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Djokic, Branislav

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A Dual-Channel Calibration System for AC Currents and Small AC Voltages

Branislav Djokic, *Fellow, IEEE*

Abstract—A new current-comparator-based dual-channel calibration system for AC currents and AC voltages in the millivolt range has been developed. The range of generated currents is 1 mA - 5 A, and the range of generated voltages is 1 mV - 500 mV. The calibration system in-phase and quadrature expanded measurement uncertainties ($k=2$) are within $25 \cdot 10^{-6}$. Although the system has been developed primarily for operation at power frequencies, it is also capable of operating at frequencies up to 1000 Hz with slightly increased uncertainties. The traceability to SI units is established through the calibration of AC voltage by means of AC/DC transfer and DC voltage reference, standard resistor, capacitor, and current comparator ratios.

Index Terms—AC voltage measurement, AC current measurement, current comparator, digital sampling, calibration, measurement uncertainty.

I. INTRODUCTION

IN the calibration of current transformers, a higher-accuracy current transformer (CT) or a current comparator (CC) is used as a ratio standard. This calibration requires the comparison of two AC currents and the determination of the ratio and phase differences between them. The ratio and phase errors of the calibrated CT is determined with a ratio-error test set [1]-[3]. The test set can be based on analog [1]-[2] or digital-sampling [3] techniques and uses two-channel current or voltage ratio measurement methods.

In addition, generating small AC voltages of high stability in a wide frequency range, and measuring them with low uncertainty, is of interest in AC voltage metrology [4]-[5]. In shunt and other impedance calibrations, digital sampling voltmeters are used [6]. Their calibration requires the comparison of two AC voltages.

For calibrating Rogowski coils at power and low audio frequencies [7]-[8], it is important to accurately measure the ratio of two small voltages and the phase angle between them in the vicinity of 0 and $\pm\pi/2$. Generating two AC voltages in the millivolt range with specified magnitude ratio and phase angle is needed to verify the digital sampling systems (DSSs) used in these calibrations. In [7], a calibration of two-channel digital sampling system by means of a current-comparator-based power bridge [9] was described. To generate two small

voltage signals with given amplitudes and phase, inductive voltage dividers were used at the power bridge voltage output, and an AC shunt was used at the power bridge current output.

This paper describes a new dual-channel CC-based calibration system [10] for generating two sinusoidal AC currents up to 5 A, or AC voltages in the millivolt range, at any phase angle. It was specifically developed for the calibration, at power frequencies, of current ratio-error test sets, and for the calibration of digital sampling systems used in the NRC Rogowski coil calibrations [7],[11].

II. DESCRIPTION OF THE CALIBRATION SYSTEM

A simplified block diagram of the calibration system is shown in Fig.1. It consists of a source of a sinusoidal AC voltage V_{AC} , reference resistor (R), two reference capacitors (C_1 and C_2), two variable-turn AC current comparators (CC_1 , CC_2), two sets of in-phase and quadrature sinusoidal voltage signals (P_1 , Q_1 and P_2 , Q_2) which are synchronized with the voltage V_{AC} , two transconductance amplifiers (TCAs, I_1 and I_2) with summing nodes, two electronically enhanced current transformers (CT_1 , CT_2) [12], two high-accuracy AC shunts (R_{S1} , R_{S2}) such as that described in [13], two (optional) precision buffer amplifiers (B_1 , B_2) [14]-[15], two amplifiers (A_1 , A_2) with their feedback resistors (R_{D1} , R_{D2}). The currents I_{O1} and I_{O2} represent the current outputs. The voltages V_{O1} and V_{O2} at the B_1 and B_2 buffers' outputs, or at the voltage terminals of the shunts R_{S1} and R_{S2} when the buffers are not used, represent the voltage outputs.

The current comparator ratio windings N_{R1} , N_{C1} and N_{R2} , N_{C2} have a variable number of turns that can be adjusted with high resolution. The number of turns of the ratio windings N_{X1} and N_{X2} can be adjusted to several discrete values. The detection windings N_{D1} and N_{D2} have a fixed number of turns. Their compensation windings are used but not shown in Fig.1.

III. PRINCIPLE OF OPERATION

The new calibration system essentially generates two output sinusoidal AC currents, or two sinusoidal AC voltages, with known frequency, amplitudes, and phase difference between them.

Fig.1 A simplified block diagram of the calibration system

A. Principle

The values of output AC currents, or AC voltages, are derived from the voltage V_{AC} , reference resistance, and reference capacitances by means of high-accuracy ratio devices (current comparators and current transformers) and shunts.

If output voltages are needed, the output currents are transformed to lower levels by the current transformers CT_1 , CT_2 and converted into voltages by the shunts R_{S1} and R_{S2} . When appreciable currents are to be drawn from the output voltages V_{O1} and V_{O2} , the buffers B_1 and B_2 are used to keep V_{O1} and V_{O2} unaffected while supplying the required load currents.

The in-phase reference current I_R is derived from the voltage V_{AC} and the reference resistance R . The CC windings N_{R1} , N_{R2} have small impedances with respect to R , and are mostly resistive when their corresponding current comparators are in balance. The quadrature reference currents I_{Q1} and I_{Q2} are derived from the voltage V_{AC} and the reference capacitances C_1 and C_2 .

Assuming that the reference resistance and capacitances have no magnitude or phase defects, the current I_2 at the CC_2 ampere-turn balance is given by:

$$\underline{I_2} = \frac{1}{N_{X2}} \left(N_{R2} \frac{V_{AC}}{R} \pm j N_{C2} V_{AC} \omega C_2 \right), \quad (1)$$

where the underscore denotes phasor.

The current $\underline{I_2}$, necessary to balance the CC_2 in-phase and quadrature reference currents is determined by the set number of turns N_{R2} , N_{C2} and N_{X2} . An initial balance is set by adjusting P_2 , Q_2 . The CC_2 detection winding N_{D2} and the amplifier A_2 with R_{D2} , provide a feedback for the transconductance amplifier I_2 to establish and maintain a final balance during the measurement. The current $\underline{I_2}$ is kept in phase with the voltage V_{AC} , and its quadrature component is zero ($N_{C2} = 0$) if the reference resistor has no appreciable phase error. If the reference resistor magnitude and phase are frequency dependent, its impedance can be represented as $\underline{Z}_R(j\omega) = R(\omega) \cdot e^{j\alpha(\omega)}$, where $\alpha(\omega)$ is the phase error. N_{C2} is set

according to (1) so as to compensate for the phase error:

$$N_{C2} = \frac{N_{R2}}{\omega C_2 R(\omega)} \sin \alpha(\omega). \quad (2)$$

A capacitor with low-loss dielectric is used for C_2 . Since the reference resistor phase error, even if not negligible, is small, the dissipation factor of C_2 is not critical.

At the CC_1 ampere-turn balance, the current $\underline{I_1}$ is given by:

$$\underline{I_1} = \frac{1}{N_{X1}} \left(\pm N_{R1} \frac{V_{AC}}{R} \pm j N_{C1} V_{AC} \omega C_1 \right). \quad (3)$$

The current $\underline{I_1}$ is set to any phase angle with respect to the voltage V_{AC} and, consequently, the current $\underline{I_2}$. The change of sign is implemented by the reversal of a corresponding winding. By adjusting the CC_1 numbers of turns N_{R1} , N_{C1} any phase angle between the voltage V_{AC} and current $\underline{I_1}$ can be set. The current $\underline{I_1}$, necessary to balance CC_1 , is determined by the set numbers of turns N_{R1} , N_{C1} and N_{X1} . An initial balance is set by adjusting P_1 , Q_1 . The CC_1 detection winding N_{D1} and the amplifier A_1 with R_{D1} , provide a feedback for the transconductance amplifier I_1 to establish and maintain a final balance during the measurement.

Since the $\underline{I_1}$ phase can be set to any angle with respect to V_{AC} , the C_1 capacitance stability and dissipation factor are important. At power frequencies of 50 Hz and 60 Hz, an active capacitor C_1 based on a low-loss gas-dielectric capacitor and current-comparator [9] is used. At other frequencies, capacitor C_1 with (a) low-loss dielectric is used. Its capacitance and dissipation factor are measured at the operating frequency and are accounted for by software.

At the ampere-turn balance of both current comparators, the ratio of currents is given by:

$$\frac{\underline{I_1}}{\underline{I_2}} = \frac{N_{X2}}{N_{X1}} \frac{N_{R1}}{N_{R2}} \left(\pm 1 \pm j \frac{N_{C1}}{N_{R1}} \omega R C_1 \right), \quad (4)$$

$$\varphi(I_1, I_2) = \arctg\left(\pm \frac{N_{C1}}{N_{R1}} \omega R C_1\right), \quad (5)$$

where $\varphi(I_1, I_2)$ represents the phase difference between I_1 and I_2 .

The currents I_1, I_2 transformed by CT₁, CT₂ generate output currents I_{O1}, I_{O2} , or voltages V_{O1}, V_{O2} at the outputs of shunts R_{S1}, R_{S2} , or buffers B_1, B_2 , respectively. This allows the CTs' secondaries and shunts to be grounded, and V_{O1}, V_{O2} to be referenced to ground. V_{O2} is in phase with V_{AC} and V_{O1} can have any phase with respect to V_{AC} , and therefore to V_{O2} .

B. Current Ranges

The calibration system maximum output current of 5 A and its minimum current is 0.1 mA. The ranges are mainly limited by the TCA and by the ratios and maximum currents of the current transformers used.

As shown above, I_1, I_2 amplitudes and, consequently, the I_{O1}, I_{O2} and V_{O1}, V_{O2} amplitudes can be varied through the selection of the CC ratio-winding number of turns. However, to preserve the N_{R1}, N_{C1} and N_{R2}, N_{C2} high resolution, an auxiliary CT with several ratios (e.g. from 1:1 to 1:50) is inserted between each TCA and its corresponding current comparator's N_X winding. These auxiliary CTs do not have to be highly accurate as they are placed in the feedback loops of their TCAs, but they increase the number of output currents and voltages that the calibration system can generate without any loss of the CC ratio winding resolution.

Two configurations of current transformers and current comparators are shown in Fig.2. The auxiliary CTs for increasing the number of current ranges are labeled as CT_a. With CT_b are labeled the electronically enhanced CTs, which transform, with high accuracy, the CT_a secondary currents to lower value replicas for the current comparators or the shunts. These configurations ensure that one terminal of the current comparator N_X windings and one terminal of the shunts are kept at the ground potential. At the same time, one terminal of each of the CT_b primary and secondary windings is also at the ground potential. This creates the best operating conditions for the CCs, CTs, and shunts.

C. Operation

After selecting a configuration of current transformers and current comparators, their transformation ratios are set based on a given AC output current or voltage magnitude. To cover any magnitude between two adjacent CT ratios, the voltage V_{AC} is set to a value less than or equal to its full scale. With this V_{AC} value set, which is common for the reference components of both current comparators, the comparators' numbers of turns N_R, N_C less than or equal to their full scale values have to be set for the other given AC output current or voltage magnitude.

Fig.2 Two configurations: a) output (shunt) current I_S is higher than the CC current I_X , and b) output (shunt) current I_S is lower than the CC current I_X .

IV. EVALUATION

The new calibration system has been evaluated through the calibrations of its components and also as a system.

A. Voltage V_{AC}

The voltage V_{AC} is 120 V and its value is established through a thermal voltage converter AC-DC difference and a DC voltage reference. The stability of V_{AC} was better than 2 μ V/V during measurements. The uncertainty ($k=2$) of the value of V_{AC} is less than 4 μ V/V. It should be noted that the exact value of V_{AC} is not critical for calibrating the ratio-error set and DSS. The ratio measurement applications require a stable and accurate magnitude ratio and phase difference of two AC currents, or two AC voltages, not their exact magnitudes, or exact phase angles.

B. Reference Resistor

The reference resistor R of 12 k Ω was built as a series-parallel combination of several metal foil power resistors to reduce the power dissipation of individual resistors mounted on the same finned heat sink. The maximum measured resistance change due to self-heating was -5.5 $\mu\Omega/\Omega$.

The reference resistor was calibrated against a 10 k Ω standard resistor, and, for phase, against a 1 k Ω calculable resistor, using current-comparator-based techniques.

The resistor phase error was compensated by small capacitance added in parallel to some of the individual resistors. After the compensation, the reference resistor frequency characteristics were measured at frequencies of up to 1 kHz. After applying the corrections, the reference resistor

in-phase and quadrature error uncertainties remained within $1 \mu\Omega/\Omega$.

Under the same phase settings of CC_1 and CC_2 (phase angle 0 or π), a change of the reference resistance R reflects equally on both current comparator balances and causes no ratio or phase error in the output currents or voltages.

C. Reference Capacitors

The active reference capacitors C_1 for 50 Hz/60 Hz were calibrated against a standard 1 nF gas-dielectric capacitor using a current-comparator-based capacitance bridge. Their in-phase and quadrature uncertainties are within $7 \cdot 10^{-6}$.

For C_1 , a low-loss solid-dielectric capacitor was used at frequencies above 60 Hz. Its capacitance and dissipation factor were measured by CC-based capacitance bridge technique. The C_1 in-phase and quadrature uncertainties are within $10 \mu F/F$ and $7 \mu rad$, respectively. The C_2 contributions to the output currents' in-phase and quadrature uncertainties are within $1 \mu A/A$ and $1 \mu rad$, respectively.

D. Current Comparators

The current comparators CC_1 , CC_2 used in this evaluation were somewhat different. The CC_1 was a 100-turn CC built for 1 AT, and CC_2 was a 500-turn CC built for 5 AT. Their N_R , N_C windings have six-decade resolution. Both CCs are calibrated by means of the CC buildup calibration method and a bank of low-loss gas-dielectric capacitors [16]. The CC_1 in-phase and quadrature uncertainties are within $0.7 \mu A/A$ and $1 \mu rad$, at 60 Hz, $3 \mu A/A$ and $3 \mu rad$, at 400 Hz, and $6 \mu A/A$ and $7 \mu rad$, at 1000 Hz. The CC_2 in-phase and quadrature uncertainties are within $1.5 \mu A/A$ and $7 \mu rad$, respectively, at 60 Hz.

E. Current Transformers

The current transformers CT_1 , CT_2 are calibrated using a current-comparator-based test set, and their in-phase and quadrature uncertainties are within $5 \mu A/A$ at the ratios of 1:10 and 1:100, burdens below 0.2Ω , and frequencies up to 5 kHz.

F. AC Shunts and Buffers

The maximum shunt currents in this application were 5 A, which is half of their rated currents. The maximum power dissipation on the shunts was thus $1/4$ of their rated power. The shunt AC-DC differences were within $1 \mu\Omega/\Omega$ up to 10 kHz. The AC shunt in-phase and quadrature uncertainties are within $3 \mu\Omega/\Omega$ and $3 \mu rad$, respectively.

At power frequency of 60 Hz, the buffer in-phase and quadrature uncertainties, obtained from a calibration using digital sampling, were within $1 \mu V/V$ and $1 \mu rad$, respectively. At audio frequencies, the buffer amplitude and phase uncertainties are still less than $1 \cdot 10^{-6}$ [15]-[16].

G. System Evaluation by Means of Transfer Instrument

The system evaluation was performed by using MSS/NRC Electrical Power Measurements Group multifunction meters of known stability as transfer instruments. Among the quantities measured were voltage; current; active, reactive and

apparent powers; power factor; phase angle between voltage and current; and frequency. The voltage input of a transfer instrument was connected to V_{AC} . Its current input was first placed in the path of one output current and then moved to the path of the other output current. The shunts of 0.1Ω were present during the measurement. The transfer instrument current input represented an additional burden of 0.04Ω , which was insignificant to change the errors of a CT if it happened to be a part of the CT_b secondary burden.

To check the lower limit of the calibration system, the current of 0.1 mA was set in both channels (generating two output voltages of $10 \mu V$ only). Through the measurements of current, active and reactive power, and phase angle, the differences between two channels were found to be less than $16 \mu A/A$ and their standard deviations were less $5 \mu A/A$. To test the sensitivity of the system at this low current setting, changes of current for $\pm 15 \mu A/A$ were implemented in one channel at a time. The change in one channel measured by the transfer instrument was in error for $-9.3 \mu A/A$, whereas the change in the other channel was in error for $3.4 \mu A/A$.

For the currents above 1 mA, the differences between two channels measured by the transfer instrument were less than $5 \mu A/A$ and their standard deviations were less $1 \mu A/A$, at 60 Hz.

H. System Evaluation by Means of Current Comparator

The system evaluation was also performed using a current-comparator-based bridge, as shown in a simplified diagram in Fig.3. A phase sensitive detector, connected to the current comparator CC_3 detection winding N_D output V_D , is part of the bridge but is not shown. The bridge compares the calibration system output currents I_{O1} and I_{O2} . Fig.3 shows the calibration system output channels in two different configurations.

The CC_3 was built as a compensated current comparator with several windings of fixed number of turns. It, too, was calibrated by means of the CC buildup calibration method and a bank of low-loss gas-dielectric capacitors [16]. Its in-phase and quadrature measurement uncertainties are less than $3 \mu A/A$ and $3.6 \mu rad$, respectively, at 60 Hz.

After selecting one of the CC_3 several possible ratios, the adjustments necessary for the CC_3 ampere-turn balance were achieved by means of the CC_1 or CC_2 settings. The agreement of the output current differences obtained by means of CC_3 and those obtained by means of transfer instrument were within $2 \mu A/A$ and $2 \mu rad$ at the same test points.

Fig.3 Comparison of output currents, I_{O1} and I_{O2} , by means of the current comparator, CC_3 .

1. Uncertainties

The uncertainties of the calibration system current outputs are given in Table I, and the uncertainties of the calibration system voltage outputs are given in Table II. These uncertainties are for operation at 60 Hz.

Table I. Uncertainties of the calibration system current outputs

Source	X [$\mu\text{A/A}$]	Y [μrad]
R	3	3
C_1	7	7
C_2	1	1
CC_1	0.7	1
CC_2	1.5	7
CT_1	2	2
CT_2	2	2
RSS (k=2)	16.7	21.6

Table II. Uncertainties of the calibration system voltage outputs.

Source	X [$\mu\text{V/V}$]	Y [μrad]
R	3	3
C_1	7	7
C_2	1	1
CC_1	0.7	1
CC_2	1.5	7
CT_1	2	2
CT_2	2	2
R_{s1}	3	3
R_{s2}	3	3
B_1	1	1
B_2	1	1
RSS (k=2)	18.9	23.4

The calibration system overall in-phase and quadrature expanded uncertainties (k=2) are within $25 \cdot 10^{-6}$.

At higher frequencies, the CC_2 measurement uncertainties increase mostly due to its higher number of turns. The calibration system in-phase and quadrature expanded uncertainties (k=2) are estimated to be within: a) $24 \cdot 10^{-6}$ at 400 Hz and $34 \cdot 10^{-6}$ at 1000 Hz for the calibration system current outputs, and b) $26 \cdot 10^{-6}$ at 400 Hz and $38 \cdot 10^{-6}$ at 1000 Hz for the calibration system voltage outputs.

The traceability to SI units is established through the calibration of AC voltage using AC/DC transfer and DC voltage reference, reference resistor, capacitor, and current comparator ratios.

V. CONCLUSION

A new current-comparator-based dual-channel calibration system for AC currents and AC voltages in the millivolt range has been developed for operation at frequencies up to 1000 Hz. The range of generated currents is 1 mA - 5 A, and the range of generated voltages is 1 mV - 500 mV. The calibration system in-phase and quadrature expanded measurement uncertainties (k=2) are within $25 \cdot 10^{-6}$ at 60 Hz. Its estimated expanded uncertainties (k=2) increase to $26 \cdot 10^{-6}$ at 400 Hz, and $38 \cdot 10^{-6}$ at 1000 Hz. The traceability to SI units is established through the calibration of AC voltage by means of AC/DC transfer and DC voltage reference, standard resistor, capacitor, and current comparator ratios.

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