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Sampling Current Ratio Bridge for Calibration of Current Transducers up to 10 kA with $5 \cdot 10^{-6}$ Uncertainty

Helko E. van den Brom, *Member, IEEE*, Gert Rietveld, *Senior Member, IEEE*, and Eddy So, *Fellow, IEEE*

Abstract—A sampling current ratio bridge has been developed, tested and validated for the accurate complex ratio measurement of AC current transducers for primary currents up to 10 kA with expanded uncertainties of $5 \cdot 10^{-6}$ in magnitude and $5 \mu\text{rad}$ in phase ($k=2$). A unique property of the bridge is the use of digitizers for sampling of the secondary current signals and step-down transformers with a large number of current ratios. Therefore, the bridge does not require the current transducer under test to be a current transformer having a nominal ratio equal to the reference current transformer. Instead, it allows for the accurate calibration of a large variety of different current transformers and other types of current transducers. A bilateral comparison between VSL and NRC confirms the stated uncertainty.

Index Terms—Alternating current, current transducers, current transformers, current measurement, current ratio, digital sampling, phase error, phase displacement, ratio error, uncertainty

I. INTRODUCTION

DUE to developments in the electricity grids during the last decade, such as the liberalization of the energy market and a continuously growing amount of local renewable energy generation such as photo-voltaic cells and wind mills, reliable and accurate measurements of energy and power quality in the electricity grids have become more and more important. The reliability and accuracy of these measurements strongly rely on the accuracy of the instrument transformers to scale down the high voltages and currents to levels that can be accommodated by the installed energy meters and power analyzers, usually 240 V or 120 V and 1 A or 5 A nominally.

In the last few years, a new sampling current ratio bridge has been developed and further improved at VSL for the accurate measurement of the complex ratio of AC current transformers (CTs) for primary currents up to 10 kA. The most accurate way to calibrate the ratio and phase errors of a high-current CT is by comparison to a current comparator, a

current ratio standard whose complex ratio deviations are negligibly small [1]. A current comparator is a relatively complicated instrument. Moreover, it requires that the current ratios of the reference system and the CT under test are nominally equal. A more simple approach is to compare the CT under test to a reference CT (calibrated for example with a current comparator) using a conventional comparator bridge. These bridges are commercially available and frequently used by calibration and test laboratories. For achieving optimal accuracy, also this approach requires that the nominal current ratios of the reference system and the CT under test are equal, or at least do not differ more than a factor of two.

In the new VSL calibration system, the second comparison technique is used for the accurate measurement of the complex ratio of current transformers (CTs). In this bridge, the CT under test is compared to a reference CT developed and calibrated by NRC [2] using an automated sampling current ratio bridge. The sampling current ratio bridge consists of two measurement branches containing a step-down transformer (SDT) to scale the secondary current signal further down, a current buffer to transform the current into a voltage signal without loading the SDT and the CT under test, and a high-accuracy digital voltmeter sampling the resulting voltage signals. This approach, which is based on measurement techniques used in the development of high-accuracy sampling wattmeters [3,4], is fundamentally different from the more commonly used analogue ratio bridges. The main advantage is the flexibility in the current ratios that can be tested; even other current transducers such as Rogowski coils and other current to voltage converters can be directly compared to the reference CT by adapting one of the two measurement branches.

Calibration results of the individual components of the sampling current ratio bridge (without making use of the reference CTs) already indicated that even with this flexibility a ratio uncertainty of $10 \cdot 10^{-6}$ in magnitude and $10 \mu\text{rad}$ in phase ($k=2$) could be obtained for CT calibrations between 45 Hz and 65 Hz [5]. First full validation measurements, in which different ratio windings of two reference CTs have been compared to each other, showed that this claim can be improved to a ratio uncertainty of $5 \cdot 10^{-6}$ in magnitude and $5 \mu\text{rad}$ in phase ($k=2$) [6]. Even though this is not as low as the uncertainties that can be reached with a current comparator bridge, it is significantly better than those achieved by

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Fig. 1. Schematic overview of the CT sampling current ratio bridge. From left to right the generation of the high primary current including a capacitance bank, the CT-under-test (DUT) and the reference CT (which is in fact an electronically compensated current transformer), step-down transformers (SDT), operational amplifiers with 100 Ω precision AC resistors (current buffers), and digital sampling voltmeters.

commercial systems and even by most other National Metrology Institutes.

This paper describes the principle of operation of the sampling current ratio bridge and its latest modifications, provides details on the validation measurements, presents the results of a bilateral comparison with NRC including its implications, and shows application of the setup in calibrations of different types of current transducers and under different circumstances.

II. DESCRIPTION OF THE MEASUREMENT SYSTEM

The principle of operation of the measurement setup is presented in Fig. 1 and has been described before [5]. The basic idea is that, when comparing a CT under test to a reference CT, the same AC current I_p is driven through the primary windings of the two CTs in series, whereas for the secondary current I_s only the *ratio* of the two output signals is measured.

The complex current ratio error of a CT is defined as

$$\alpha + j \cdot \beta = \frac{n \cdot I_s}{I_p} - 1, \quad (1)$$

where α and β are the in-phase and quadrature components of the ratio error, respectively, and n is the nominal current ratio of the CT. For quadrature components much smaller than the in-phase component, the in-phase and quadrature components are equal to the magnitude ratio error and the phase displacement (expressed in radians); the latter is the terminology used in this paper. From (1) one can derive that the complex ratio error of the CT under test, $\alpha_{dut} + j \cdot \beta_{dut}$, can be expressed in terms of the complex ratio of the two measured secondary currents I_s^{ref} and I_s^{dut} , the nominal ratios of the reference CT and the CT under test n_{ref} and n_{dut} , and the complex ratio error of the reference CT, $\alpha_{ref} + j \cdot \beta_{ref}$:

$$\alpha_{dut} + j \cdot \beta_{dut} = 1 - \frac{n_{ref}}{n_{dut}} \cdot \frac{I_s^{ref}}{I_s^{dut}} + \alpha_{ref} + j \cdot \beta_{ref}, \quad (2)$$

where the equality holds up to first order in the ratio errors. Hence, the ratio error of the CT under test can be read directly from the measured secondary currents after a simple correction for the ratio error of the reference CT.

A. Reference CTs

The reference CT is an electronically compensated two-stage compact wideband multistage CT developed by NRC. It consists of two high-current CTs and one summing CT [2], all with different and adjustable numbers of primary and secondary turns, such that they can be combined to measure primary currents between 5 A and 5 kA. The two high-current CTs, the summing CT, and their combination have been calibrated at NRC using a current comparator-based test set for measurements at 50 Hz and an audio-frequency current comparator with estimated ratio errors of less than $1 \cdot 10^{-6}$ up to 5 kHz [7]. The ratio errors at 50 Hz are within $1 \cdot 10^{-6}$ in magnitude and 1 μ rad in phase for the high-current CTs and within $3 \cdot 10^{-6}$ in magnitude and 3 μ rad in phase for the summing CT and for the combination, for all primary currents up to 5 kA. The frequency dependence is within $20 \cdot 10^{-6}$ in magnitude and 20 μ rad in phase for frequencies up to 5 kHz. The effect of increasing the burden from 0.1 Ω to 0.5 Ω is less than $1 \cdot 10^{-6}$ in magnitude and 1 μ rad in phase at 50 Hz for all three CTs. The expanded uncertainty is $3 \cdot 10^{-6}$ in magnitude and 3 μ rad in phase at power line frequencies. These outstanding numbers make the CTs very reliable references.

Although the combined reference CT is only rated for currents up to 5 kA, it can be used for calibrating CTs up to 10 kA by using two turns as the primary winding of the CT under test. At a test current of 5 kA this corresponds to 10 kiloampere-turns, equivalent to the CT under test being operated at 10 kA. The influence of the position of the primary return conductors that were not fed through the reference CT on the error of the reference CT was verified to be less than 2 μ A/A and 5 μ rad.

B. Primary current generation

The primary current is generated by a power source feeding a generation coil to scale the current up to the kilo-ampere range. A capacitance bank is used to compensate for the inductive load, minimizing the phase between current and voltage and therefore the reactive power required from the power source. The generation coil used in [5] has been replaced by an improved model that allows for changing the number of primary and secondary windings such that the power source can be used close to both its voltage and current compliance limits.

C. Measurement branches

Two electronically aided two-stage step-down transformers (SDTs) are used to scale the nominal secondary 5 A or 1 A currents down to 8 mA. The SDTs have 20 single-turn primary windings and six 125-turn secondary windings that can all be connected in series or in parallel resulting in a high flexibility. The secondary outputs of the SDTs are fed through 100 Ω precision AC resistors being part of a current buffer that is directly connected to the sampling voltmeter input to reduce the influence of capacitive loading of the buffers.

The individual components of the measurement branches have been investigated in great detail before [5]. The ratio errors and linearity of the SDTs at different ratio settings, the

effective resistance value of the current buffers, the linearity of the sampling voltmeters, and the error and linearity of the combined measurement branches (consisting of SDT, current buffer and sampling voltmeter) have been determined. For current ratios that do not differ more than a factor of 5 from the ratios of the reference CT, the uncertainty ($k=2$) of the bridge is $2 \cdot 10^{-6}$ in magnitude and $1 \mu\text{rad}$ in phase, whereas the linearity for currents between 1 % and 120 % of the nominal value is better than $4 \cdot 10^{-6}$ in magnitude and $2 \mu\text{rad}$ in phase [5].

D. Sampling technique

The output voltages of the current buffers are measured by two simultaneously triggered sampling voltmeters. Since the power source cannot be synchronized to the voltmeters, an asynchronous sampling technique has to be used. The goal of this technique is to re-sample the data at a rate that is an integer multiple of the signal frequency by using time domain spline interpolation in combination with a proper frequency estimation. This way, each cycle of the re-sampled signal contains an integer number of samples, which guarantees that the Fourier transform does not suffer from spectral leakage and all available power is stored in the proper frequency bin.

In the original approach [5], the subsequent process of frequency estimation, time domain interpolation and re-sampling, was iterated until a minimum in a certain cost function (in this case the amount of spectral leakage) was found. This mechanism has been replaced by a significantly faster algorithm that is especially suitable for pure sine waves, based on phase comparison. The basic idea is that first a rough frequency estimate is done and the data is re-sampled accordingly. The re-sampled data is split in two parts, and the phase of the fundamental frequency component of both parts should be equal. The difference in phase is then used to calculate a new frequency for the final re-sampling. This algorithm is sufficiently effective to avoid further iterations.

The accuracy of the new frequency estimation based on this algorithm was verified by measuring a sine wave generated by a source having its time base locked to the 10 MHz reference frequency from the VSL atomic clock. The frequency estimate at power frequencies was found to be accurate to well within the relative standard deviation of the measurements of $1 \cdot 10^{-8}$ (or $0.5 \mu\text{Hz}$ in absolute terms).

Another improvement was to use fewer samples per period in combination with a longer aperture time of $100 \mu\text{s}$. This increases the speed of the re-sampling algorithm significantly as well, while retaining the high accuracy.

Finally, the fundamental components of the Fourier spectrum of the two secondary current signals are used to determine the magnitude ratio of the two transformers and their phase difference using (2). In order to suppress the influence of 50 Hz pickup, measurements are performed at 52.67 Hz and data sets of 1.5 s are analyzed. The spectrum of the waveforms after re-sampling indeed shows sharp peaks at 50 Hz and 52.67 Hz without any side lobes above the noise floor.

III. VALIDATION OF THE COMPLETE SETUP

A. Cross-check

As a cross-check and validation of the complete set-up, the reference CTs can be compared against each other by using the schematic setup of Fig.1 [6]. The influence of the measurement branches can be cancelled out by interchanging the two reference CTs while keeping the rest of the setup as it is. These measurements can be performed at different nominal currents up to 2500 A. Different settings of the turns ratio can be used, and also different ratios can be compared to each other, although in the latter case the calibration of the two measurement branches (step-down transformer, current buffer and sampling voltmeter) cannot be cancelled out anymore.

A first test at 500 A comparing the two high-current CTs at their 100:1 nominal ratio showed a ratio difference of only $(0.05 \pm 0.05) \cdot 10^{-6}$ in magnitude and $(0.00 \pm 0.05) \mu\text{rad}$ in phase. When comparing the 50:2 ratio of the summing CT at 2.5 A and 25 A or its 100:2 nominal ratio at 5 A and 50 A with the 100:1 or 100:2 nominal ratio, respectively, of one of the two high-current CTs a difference in complex ratio within $(1 \pm 4) \cdot 10^{-6}$ for magnitude and $(1 \pm 4) \mu\text{rad}$ for phase was found, where the uncertainty reflects the root-sum-square of the NRC certificate values of the two CTs compared.

The burden dependence has been verified by connecting a burden to only one of the two CTs under test while leaving the other with zero burden (i.e., the combined wiring and measurement branch impedance of 0.05Ω). The effect of loading the CT with resistive burdens ($\cos \varphi = 1$) of 0.1Ω up to 0.8Ω was found to be within $0.5 \cdot 10^{-6}$ in magnitude ratio and $1.0 \mu\text{rad}$ in phase displacement for both high-current CTs and the summing CT. Furthermore, the burden effect on the magnitude ratio for the secondary 200 turns winding ($0.1 \cdot 10^{-6}$) is approximately two times as small as on the secondary 100 turns winding ($0.2 \cdot 10^{-6}$), whereas for phase displacement the effect is approximately four times as small ($0.7 \mu\text{rad}$ as compared to $0.2 \mu\text{rad}$). For the secondary 400 turns winding the effect of burdens up to 0.8Ω is negligible: less than $0.05 \cdot 10^{-6}$ in magnitude and $0.05 \mu\text{rad}$ in phase.

B. Bilateral comparison

A bilateral comparison with NRC has been performed to validate the new VSL sampling current ratio bridge and to underpin the uncertainty claim. NRC used their most accurate current comparator bridge to calibrate the device under test. The two systems were compared by use of a passive 1000 A : 1 A transformer as a traveling standard. For the VSL system this nominal current ratio implies that linearity and ratio errors of the measurement branches are important, since the high-current reference CT maximum nominal current ratio is 2000 A : 5 A and further scaling has to be performed using the SDTs. Consequently the two measurement branches were not used in identical settings, and therefore the linearity and scaling errors come into play.

Measurements have been performed with primary currents of 10 A, 50 A, 100 A, 200 A, 500 A, and 1000 A with a 0.1Ω resistive burden (power factor $\text{PF} = 1$). To be able to measure

Fig. 2. Measurement results with extended uncertainties ($k=2$) of the bilateral comparison between VSL and NRC. For the NRC results the horizontal axes have been offset by 10 % for graphical illustration purposes only.

currents with the VSL setup as low as 10 A, which is divided by a factor of 1000 by the CT under test, the SDT was used with a nominal ratio of 10:125, whereas for the highest currents a nominal ratio of 1:125 was sufficient. To measure the reference CT the second SDT was used with a nominal ratio of 1:625.

The results of the magnitude ratio error and the phase deviation as measured by VSL and NRC, respectively, are presented in Fig. 2. As can be clearly seen in this figure, the VSL and NRC measurements of the phase displacement agree to within $0.5 \mu\text{rad}$ over the whole range of primary currents, which is much better than the stated uncertainty. For the measurements of the magnitude ratio at the highest currents (500 A and 1000 A) we see that the agreement is within $1.1 \cdot 10^{-6}$, which is also much better than the stated uncertainty. For currents of 100 A and below, however, we see that the difference between the VSL and NRC measurements is significant, although still well within the combined uncertainty.

From the results for the magnitude ratio at the lowest primary currents we conclude that observed difference must be due to an error in the VSL measurement bridge. This is

TABLE I
UNCERTAINTY BUDGET FOR MAGNITUDE RATIO ERROR

Error contribution	Standard uncertainty ($\mu\text{A/A}$)
Experimental standard deviation	0.5
Reference CT magnitude ratio error	1.5
Measurement branch ratio error	0.5
Measurement branch ratio linearity	1.0
SDT ratio settings	0.5
Configuration primary winding	1.0
Total ($k=2$)	3.5

because the VSL reference CTs are calibrated at NRC using the same current comparator bridge as used in this comparison. The most likely cause of the observed error in the VSL bridge is the linearity and ratio errors of the SDTs which are used in different settings. When testing these linearity and scaling errors, the conclusion was that the linearity of the SDTs for input currents between 10 % and 100 % of the nominal 5 A current is better than 2 parts in 10^6 in magnitude and $0.2 \mu\text{rad}$ in phase for both transformers [5], which is in agreement with the equivalence in phase displacement and the difference in magnitude ratio as found in this comparison. However, note that in this comparison, the SDTs were used at even lower currents, down to $10 \text{ A} : 1000 = 10 \text{ mA}$, which corresponds to 0.1 ampere-turn (or 2 % of the nominal 5 A primary current) as measured by the SDT when used with 10 primary windings in series. Therefore, the influence of the non-linearity on the magnitude ratio could be even larger than 2 parts in 10^6 . The differences found in this comparison might be even improved upon by correcting for the exact non-linearity curve, instead of attributing an overall uncertainty to the whole range. However, the results found in this comparison do confirm the VSL uncertainty claim of $5 \cdot 10^{-6}$ in magnitude and $5 \mu\text{rad}$ in phase ($k=2$). Note that for CTs under test having the same nominal ratio as the reference CT, even lower uncertainties can be obtained because the influence of the measurement branches (including linearity and scaling errors) can be cancelled out by interchanging the two reference CTs while keeping the rest of the setup as it is, as mentioned in section III A.

C. Uncertainty budget

The mathematical model for the uncertainty budgets for the complex ratio error of a CT when calibrated with the sampling current ratio bridge is based on (2). The uncertainty budgets for the magnitude ratio error and the phase displacement as determined in the bilateral comparison described in the previous section are shown in Table I and II, respectively. The numbers in the tables also hold for the calibration of other CTs that do not suffer too much from errors due to the configuration of the primary winding.

TABLE II
UNCERTAINTY BUDGET FOR PHASE DISPLACEMENT

Error contribution	Standard uncertainty (μrad)
Experimental standard deviation	0.5
Reference CT phase error	1.5
Measurement branch phase error	0.5
Measurement branch phase linearity	0.3
SDT ratio settings	0.5
Configuration primary winding	1.0
Total ($k = 2$)	3.3

The uncertainty due to the reference CT, which is the dominant factor under these ideal circumstances, is taken from the calibration certificate provided by NRC based on a calibration using their current comparator-based test set.

The uncertainties of the measurement branch magnitude ratio error and phase displacement are small because they cancel out in the ratio between the two, as can be seen from (2). This ratio is in fact determined independently before each measurement by connecting the inputs of the two branches in series, such that they transform the same input current.

The linearity of the measurement branches and the influence of the SDT settings have been determined in great detail in [5].

The influence of the position of the primary winding and the measurement configuration was tested by changing the position of the primary return conductor; the position of the conductor in the center of the transformer opening was varied slightly as well, although it was fixed in the center of the opening.

IV. CALIBRATIONS IN PRACTICE

Apart from the bilateral comparison described in section III B, the improved VSL sampling current ratio bridge has been used for various calibrations. In this section we describe three different types of calibrations. First, we took part in the EURAMET.EM-S37 comparison, in which a 10 kA passive CT was to be measured. Second, a Rogowski coil with voltage output was calibrated. And third, the setup was made transportable and an on-site calibration abroad was performed.

A. EURAMET.EM-S37 comparison

The sampling current ratio bridge has been used to take part in the EURAMET.EM-S37 comparison, in which the traveling standard was a CT with five different nominal ratios between 4 kA : 5 A and 10 kA : 5 A. All measurements have been performed in the double-loop configuration explained at the end of section II A (see Fig. 3). In the 4 kA range also a single loop measurement was performed, which revealed differences between the double-loop and single-loop configuration of at most $2 \mu\text{A/A}$ and $20 \mu\text{rad}$ for 15 VA burden and $2 \mu\text{A/A}$ and $15 \mu\text{rad}$ for 5 VA burden. Significantly changing the position of the return conductors produced similar differences in results. The primary conductors were fixed at the center of the transformer opening, as can also be seen in Fig. 3. The current

Fig. 3. Picture of the measurement arrangement. The primary conductors are looped twice through the primary winding of the transformer under test (shown in the middle). The resulting eight primary conductors are bundled and fed through the center of the opening. The two reference CTs (the outputs of which are connected to a summing CT, not visible in this picture) are positioned in the left and right loop, respectively, sensing only half of the primary current.

was carefully increased or decreased to avoid saturation of the magnetic material in the CT.

From these measurements we conclude that the effect of the configuration and positioning of the primary conductors on the transformer under test is the dominant source of uncertainty.

B. Rogowski coil calibration

A Rogowski current transducer is a toroidal wire used to measure an AC current through a conductor enclosed by the toroid. The voltage induced in the coil is proportional to the derivative of the current, so the output terminals are usually connected to an integrator circuit to obtain an output voltage proportional to the measured current.

As compared to the sampling current ratio bridge configuration shown in Fig. 1, Rogowski coils can be calibrated by leaving out the SDT and current buffer in the measurement branches connected to the Rogowski coil output voltage. In this case, the absolute error of the SDT and the current buffer in the other measurement branch, connected to the reference CT, becomes important.

The output voltage of the Rogowski coil was measured at 50 Hz as a function of the input current by comparison to a reference current transformer for currents between 100 A and 4 kA. The return current was sufficiently far away from the Rogowski coil to have no noticeable effect. The dependence on the position of the primary current within the Rogowski coil was investigated (not directly adjacent to the opening mechanism of the coil) and found to be the dominant contribution to the uncertainty of 0.5 %.

C. On-site CT calibration

To calibrate the complete power transformer measurement system of an instrument transformer manufacturer on-site, one of the measurements to be performed was the calibration of the manufacturer's reference CTs. For applications like this the sampling current ratio bridge was made transportable. In the specific application described here, the distance between the CT under investigation and the secondary current readout equipment was of the order of 100 meter. The electromagnetic environment was far from ideal in the sense that the daily

business, including high-voltage and high-current operation, continued during the measurements. Therefore, very long shielded high-quality secondary current measurement cables were used. Optically isolated Ethernet communication between computer, power source and measurement equipment was incorporated to avoid interference with the measurements as much as possible. Even under these conditions, the sampling current ratio bridge turned out to enable reliable measurements and to provide very consistent measurement results.

V. CONCLUSIONS AND FUTURE WORK

The VSL sampling current ratio bridge for calibration of CTs and other current transducers with primary currents up to 10 kA at power frequencies has been tested and further optimized. A full validation of the bridge shows that the CT ratio uncertainty ($k=2$) has been improved to $5 \cdot 10^{-6}$ in magnitude and $5 \mu\text{rad}$ in phase. A bilateral comparison between VSL and NRC revealed differences that could be traced back to the non-linearity of the step-down transformers used in the VSL setup. An additional confirmation of the CT sampling current ratio bridge capabilities is expected to be achieved through participation in the EURAMET.EM-S37 comparison.

In the future the frequency range of the setup will be increased to the kHz range. The reference CT has already been calibrated using an audio-frequency current comparator for frequencies up to 5 kHz [8], where the frequency dependence of the reference CT was found to be within $20 \cdot 10^{-6}$ in magnitude and $20 \mu\text{rad}$ in phase for frequencies up to 5 kHz. Therefore, the investigations should focus on the frequency dependence of the SDTs, the current buffers, and the sampling mechanism.

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