error was determined at an ambient temperature of 23 °C, and the test current of 3 kA, 50 Hz. The Rogowski coil was rotated in steps around its center, and also the coil center was moved away from the center conductor close to a side of the coil window. The positional error was determined as the maximum deviation of all measured values of the coil transimpedance at the fixed frequency of 50 Hz from that at the central reference position, and it was less than 0.28 %. This test was repeated with two Rogowski coils of the same design and construction, and similar values of their positional errors were obtained.

### D. Calibration of the Rogowski Coil and Integrator at NRC

The INTI Rogowski coil and integrator were also calibrated at NRC using the NRC Rogowski coil calibration procedures compliant to ISO/IEC17025 Standard [21]. The Type B uncertainties (coverage factor  $k=2$ ) of the NRC calibration system are 100  $\mu$ A/A for magnitude and 100  $\mu$ rad for phase. The calibrations were performed separately for the Rogowski coil alone and for the Rogowski coil and integrator as a group, at steady-state AC test currents of up to 20 kA of power frequencies of 50 and 60 Hz. This allowed an insight into the Rogowski coil contribution to the measurement uncertainty of the Rogowski coil and integrator group.

In the calibration, two different calibration setups were used, one for lower currents of 50 A – 1,400 A and the other for higher currents of 1 kA – 20 kA. The measurements were carried out with repeats in series, on separate days, to check for the short term stability and to obtain information on Type A uncertainty of the devices under test.

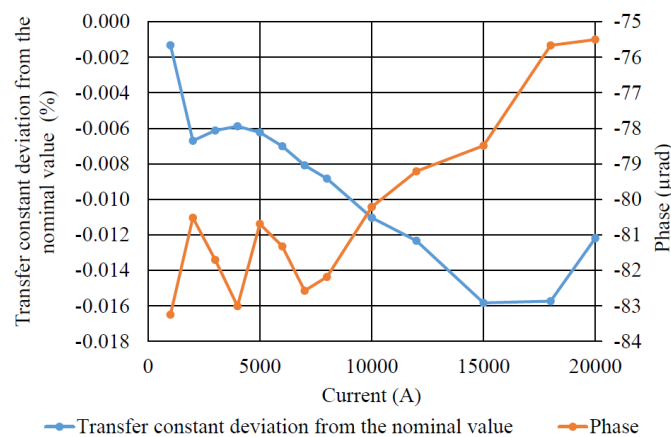
At the tests currents up to 1,400 A, the Type A uncertainty

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( $2\sigma$ ) of the Rogowski coil mutual inductance measurements was less than 0.017 %, and of its phase displacement was less than 10  $\mu\text{rad}$ . In the same current span, the linearity vs. current of the coil mutual inductance was within 0.005 %, and of its phase displacement was within 10  $\mu\text{rad}$ . When the load at the Rogowski coil output changed from that represented by the integrator input to no load, the change of the coil mutual inductance was 0.01 %, and the change of its phase displacement was less than 5  $\mu\text{rad}$ . When the Rogowski coil was moved from the low current to the high current calibration setup, the change in its measured mutual inductance was 0.01 %, while the change in its measured phase displacement was 50  $\mu\text{rad}$ .

At the tests currents up to 16 kA, the linearity vs. current of the coil mutual inductance was within 0.02 %, and of its phase displacement was within 15  $\mu\text{rad}$ . The increased linearity error of the coil mutual inductance is attributed to changing temperature in the coil surroundings caused by the center conductor heating at elevated currents.

At the tests at currents up to 20 kA, the Type A uncertainty ( $2\sigma$ ) of the Rogowski coil and integrator transfer constant measurements was less than 0.02 %, and of its phase displacement was less than 15  $\mu\text{rad}$ . The linearity vs. current of the transfer constant was within 0.02 %, and of its phase displacement was within 10  $\mu\text{rad}$ .



**Fig. 6.** Rogowski coil and integrator transfer constant deviation from the nominal value and phase vs. current at 50 Hz.

In addition, a commercial weld current meter together with its current sensing coil was tested at near-sinusoidal high pulsed currents with RMS values of up to 13 kA (peak values of up to about 19 kA). Its errors were found to be within 0.1 % of those obtained at INTI by means of the described new calibration system, with a total combined uncertainty of 0.1 %.

## IV. UNCERTAINTIES

### A. Data Acquisition Board

The uncertainty of the digital sampling board is calculated considering its DC specifications, THD (total harmonic distortion), and the spectral leakage due to non-synchronous measurement. The DC specification was propagated in the RMS value calculation. The uncertainty for each sample was calculated including the gain error (0.05 % of reading), non-linearity (1.5 digits), noise (122  $\mu\text{V}$  rms), resolution (16 bits), and sampling time uncertainty (50  $\mu\text{s/s}$ ). This calculation was repeated for several simulated and measured signals of different amplitudes and with different numbers of samples. Then, the THD was taken from the specification (16 ppm). The spectral leakage was also simulated for a full-scale near-sinusoidal signal with several sampling lengths, one with an integer number of cycles and others with a total sampling time up to 3 ms longer or shorter. The maximum error of 250 ppm was obtained. Thus, the total uncertainty due to the acquisition board is calculated to be 0.07 %. This value does not include long term stability effects as it was evaluated with the Rogowski coil and integrator.

### B. Uncertainty of the Reference Calibration System

The reference calibration system consists of the reference Rogowski coil, integrator and data acquisition board. The calibration uncertainty of the reference calibration system is determined from the measurement uncertainties of the reference current transformer 10 kA/5 A, reference AC shunt, and digital voltmeter. Another INTI standard 3 kA current transformer with multiple ratios and a current comparator bridge [22] are used in the calibration of the reference current transformer. This is performed at 10 kA AC steady-state currents, with the primary winding of 10 turns carrying 1 kA, or with the primary winding of 5 turns carrying 2 kA. The uncertainty of this calibration is less than 10 ppm with  $k = 1$ .

The digital voltmeter introduced the largest uncertainty, which can be reduced by using a digital voltmeter of higher accuracy, or by using a calibrated thermal voltage converter.

Table I shows the uncertainty budget for the reference calibration system at 10 kA.

TABLE I  
UNCERTAINTY BUDGET OF REFERENCE CALIBRATION SYSTEM

Uncertainty component	Distribution	Value (%)
Reference current transformer ( $k = 1$ )	Normal	0.001
Reference AC shunt ( $k = 1$ )	Rectangular	0.012
Reference Digital Voltmeter ( $k = 1$ )	Rectangular	0.081
Type A uncertainty ( $k = 1$ )	Normal	0.030
<b>Expanded combined uncertainty (<math>k = 2</math>)</b>		<b>0.174</b>

### C. Uncertainty Budget of the Current RMS Measurements by the Reference Calibration System at AC Currents

Table II shows the uncertainty of the reference calibration system at AC steady-state currents. The uncertainty

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components include the uncertainties of the Rogowski coil, integrator, and the data acquisition board.

The impact of the Rogowski coil positional sensitivity is significantly reduced by centering the reference coil on the current carrying center conductor by means of custom non-conductive non-magnetic split disks that keep the reference coil in this fixed position. The positional sensitivity was determined to be 0.030 % by repeatedly unmounting and mounting the coil on the measurement setup. The influence of external magnetic fields was not noticeable because of the use of the reference and DUT Rogowski coils inside the hexagonal coaxial cage.

TABLE II

UNCERTAINTY BUDGET OF THE CURRENT RMS MEASUREMENTS WITH THE REFERENCE CALIBRATION SYSTEM AT STEADY-STATE AC CURRENTS

Uncertainty component	Distribution	Value (%)
Reference calibration system ( $k = 1$ )	Normal	0.087
Short term stability (one month) ( $k = 1$ )	Rectangular	0.010
Rogowski coil positional sensitivity ( $k = 1$ )	Rectangular	0.030
Rogowski coil and integrator TC (for $\pm 2$ °C) ( $k = 1$ )	Normal	0.008
Rogowski coil and integrator linearity ( $k = 1$ )	Normal	0.010
Data Acquisition Board ( $k = 1$ )	Normal	0.035
<b>Expanded combined uncertainty (<math>k = 2</math>)</b>		<b>0.202</b>

#### D. Uncertainty of the Weld Current Meter Calibration

The transfer constant of the reference calibration system obtained in the calibration at the AC steady-state currents is subsequently used in the calibrations of WCMs by the same reference system at short duration currents.

Table III shows the uncertainty budget for the calibration of Weld Current Meters at 20 kA. The uncertainty components include the uncertainty of pulsed current measurement by the reference calibration system given by Table II, the WCM resolution, and the Type A uncertainty of measurements. The laboratory tested several WCMs of three different models from different manufacturers of 3, 3.5, and 4.5 digits. In the case of a WCM with 4.5 digits in the range of 20 kA, the instrument has a resolution of 1 A. The maximum value of type A uncertainty for three measurements obtained in the same day was 0.06%. This WCM was calibrated at test current of 40 power line cycles. The meter and the reference system were configured to eliminate the first ten and last ten power line cycles in order to suppress transients from the calculation.

A note is added to calibration certificates stating that the calibration results were obtained at the specified laboratory conditions and that the user is responsible to evaluate the impact of actual field conditions on the coil performance, since the conditions in which the coil is used may be significantly different such as the temperature, position of the coil, and external fields.

TABLE III

UNCERTAINTY BUDGET FOR THE CALIBRATION OF WELD CURRENT METERS

Uncertainty component	Distribution	Value (%)
Pulsed current measurement by the reference calibration system ( $k = 1$ )	Normal	0.101
Weld Current Meter resolution ( $k = 1$ )	Rectangular	0.003
Type A uncertainty ( $k = 1$ )	Normal	0.060
<b>Expanded combined uncertainty (<math>k = 2</math>)</b>		<b>0.235</b>

The WCM with its current sensing coil is calibrated by direct comparison, with a final uncertainty ( $k = 2$ ) of less than 0.25 %.

#### V. TRACEABILITY

The traceability of this calibration system is achieved through the traceable calibrations of the reference AC shunt, AC voltage measurements by the digital voltmeter, reference current transformer as a ratio device, and a reference time/frequency base, performed at their respective INTI labs against the Argentinian national measurement standards. In addition, Rogowski coil and integrator are calibrated at NRC according to the NRC Rogowski coil calibration procedures compliant to ISO/IEC 17025 Standard [21].

#### VI. CONCLUSION

An improved calibration system for traceable calibrations of weld current monitors at high pulsed currents of short duration developed recently at INTI, Argentina, was presented in the paper. The system has an increased pulsed current generating capability of 25 kA, and measurement of the current RMS values with an improved uncertainty of 0.25 %. The performance evaluation of the improved calibration system was conducted at INTI and also at NRC Canada is presented. The calibration system represents a significant and valuable upgrade in providing a traceable calibration service by INTI to the automotive industry in Argentina.

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