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Calibrations of Resistance Welding Equipment with High Pulsed Currents

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Abstract—Rogowski coils are widely used as high pulsed current sensors in resistance welding applications. The operating conditions of the coils determine the requirements for their calibration. A new calibration system has been developed at NRC Canada for calibrating current sensing coils and weld current monitors used in AC resistance welding. The calibration system, which includes a high current source and a coaxial copper cage, has been evaluated at peak pulsed currents of up to 80 kA, at 60 Hz. The expanded measurement uncertainties ($k=2$) have been estimated to be less than 350 $\mu\text{A/A}$ for magnitude. A method for the calibration of weld current monitors separately from their Rogowski coils at conditions that correspond to those obtained at high pulsed currents, but without the need to use actual high pulsed currents has also been developed.

Index Terms— AC current measurement, pulsed currents, Rogowski coils, weld current monitors/meters, calibrations, digital sampling, measurement uncertainty.

I. INTRODUCTION

Rogowski coils are useful and versatile devices used for the measurement of high AC, transient, impulse and pulsed currents in various applications. High-accuracy calibrations of the coils at continuous AC currents of power and audio frequencies have been described in [1],[2]. The calibration at high pulsed currents used in AC resistance welding has been discussed in [3],[4].

Despite many papers published on new Rogowski coil designs and applications, as well as several related technical standards, there is a noticeable lack of information and guidelines concerning the calibration of Rogowski coils and their accompanying equipment. Presently, the American Welding Association Standard AWS A10.1 “*Calibration and Performance Testing of Secondary Current Sensing Coils and Weld Current Monitors used in Single-Phase AC Resistance Welding*” [5] is under revision. Significant efforts are being made to ensure that the revised standard is more practical and easier for the industry to implement. The more important technical considerations include determining measurement uncertainties under the test conditions similar to the conditions encountered in the industry, and establishing traceability to SI units at high pulsed currents.

To address some of these needs, a new calibration system

has recently been developed at NRC Canada to provide calibrations for the resistance welding industry. Preliminary test results were reported in [6]-[7]. This paper describes in more details the new system, its use for calibrations of the current sensing coils (CSCs) and weld current monitors/meters (WCMs) at high pulsed currents, and presents an evaluation of the performance of the system.

II. DESCRIPTION OF THE CALIBRATION SYSTEM

A simplified block diagram of the new calibration system is shown in Fig.1. A main circuit breaker (MCB) connects AC power line voltage V_{AC} to a weld-current controller (WCC), which consists of an internal circuit breaker (CB), micro-computer (μC) and silicon controlled rectifiers (SCRs). The weld-current controller output is connected to a set of auto-transformers (AT). The auto-transformers supply a transformer (T), which in turn provides test current for a reference Rogowski coil (REF) and a current sensing coil (CSC) under test (DUT) mounted in a coaxial copper cage (CC).

The CSC is connected to a weld current monitor/meter under test (WCM). A high-accuracy digital sampler (DS1) samples the voltage from the reference Rogowski coil output, and a digital sampler (DS2) samples the secondary voltage of a voltage transformer (VT). A computer (PC) communicates with WCC and WCM (through a serial communication link) and with DS1 and DS2 (through IEEE-488 interface bus); controls the operation of the calibration system; and acquires and processes the measurement data.

The controller WCC is a micro-computer-based device with processing, storage, diagnostic and communication capabilities.

The transformer T is used as a current step-up transformer to provide high pulsed current. The coaxial copper cage provides a radially symmetrical magnetic field around the cage center conductor. The CSC and REF coils are mounted inside the CC such that they encircle the same current in the CC center conductor. Each of these coils provides at its output a voltage proportional to the first derivative of the high current. The REF output voltage is sampled equidistantly by the reference digital sampler DS1 (digital sampling voltmeter, DVM), while the DUT output voltage is processed by the weld current monitor/meter WCM, to provide the primary current RMS value and other parameters.

Fig. 1 A simplified block diagram of the calibration system at pulsed currents.

The WCM is a microcontroller-based device with processing, storage and communication capabilities. It processes the output voltage of a CSC connected to its input, calculates the CSC primary current and other parameters, and makes the results available on the WCM display, possibly a local printer, and through a communication link (most often RS232).

The voltage transformer VT scales down the supply voltage V_{AC} , so that it can be sampled by the digital sampler DS2.

Processing of the samples acquired by DS1 and DS2, and a comparison of the results with those from the WCM are performed at the computer PC.

Fig. 2 is a photograph of the main components of the calibration system.

Fig. 2 Photograph of the calibration system.

III. OPERATION

A. Principle of Operation

The operation of the calibration system consists of a) generating a test pulsed current, similar to what is used in resistance welding, b) measuring the test current with the

reference measurement system and the device under test, and c) comparing their measurement results.

The AC power supply, WCC, T and CC are used to generate and control the test current. The REF, DS1, VT, DS2 and PC are the components of the reference current measurement system. The device under test typically consists of a weld current monitor/meter WCM and its current sensing coil CSC, or a standalone CSC.

The calibration system uses non-synchronous digital sampling. The DS1 samples of the REF coil output voltage are numerically integrated to obtain the current and to calculate its RMS value. The DS2 samples of the VT secondary voltage are filtered by a multi-rate non-synchronous low-pass digital filter [1] to suppress higher harmonics, and then used to estimate the power line frequency during the same measurement interval when the current is measured. If a standalone CSC represents device under test, another digital sampler (DS3) not shown in Fig 1 is used to sample the coil CSC output voltage. These samples are also numerically integrated to obtain the current and its RMS value.

The amplitude of the test current is set by adjusting the auto-transformers' setting. The test current duration, specified as a number of power line cycles, heat setting (related to the SCR conduction angle), and other weld-schedule parameters are programmed in the weld-current controller WCC. A start command is initiated from the PC. The controller WCC initiates the pulsed current generation while the external trigger XT initiates the measurements of the WCM and the digital samplers DS1, DS2. After the test current generation and measurements are done, the PC collects the measurement data, performs the data processing, and provides the measurement error of the device under test.

B. Generating Pulsed Currents

The coaxial copper cage represents small and constant inductive impedance for the transformer, which operates with a secondary essentially short-circuited. The transformer represents small impedance for the auto-transformers output. The auto-transformers are used as an independent means for adjusting the voltage at the transformer primary, and

consequently for adjusting the amplitude of the transformer output pulsed current. At any given AT setting, the combined impedances of CC, T, and AT form an equivalent impedance Z_e , which is connected to V_{AC} through the weld-current controller WCC. The WCC, through a pair of silicon-controlled rectifiers in anti-parallel connection and the control of their conduction angle sets the duration and waveform shape of a test pulsed current.

A typical current waveform is shown in Fig.3.

Fig.3 A typical test current waveform.

For generating high pulsed currents, a power supply rated at a sufficiently high output current is needed, so that it can deliver the required pulsed current for the calibration system without affecting other loads supplied from the same power line. Self-heating at high pulsed currents, the high current source requires liquid cooling of the SRCs and T, and air cooling of AT.

C. Coaxial Copper Cage

The CSC mutual inductance calibration is required to be performed in a $1/R$ -type magnetic field, which is provided in the coaxial copper cage, CC [5],[8]. The coaxial copper cage provides evenly distributed return current in the cage shield and a radially-symmetrical magnetic field around the center conductor inside the cage, for both CSC under test and REF coils. This is achieved by a CC of circular coaxial design. The magnetic induction, B , inside a long coaxial cable [9], is:

$$B = \begin{cases} \mu_0 \frac{i}{2\pi a^2} r, & r \leq a \\ \mu_0 \frac{i}{2\pi r}, & a \leq r \leq b \\ \mu_0 \frac{i(c^2 - r^2)}{2\pi r(c^2 - b^2)}, & b \leq r \leq c \\ 0, & r \geq c \end{cases}, \quad (2)$$

where i is the current, a is the center conductor radius, b and c are the cylinder inner and outer radii, and r is the distance from the center. The magnetic field B in the cage is shown in Fig.4. The values a , b and c in Fig.4 are proportional to the radial dimensions of the actual cage.

Fig. 4 Magnetic field B around the current-carrying conductor inside a long coaxial cage

D. Measuring Pulsed Currents

The test pulsed current is measured by the device under test Rogowski coil (CSC), or CSC with WCM. In the former case, the test current is derived from the CSC output voltage; and in the latter, the test current is processed by the WCM and shown on its display and available via its communications link.

The reference Rogowski coil REF is a machined coil of a design similar to that described in [10]. It has a high positional and temperature stability. The REF output voltage is sampled equidistantly by the precision digital sampler DS1. The transformer T output current, which represents the REF input current, is reconstructed by numerical integration of the REF output voltage.

Although the frequency is not needed for comparing the DUT and REF mutual inductances and the phase difference between their outputs, it is needed for determining the RMS current value. The frequency is calculated from the voltage V_{AC} replica at the VT secondary, sampled by the digital sampler DS2.

In addition to scaling down V_{AC} , the VT allowed the V_{AC} replica to be referenced to the ground potential. The copper screen, which is grounded, and the insulation between the screen and the VT primary and secondary windings provided the necessary isolation from the supply voltage and reduced the capacitive coupling between the windings and the ground.

IV. TESTS FOR RESISTANCE WELDING EQUIPMENT

Although the main quantities to be calibrated are mutual inductance in the case of a CSC, and RMS current in the case of a CSC-WCM group, other parameters have also to be measured [5],[8]. Eight tests relevant for resistance welding are described in [5]. Some of them require testing CSC alone, and some require testing CSC-WCM group.

Tests 1-2 require the CSC mutual inductance, M_{CSC} , to be measured at the manufacturer recommended load and at no load, respectively. The load represents the input impedance of a WCM to be used with the CSC. The mutual inductance is the basic property characterizing the CSC. It is related to the transfer characteristic of the coil, defined as the ratio of the output voltage and input current, at a given frequency. It is also referred to as the CSC conversion characteristic or transimpedance, $Z_T = \omega M_{CSC}$. The *test 2* is designed to help evaluate the CSC interchangeability from one WCM to another.

Tests 3-4 require the CSC position and tilt sensitivities to be determined. This is done by measuring the CSC mutual inductance, or the primary current RMS value using a WCM with sufficiently high resolution, at different CSC positions and tilts with respect to the current-carrying conductor.

Test 5 requires the CSC sensitivity to external magnetic fields to be measured. This is related to the positional sensitivity, and is particularly important for CSCs mounted in the space-constrained welding transformer secondary loops. The test is performed with the CSC in different positions and tilts with respect to the current carrying conductor when the conductor is not going through the CSC opening (window). Since no CSC output voltage should be induced when there is no primary current, the measurement using WCM is possible only if the WCM has sufficient resolution near zero. However, WCMs often do not operate below some minimum current.

Test 6 requires the CSC temperature coefficient (TC) to be determined. This is an important measurement since CSCs are commonly used at temperatures different from those at which they are calibrated. The TC is defined as ratio of the change in CSC mutual inductance measured at an altered test temperature and at room temperature, and the difference of these two temperatures [5]. The test is to be conducted in a temperature chamber, and the CSC is allowed to reach thermal equilibrium at each of these temperatures. It is recommended to conduct several tests to determine any nonlinearity of the temperature coefficient and repeatability of the test results.

As per a requirement of the standard in reference [8], the thermal test is to be completed within 3 minutes of removal of the CSC from the temperature-controlled oven, after the CSC has reached its thermal equilibrium at an elevated or reduced

temperature with respect to the ambient temperature. A similar procedure with pre-cooled CSCs was used in [12].

Test 7 requires measuring the frequency response of a CSC. As it can be seen from the waveform in Fig.3, the pulsed currents contain higher harmonics. Their harmonic amplitudes are increased by the harmonic's order in the CSC output voltage. Both the CSC frequency response and the CSC output voltage spectrum are needed for estimating this uncertainty.

For these measurements, voltage insertion method and high-frequency high-current method are recommended [5]. The first is shown in Fig.5 with a variable-frequency voltage source, and is used for untrimmed, or series trimmed, CSCs. The second is shown in Fig.6 with a variable-frequency current source. It is used for CSCs with resistive dividers or other series-parallel resistive networks at the output, with which manufacturers often trim the CSC output voltage to reduce the dispersion of mutual inductance in production.

In Fig.5, VS is a frequency-variable voltage source, V_1 and V_2 are AC voltmeters of sufficiently wide bandwidth, PM is an optional phase meter with two high-impedance inputs, reference input (R) and signal input (S), and R_L is a load at the CSC output. From the voltage measurements at various frequencies, the V_2/V_1 ratio is calculated. Optionally, the phase between the PM inputs is measured.

Fig.5 Frequency Response Testing of an untrimmed, or series trimmed, CSC.

In Fig.6, CS is a frequency-variable current-source, REF and DUT are the coils to be compared, R_R and R_C are their required loads, and V_1 , V_2 and PM are as above. The reference coil has to have a known and sufficiently high frequency bandwidth. The measurement and calculation for this method are similar to those described for the test in Fig.5.

The high-frequency high-current test is more demanding equipment-wise as it requires two coils and two loads, and the frequency-variable current-source, which is less common and more expensive than a frequency-variable voltage-source. It also requires a custom test-setup for mounting two coils around the same current carrying conductor. This conductor is likely to be multi-turn in order to increase the equivalent primary current for the coils, and to ensure the coils' output voltages sufficiently high for the measurement.

Fig.6 Frequency Response Testing of a parallel, or series parallel trimmed, CSC.

Most high current sources are capable of generating high currents at power frequencies of 50/60 Hz only. Their maximum output currents drop quickly with the increase of operating frequency. Thus, the name “high-frequency high-current” may not be the best fit for this method. The commercially available transconductance amplifiers (TCAs) could be used to generate currents of up to about 100 A at 100 kHz for small impedances. However, multiple turns in the primary increase the set-up impedance, and bring TCA closer to its compliance voltage and output current limits, at a set frequency. A mitigating factor is that the coil output voltage increases with frequency increase.

Test 8 requires the calibration of a CSC-WCM group. The calibration is performed with the system shown in Fig.1. A note in [5] states that this test is commonly performed, but the uncertainties and traceability aspects are usually not taken into account. These two aspects are addressed in the next section.

In addition to the described system for the CSC-WCM calibration at high pulsed currents, a new method for the calibration of weld current monitors separately from their Rogowski coils at the conditions that correspond to those obtained at high pulsed currents, but without the need to use actual high pulsed currents has been developed.

The test voltage, based on the waveforms recorded during calibrations with CSCs when high pulsed current was used, is generated and applied to a WCM under test. The voltage applied is a replica of a CSC waveform obtained from an actual CSC-WCM measurement with the pulsed current at the specific current setting, heat setting, and number of cycles. The CSC waveform could be obtained either from the CSC belonging to the WCM under test, or from a reference coil and then scaled by the ratio of the WCM CSC and reference coil mutual inductances. The measurement method has been implemented and is under evaluation.

V. EVALUATION

A. Evaluation of CSC-Related Measurements as per Tests 1-7

The calibration of CSCs at steady-state sinusoidal AC currents [1] provides, in general, lower measurement uncertainties and higher resolution than the calibration of CSCs at high pulsed currents. However, the maximum pulsed currents are usually higher than the maximum continuous AC

currents, WCMs do not operate at continuous AC currents, and the resistance welding labs are not usually equipped for testing at continuous AC currents.

In the labs which have such equipment and for the tests where it is possible, the advantage should be taken of the calibrations at steady state currents. This means the measurements for obtaining the CSC mutual inductance at the manufacturer recommended load and at no load; determining the CSC position and tilt sensitivities; sensitivity to external magnetic fields; and CSC temperature coefficient, as described in *tests 1-6*. The NRC calibration of Rogowski coils at AC currents [1], which is compliant to [13], can provide measurement uncertainties of less than 50 $\mu\text{A/A}$ for magnitude and 50 μrad for phase at power frequencies of 50/60 Hz.

The measurements of the CSC position, tilt, and external field sensitivities, described in *tests 3-5*, are important as they may be the highest sources of uncertainty in measurements with CSCs.

Another important measurement is that of CSC temperature coefficient. The temperature variations in actual welding environments are often large. When a poorly designed CSC with a high TC is exposed to large changes of temperature, measurement errors as high as a few percent can happen.

The coil TC is determined by the mutual inductance and temperature measurements at two different temperatures, as per *test 6*. The expanded uncertainty ($k=2$) of the coil TC measurement was found in previous calibrations at NRC to be less than 0.0008 $\%/^{\circ}\text{C}$.

The CSC frequency response measurement, as per *test 7*, has been evaluated through measurements with several Rogowski coils. The AC voltmeters were calibrated against a high-accuracy AC voltage calibrator at the same voltages and frequencies used in the *test 7*. After corrections of the AC voltmeters' differences, the expanded uncertainty ($k=2$) of the amplitude response measurement was less than 200 $\mu\text{V/V}$ up to 100 kHz.

B. Measurement Capability at Pulsed Currents

For the calibration of CSC-WCM groups, as per *test 8*, the new calibration system for high pulsed currents is used. The CSC-WCM provides no phase information, and therefore phase measurement is not a part of the CSC-WCM calibration.

The new calibration system has been tested at the AC power line voltage of 600 V, 60 Hz. It has been used for generating peak pulsed currents of up to approximately 80 kA. The maximum current is constrained primarily by the current rating of the AC power supply available in the lab. To limit heating effects, the test duration has not exceeded five power line cycles at the highest currents. The heat settings are in the range 0-99%.

C. Measurement Uncertainties at Pulsed Currents

Measurements at various settings of the pulsed-current amplitude, number of power line cycles, and heat settings have been conducted. The pulsed-current amplitude was adjusted by the auto-transformers' setting.

The linearity of the REF coil versus current amplitude [12],

positional sensitivity, temperature sensitivity, frequency response and repeatability were measured. The REF coil combined uncertainty ($k=2$) was found to be less than $200 \mu\text{A/A}$ for magnitude and $100 \mu\text{rad}$ for phase.

The contribution of numerical integration of the REF output voltage to measurement uncertainty was evaluated through computer simulations. The discontinuities in the CSC output voltage increase the uncertainty at lower heat settings. The uncertainty was estimated to be below $100 \mu\text{A/A}$.

The uncertainty of frequency measurement with a use of VT was evaluated. A signal generator of known and stable frequency was driving a power amplifier which has an output transformer. The output transformer secondary voltage of 260 V was connected to the VT primary. The frequency was estimated from the VT secondary voltage samples and compared to the signal generator frequency. Their difference was well within $10 \mu\text{Hz/Hz}$, and standard deviation of repeated measurements was about $1 \mu\text{Hz/Hz}$. A short measurement interval at the highest currents has more of an impact at the power line fluctuating frequency. Since frequency of the power line supplying the weld-current controller WCC and VT fluctuates, the uncertainty of frequency measurement was conservatively estimated to be below $100 \mu\text{Hz/Hz}$.

The calibration of the digital sampling system and its uncertainties are described in [1]. The sampling signal time base error is less than $1 \mu\text{Hz/Hz}$ and its stability is better than $1 \mu\text{Hz/Hz}$, which can be neglected with respect to other sources of uncertainty.

A combined expanded measurement uncertainty ($k=2$) of the calibration system at high pulsed currents was less than $350 \mu\text{A/A}$.

D. Traceability

Traceability to SI units of the new calibration at high pulsed currents was established through the calibration of the reference Rogowski coil, REF, frequency, and digital sampling system, DSS. The REF was calibrated using the NRC calibration procedure for Rogowski coils at continuous AC currents, which is compliant with IEC/ISO Standard 17025 [13]. The REF coil has been calibrated at the AC continuous currents of both synthesized and fluctuating power line frequencies at the NRC calibration systems for Rogowski coils using digital sampling based on [1],[2]. The frequency was calibrated using an EPMG frequency standard calibrated at NRC. The DSS was calibrated as in [1].

VI. CONCLUSION

A new traceable calibration of current sensing coils and weld current monitors at high pulsed currents for AC resistance welding has been developed at NRC Canada. The new calibration system includes a high pulsed current source and a coaxial copper cage. The performance of the calibration system has been evaluated at peak pulsed currents of up to 80 kA at 60 Hz and various currents, heat settings (SCR conduction angles), durations and other test settings. The

calibration system expanded measurement uncertainties ($k=2$) are less than $350 \mu\text{A/A}$.

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