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Effects of Multiple Influence Quantities on Rogowski-Coil-Type Current Transformers

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Abstract—This paper presents a study on Low-Power Passive Current Transformer. In particular, the performance analysis of 3 Rogowski coils have been assessed when multiple influence quantities were acting on them: conductor position, frequency, and ambient temperature. First of all, their single effects have been assessed, then all their possible combination have been tested. From the results it can be concluded that ratio error is mostly affected by the combination of uncentered positions and temperature applied to Rogowski coils. Conversely, phase error is substantially not influenced by any quantities. Therefore, the proposed set of tests could become a benchmark in the Rogowski coils testing.

Index Terms—Automatic measurement system, multiple influence, passive current transformer, position, Rogowski coil, temperature, Standard tests

I. INTRODUCTION

THE evolution towards smart grids has brought among the networks a variety of new intelligent electronic devices, measurement instruments, and power grid accessories. Their introduction should have no impact on both the operation of the network and on the Distribution System Operators' (DSOs) efforts for its management and maintenance [1, 2].

As for the medium voltage distribution network, it experienced a huge penetration of the so-called Low-Power Instrument Transformers (LPITs) [3] to substitute the legacy inductive ones. Such a new kind of transformers allows to measure the rated voltages and currents, providing low-power outputs (typically lower than 1 VA) which are, most of the time, already suitable for typical acquisition systems. Among the benefits obtained from their introduction, the LPITs have reduced dimensions, high robustness and large bandwidth compared to the inductive ones. This make them suitable for a variety of new applications arose, in recent years, among the network [4-6].

To guarantee the reliability of such applications and of the equipment they involve, such equipment has to be subjected to several compliance tests defined by the Standards. With this aim, this paper presents a complete series of tests performed on LPITs, in particular on passive Rogowski-coil-type Low-Power Current Transformers (LPCTs), which could become benchmark type-tests in the future Standards. As a matter of fact, Standards provide a variety of tests for each kind of instrument. For example, IEC Standard 61869-10 [7] defines accuracy tests for the LPCT vs. position, vs. frequency, and vs.

temperature. Even literature contains several works on this critical topic, for example [8] assesses the mutual inductance of the Rogowski vs. primary conductor position. In [9] their performances are evaluated when the geometrical parameters are varying, while [10] studies the thermal expansion of the Rogowski as a principle cause of performance decreasing. Finally, the single effect of the primary conductor position and of the electromagnetic fields on the Rogowski measurements are analyzed in [11] and [12], respectively. Hence, in light of the aforementioned and by considering the growing importance of LPITs in smart grid operations, authors made a further step towards a better knowledge of their behavior under the typical influence quantities. This has been done by assessing the effects of multiple influence quantities simultaneously affecting the LPCTs. As a matter of fact, to the authors knowledge, no accuracy performance has been tackled neither in the literature nor in the Standards to understand which effects a quantity could have on the Rogowski's performance, when combined with others. Hence, in light of this and by considering the key role of the LPCTs accuracy analysis [13, 14], this paper presents a full set of tests combining three different influence quantities: primary conductor position, frequency, and ambient temperature. Tests have been performed according to [7] when possible, otherwise they have been designed by starting from it. The input signal of the tests is always a sinusoidal waveform at rated frequency (except for the frequency tests). Such way of proceeding fulfils the Standard's requirements. As a matter of fact, the Standards characterize the accuracy performance of an IT in terms of ratio and phase errors at rated frequency and under sinusoidal condition. Therefore, up to now the best way to assess if and how a combination of influence quantities affects the performance of an IT is to measure its ratio and phase error and this can be done only in the above recalled conditions. Finally, the use of more complicated, even if more actual, signals would not have allowed to appreciate the effects of the tested influence quantities.

From the results it is even more confirmed the authors proposal of using the presented tests as benchmark for the future Standards.

The paper is structured as follows: Section II briefly recalls the operating principle of the Rogowski coils. In Section III the automatic measurement setup adopted for the experimental tests is fully described. All performed tests are detailed in Section IV, whereas Section V presents the experimental results obtained. Finally, conclusion and comments arose from the

work are drawn in Section VI.

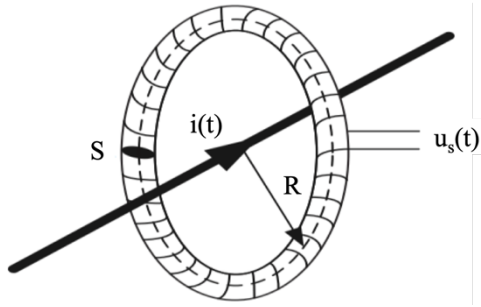


Fig. 1. Working principle schematization of the Rogowski coil. S and R are its cross-section and radius, respectively

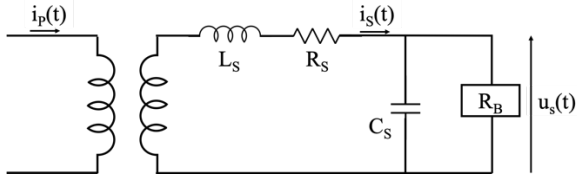


Fig. 2. Circuit diagram of the Rogowski coil equivalent circuit.

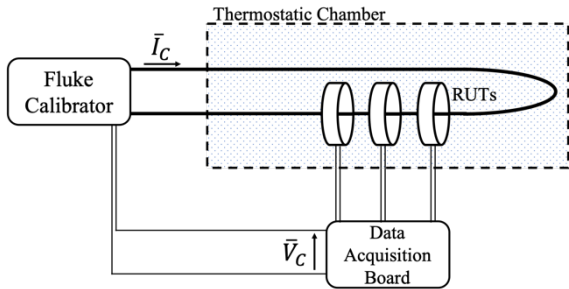


Fig. 3. Schematic representation of the developed automatic measurement setup.

TABLE I. ACCURACY SPECIFICATION OF THE CALIBRATOR FLUKE 6105A

| Range [V] | Accuracy (ppm + mV) |
|------------|-------------------------------------|
| 1 – 23 | 42 + 0.2 |
| 70 – 1008 | 60 + 10 |
| Range [A] | Accuracy (% of output + % of range) |
| 120 | 0.009 + 0.002 |
| Frequency | Accuracy (ppm) |
| Full range | 50 |

TABLE II. MAIN CHARACTERISTICS OF THE ROGOWSKI COILS UNDER TEST

| Feature | X | Y | Z |
|----------------|--------------|----------------|----------------|
| Type | Window | Split-core | Split-core |
| Ratio | 100 A/ 31 mV | 1000 A/ 100 mV | 1000 A/ 100 mV |
| Inner Diameter | 50 mm | 115 mm | 75 mm |
| Accuracy | Class 0.5 | ±1 % | ±1 % |

II. ROGOWSKI COILS

The Rogowski coil is an instrument transformer which works under the same principles of the typical inductive ones. The

main difference consists of the material on which the conductors are wound: air for the Rogowski coil, iron for the legacy one. This aspect results in a linear behavior, conversely to the inductive type which saturates due to the presence of the iron core. By considering Fig. 1, where the Rogowski coil is depicted, the primary conductor (which current has to be measured) is placed inside the coil (of cross-section S and radius R). Then, the output is a voltage proportional to the derivative of the primary current, and follows the equation:

$$u_s(t) = -M \frac{di(t)}{dt}, \quad (1)$$

where $i(t)$ and $u_s(t)$ are the primary current and the secondary output voltage, respectively. M instead, is the mutual inductance between the conductors. From (1) it can be observed that the output is 90° shifted from the input; this can be also seen by considering the Rogowski's equivalent circuit shown in Fig. 2. It is composed by the series of a resistor and an inductor (R_s and L_s), followed by the parallel of the straight capacitance and the high impedance burden (C_s and R_B , respectively).

As for their design, Rogowskis are mainly divided in two categories: split-core and window-type. The former type can be opened to be placed around a conductor, while the latter type needs to be inserted over the conductor, which should be disconnected from its original place. Both types of transformers can be rigid or flexible (high accuracy obtained with the rigid ones) [7].

The use of Rogowski coil is typical among utilities and DSOs for various applications [15-18]; furthermore, literature has been and is very vivid about their study. In particular, their modelling [19, 20] is a current and broad topic along with the design of new possible and innovative solutions [21, 22]. Furthermore, in light of their massive deployment among the network, the evaluation and assessment of their accuracy is a paramount aspect [23, 25], tackled in this work.

III. AUTOMATIC MEASUREMENT SYSTEM

In this Section is provided the detailed description of the adopted measurement system. Its simple schematic representation is depicted in Fig. 3. In the picture, the following elements can be distinguished:

1. Fluke Calibrator 6105A. It is used as a current and voltage reference source (\bar{I}_C and \bar{V}_C : current and voltage phasors) for all performed tests. Its main characteristics, including the accuracy ones, are listed in Table I.
2. Thermostatic chamber. It allows to vary its internal temperature in the range $(5 - 70)^\circ\text{C}$. In addition, a Chauvin Arnoux 863 thermocouple-based temperature sensor has been used to verify the desired temperature in each performed test. It features: measurement range $(-50$ to $+1300)^\circ\text{C}$, 0.1°C resolution and accuracy of $\pm 0.3\%$ of the reading.
3. A set of three Rogowski-coil-type current transformers. From here on out they are referred to as X, Y, and Z for the sake of privacy, and they are made by three different manufacturers. X is a window-type Rogowski, while Y and Z are of the split-core-type. The characteristics of the Rogowski Under Test (RUT) are summarized in Table II.

In addition, the RUTs come from manufacturers which guarantee that their products are compliant with the most

TABLE III. MAIN CHARACTERISTICS OF THE NI 9238

| Architecture | 24-bit | Max input signal | ± 500 mV |
|--------------|--------------|-----------------------|---------------|
| Sample rate | 50 kS/s/ch | Simultaneous channels | YES |
| ADC | Delta Sigma | Temperature range | -40 to 70 °C |
| Gain Error | ± 0.07 % | Offset Error | ± 0.005 % |

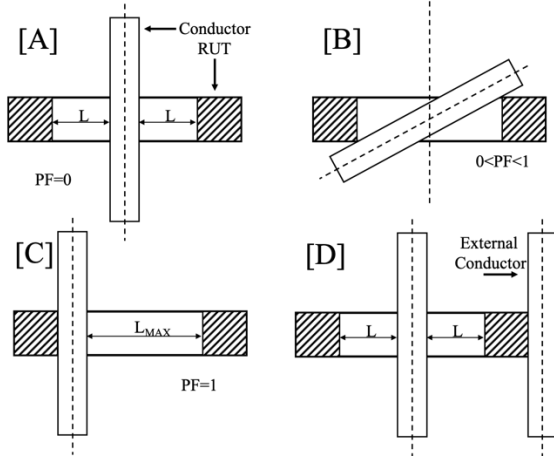


Fig. 4. Pictures of the 4 test configurations adopted. Each of them describes a different relative position between the LPCT and the internal and/or external conductor.

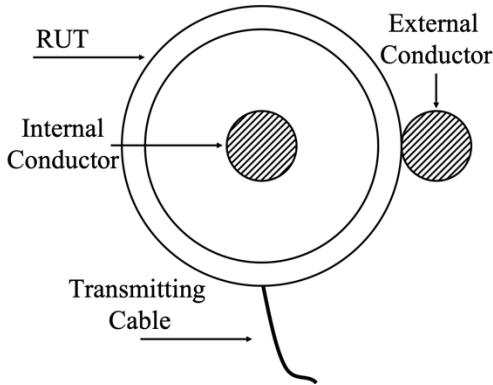


Fig. 5. Different perspective of the test D to highlight the relative position between the transmitting cable and the external conductor.

recent Standards. This way, one can assume that the sample choice would not affect the tests' results.

- A NI-9238 Data Acquisition board (DAQ) and its USB chassis NI-9171. The DAQ main features are summarized in Table III. It has been used to collect the RUTs output and the voltage phasor of the calibrator, used as phase reference.

Such a measurement setup has been adopted to perform the tests described in the following Sections.

IV. EXPERIMENTAL TESTS

In this Section, tests to assess the effects of several influence quantities on the RUTs have been described. With the same

structure, results are presented in the next Section.

A. Resistive Burden Characterization

Before performing the main tests, the resistive burden connected to each RUT has been characterized to estimate its value. To this purpose, 200 measurements have been performed with the HP Digital Multimeter 3458a on three 22 kΩ resistors.

B. Accuracy vs. Position Tests

The first set of tests aimed to verify the effects of both the position of the internal and external conductors on the accuracy of the RUTs. To this purpose, according to [7], four different positions have been tested. As clarified by Fig. 4, they are referred to as A, B, C, and D. For the first three positions, [7] defines the Position Factor (PF) as:

$$PF = \frac{d_{max} - d_{min}}{d_{max} + d_{min}}, \quad (2)$$

where d_{max} and d_{min} are the maximum and minimum distances between the primary conductor and the Rogowski window. The PF ranges between 0 and 1.

Position A is the rated one, where the internal conductor is centered with respect to the RUT, hence it has a PF of 0. As for positions B and C they refer to not-zero PF, $0 < PF < 1$ and 1, respectively. In particular, in B the conductor is completely bend over the RUT, whereas in C the conductor is perpendicular to the RUT but attached to it, hence not centered at all. Last position is D, where an external conductor is attached to the outer part of the RUT. Moreover, as for D, [7] states that the transmitting cables of the LPCT must be 90° with respect to the external conductor. To better clarify this aspect, in Fig. 5 the correct positioning is depicted.

Afterwards, for the 4 test configurations, a primary current $\bar{I}_C = 100$ A (at 50 Hz and 22 °C) has been injected with the calibrator through the primary conductor and measured with the 3 RUTs. Their outputs (\bar{U}_S) have been acquired without using any integrator in-between to avoid any interference with the RUT performance evaluation. Then, 100 measurements of \bar{U}_S have been collected, and 100 values of ratio and phase error (ε and φ) have been computed as:

$$\varepsilon = \frac{k|\bar{U}_S| - |\bar{I}_C|}{|\bar{I}_C|} \quad (3)$$

$$\varphi = \hat{U}_S - \hat{V}_C, \quad (4)$$

where, $|\bar{U}_S|$ and $|\bar{I}_C|$ are the modules of the Rogowski's output voltage and the primary current phasors, respectively. As for k , it is the nominal ratio of the RUTs, \hat{U}_S and \hat{V}_C instead, are the phases of the related abovementioned phasors. Afterwards, the mean value of the 100 measurement of ratio and phase error ($\bar{\varphi}$) have been computed (for all performed tests).

Then, the described tests have been repeated at 48 Hz and 51 Hz. Such values have been adopted from [7] to tackle the harshest conditions, which refer to the use of the LPCTs for protective purposes. For the frequency tests, [7] states that the obtained ratio errors must be corrected as:

$$\varepsilon_{CF} = \frac{CF * k * |\bar{U}_S| - |\bar{I}_C|}{|\bar{I}_C|}, \quad (5)$$

where CF is the Correction Factor obtained as the ratio between the rated and the actual frequency, f_r and f_a , respectively:

$$CF = \frac{f_r}{f_a}. \quad (6)$$

TABLE IV. LIST OF ALL THE PERFORMED TEST: 36 FOR EACH RUT

| Position | 5 °C | | | 22 °C | | | 40 °C | | |
|----------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| | 48 [Hz] | 50 [Hz] | 51 [Hz] | 48 [Hz] | 50 [Hz] | 51 [Hz] | 48 [Hz] | 50 [Hz] | 51 [Hz] |
| A | #30 | #28 | #29 | #9 | #1 | #5 | #15 | #13 | #14 |
| B | #33 | #31 | #33 | #10 | #2 | #6 | #18 | #16 | #17 |
| C | #36 | #34 | #35 | #11 | #3 | #7 | #21 | #19 | #20 |
| D | #27 | #25 | #26 | #12 | #4 | #8 | #24 | #22 | #23 |

TABLE V. RESISTIVE BURDEN CHARACTERIZATION RESULTS

| Quantity | X | Y | Z |
|------------------------|---------|---------|---------|
| \bar{R} [Ω] | 21893.9 | 22032.5 | 21818.8 |
| u_c [Ω] | 0.4 | 0.5 | 0.3 |

TABLE VI. TEST #1 RESULTS. USED TO DETERMINE THE ACTUAL RATIO OF THE ROGOWSKI COILS

| Quantity | X | Y | Z |
|--------------|---------|---------|---------|
| K [1/mV] | 3720.26 | 10536.1 | 10162.7 |
| u_c [1/mV] | 0.09 | 0.2 | 0.2 |

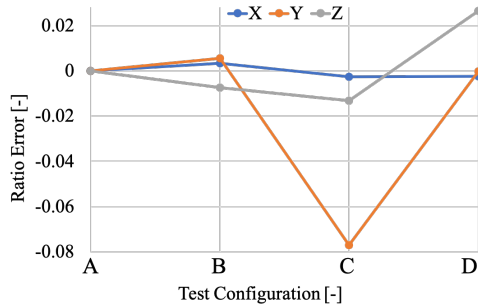


Fig. 6. Ratio Error results for tests #1 to #4. Accuracy vs. positions, 22 °C, 50 Hz.

C. Accuracy vs. Temperature tests

The second set of tests wanted to assess the effects of the working temperature on the accuracy of the RUTs. To this purpose, the temperatures defined for the tests are 5, 22, and 40 °C. The upper limit has been defined according to [7], while the lower one is in accordance with a typical outdoor average ambient temperature in Italy during cold seasons. Therefore, each temperature has been set on the thermostatic chamber and kept for 8 hours. This, to ensure a proper thermal stability for both the chamber and the RUTs. Once such a condition has been obtained, 100 measurements of \bar{U}_S have been acquired for the 4-test configurations and for the 3 frequencies (48, 50, and 51 Hz). Again, from the measurement results, ε and φ have been computed for each test configuration. In light of the aforementioned, an overall amount of 36 tests have been performed. For the sake of clarity, and for a better comprehension of the next Section, they have been numerated and listed in Table IV.

V. EXPERIMENTAL RESULTS

A. Resistive Burden Characterization Results

Table V collects the mean values \bar{R} and related combined uncertainty u_c of the three resistors (R_X , R_Y , and R_Z). As for u_c , it has been calculated, according to the Guide to the expression of Uncertainty in Measurement [26], as:

$$u_c = \sqrt{(u_a)^2 + (u_b)^2}, \quad (7)$$

where u_a and u_b are the uncertainties evaluated with type A and type B methods, respectively. In particular, u_b has been computed by starting from the accuracy specifications of the multimeter 3458a used for the resistance measurements: $2 \cdot 10^{-6}$ error on the reading and $2 \cdot 10^{-7}$ error on the range. As for u_a , as well-known, is computed by dividing the variance of the mean value measured by the number of measurements. From Table V it is possible to highlight the low uncertainty associated to the resistors' values.

B. Results of the Accuracy vs. Position Tests

By considering that no calibration coefficients were provided by the manufacturers of the LPCTs, test #1 has been used as a reference test to determine the actual ratio of the 3 RUTs (K_X , K_Y , and K_Z). They are listed in Table VI along with their associated combined uncertainty (computed according to (7)). In addition, all ratio errors presented in the following have been computed by taking the ratios in Table VI as the rated ones. Hence, for the sake of comparison, test #1 ratio error is always set at value zero.

Moving to the aim of the subsection, in Fig. 6 the results of the accuracy vs. position tests are shown at 50 Hz and at room temperature, 22 °C (#1, #2, #3, and #4). In the graph, and in all the following ones, the standard deviation of the ratio error (obtained from the mean of 100 measurements) is not presented for the sake of brevity. As a matter of fact, it was always in the order of 10^{-5} for all performed tests. As it can be seen, the window-type RUT (X) is almost not affected by the PF of the conductor, whereas Y and Z are sensitive to PF=1 (position C) and to the presence of an external conductor (position D), respectively. The phase error of this four set of results has not been plotted for the sake of brevity because it has been not affected by the PF. Moreover, it was always in the order of fraction of milliradians, for the three RUT.

In light of the position-tests results, it can be concluded that the conductor position is critical for the Rogowski performance. As confirmed in [8] the changes in the conductor position cause a variation of the mutual inductance M between conductors.

Therefore, according to (1), it results in a different output voltage (by starting from the same input current). Hence, in the overall accuracy of the Rogowski coil. However, this issue is typically solved by using external accessories (usually of insulating material) aimed at keeping the conductor centered with respect to the Rogowski. However, as experienced by the authors in many in-field applications, this is not always possible, hence compensating solutions should be adopted as it has been demonstrated in [8].

By adding the contribution of another influence quantity, the frequency, the related results are depicted in Fig. 7 (dotted lines refer to 48 Hz while the solid ones to 51 Hz). From it, a general comment is that the results confirm the overall trend (and absolute values) obtained from Fig. 6. However, aside for the case of X, which is not affected by frequency, it is possible to appreciate its negative effect, which increase the one due to the positions tested. As for φ , neither the frequency is affecting it, confirming what already obtained from the 50 Hz cases. As a final comment on this first set of results, it can be stated that at 50 Hz (rated frequency), positions C and D are critical for the split-core type Rogowski. As a matter of fact, ε significantly overcomes the limits declared by the manufacturers ($\pm 1\%$). Instead, for frequencies different from the rated one, even position B becomes critical. In particular, Y accuracy is noncompliant for positions B and C, whereas Z one for positions B and D. It is worthy to emphasize that in all the frequency test results the proper CF has been applied.

C. Results of the Accuracy vs. Temperature Tests

In this subsection, the effects of a working temperature variation on the accuracy of the RUTs is assessed. To this

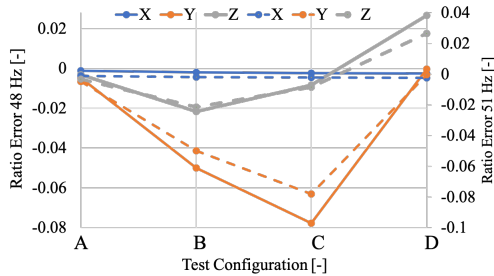


Fig. 7. Ratio Error results for tests #5 to #12. Accuracy vs. positions, 22 °C, 48 Hz (solid) and 51 Hz (dotted).

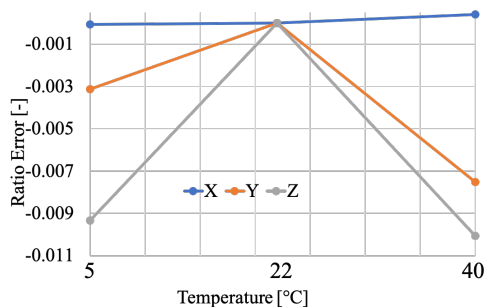


Fig. 8. Ratio Error results for tests #1, #13 and #28. Accuracy vs. temperature, 50 Hz.

purpose, let us start from the basic position A, where the LPCT is centered with respect to the internal conductor. Hence, Fig. 8 shows the results of the test #1, #13, and #28 (position A, at 50 Hz). From the picture, it can be concluded that X, the window-type Rogowski, is almost not affected by temperature when working at 50 Hz. Conversely, for Y and Z, the split-core type ones, temperature is reducing significantly their accuracy. In particular, at 40 °C the ratio error is increased up to 1 order of magnitude. However, for all the RUTs, either at 5 °C or at 40 °C, ε remains within the accuracy limits provided by the manufacturers and listed in Table II.

As for the computed phase errors, they are listed in Table VII along with their associated combined uncertainty. From the Table it emerges that, even the temperature is not affecting φ for all the studied RUTs and they are always contained within the accuracy limits.

In accordance with what already done in the previous subsection B, the abovementioned results are now evaluated at frequencies different from the rated one. All results are depicted in Fig. 9, where the dotted lines represent the 51 Hz tests (#5, #14, and #29) whereas the 48 Hz ones (#9, #15, and #30) are represented by a solid line. The first comment that arise from the graph is the overall confirmation of the trend observed in Fig. 6 for the tests at 50 Hz. Second, both 48 and 51 Hz tests provide almost the same results (in absolute value terms) for each tested temperature.

As for the evaluation of the combined effects of temperature and frequency, Fig. 8 and Fig. 9, must be compared. From the comparison, it can be stated that the significant contribute to the accuracy worsening is provided by the temperature. As a matter of fact, the frequency contribution is negligible and cannot be

TABLE VII. PHASE ERROR RESULTS FOR TESTS #1, #13, AND #28

| Test | X | | Y | | Z | |
|------|--------------------------|--------------|--------------------------|--------------|--------------------------|--------------|
| | $\tilde{\varphi}$ [mrad] | u_c [mrad] | $\tilde{\varphi}$ [mrad] | u_c [mrad] | $\tilde{\varphi}$ [mrad] | u_c [mrad] |
| #1 | -0.17 | 0.09 | -0.91 | 0.09 | -0.65 | 0.09 |
| #13 | 0.26 | 0.09 | 1.01 | 0.09 | 0.01 | 0.09 |
| #28 | 0.27 | 0.09 | 1.35 | 0.09 | 0.01 | 0.09 |

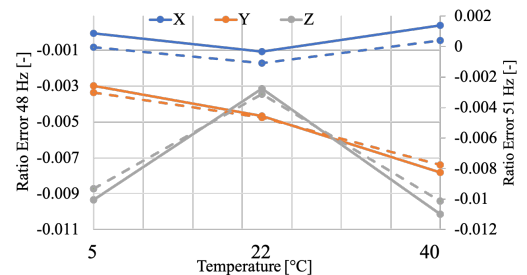


Fig. 9. Ratio Error results for tests #5, #9, #14, #15, #29 and #30. Accuracy vs. temperature, 48 Hz (solid) and 51 Hz (dotted).

distinguished from the temperature one. Moving to the phase error evaluation, in the position A studied in this subsection, it can be concluded that φ is not affected neither by the

temperature nor by the frequency. Hence, results are not reported for the sake of brevity.

As an overall comment on the effects of temperature, this quantity seems to have a critical effect on the Rogowski performance. This can be associated to two different

phenomena affecting the RUT when the temperature varies: changes in its geometry and thermal expansion of the copper windings. Both are confirmed to have an effect on the Rogowski performance [9, 10], hence two possible solutions to

TABLE VIII. PHASE ERROR COMPUTATION RESULTS FOR ALL THE ACCURACY VS. TEMPERATURE + POSITION TEST COMBINATIONS

| Position | Quantity | X | | | Y | | | Z | | |
|----------|--------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| | | 5 °C | 22 °C | 40 °C | 5 °C | 22 °C | 40 °C | 5 °C | 22 °C | 40 °C |
| A | $\tilde{\varphi}$ [mrad] | -0.27 | -0.17 | -0.25 | -1.35 | -0.91 | -1.01 | 0.01 | -0.65 | 0.01 |
| | u_c [mrad] | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 |
| B | $\tilde{\varphi}$ [mrad] | -0.24 | -0.18 | -0.23 | -1.22 | -0.74 | -0.44 | -0.65 | -0.91 | -1.21 |
| | u_c [mrad] | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 |
| C | $\tilde{\varphi}$ [mrad] | -0.24 | -0.08 | -0.18 | -1.27 | -1.42 | -1.25 | -0.32 | -0.45 | 0.02 |
| | u_c [mrad] | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 |
| D | $\tilde{\varphi}$ [mrad] | -0.21 | -0.11 | -0.17 | -0.94 | -0.92 | -0.97 | 0.08 | -0.15 | 0.02 |
| | u_c [mrad] | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 |

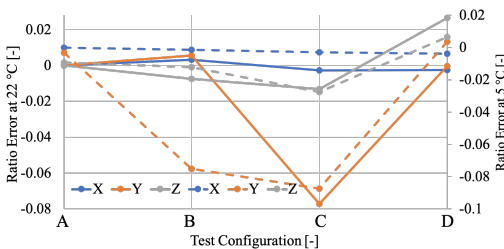


Fig. 10. Ratio Error results for tests at 50 Hz, for two different temperatures (22 °C, solid line; 5 °C, dotted line), for all the positions.

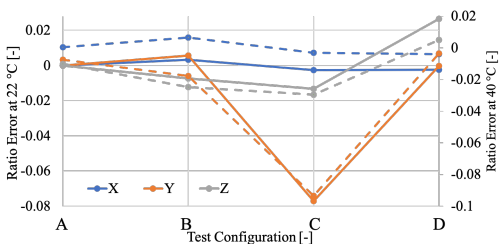


Fig. 11. Ratio Error results for tests at 50 Hz, for two different temperatures (22 °C, solid line; 40 °C, dotted line), for all the positions.

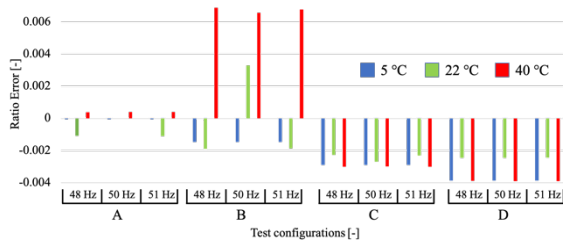


Fig. 12. Ratio Error results for tests concerning all the influence quantities acting on the RUT (X).

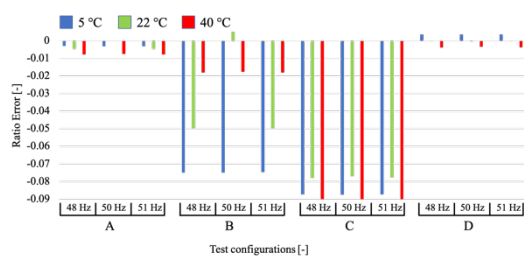


Fig. 13. Ratio Error results for tests concerning all the influence quantities acting on the RUT (Y).

mitigate such effects might be: (i) using an external cage for the Rogowski with thermal properties aligned with the working temperatures; (ii) development of compensating (hardware or software) techniques to consider the effects of temperature on the Rogowski output. As for this last point, [26] and [27] describe two interesting researches that suggest how to consider the effect of temperature when dealing with Rogowski's measurements.

D. Evaluation of Temperature and Position combined effect on the RUTs accuracy

Among the novelties of the paper, the evaluation of multiple influence quantities effects on the LPCTs performance is one of the most interesting. To this purpose, Fig. 10 and 11 show the results of the position and temperature combined tests.

By starting from Fig. 10, it contains the comparison between the tests performed at 22 °C (solid lines) and the ones performed at 5 °C (dotted lines). From the graph analysis, it results that the RUTs are affected by temperature even in rated position A. This, leading X, Y, and Z to exceed their accuracy limits. Such trend is then confirmed for the other positions tested and for all RUTs. In addition, by considering that the solid curves represent the computed ϵ obtained from the single effect of the conductor position, from the graph it is possible to quantify the temperature contribution on the overall value of ϵ .

Similar comments can be drawn by the graph in Fig. 11, where the comparison between the tests performed at 22 °C (solid lines) and the ones at 40 °C (dotted lines) is presented. However, compared to Fig. 10, a slight difference can be highlighted: a higher temperature seems to less affect the RUTs performance. This is true for all the RUTs except for X, the window-type one, which is affected by both high and low temperatures. For the sake of the work completeness, the phase error results obtained by all above-mentioned test combinations are listed in Table VIII. However, as obtained for the previous tests, the phase displacement is not affected by the combination of temperature and conductor position.

E. Evaluation of Temperature, Position, and Frequency combined effect on the RUTs accuracy

The last set of test results concern the combination of three influence quantity applied to the RUTs in order to evaluate their performance. Results are presented in Fig. 12, 13, and 14 for the LPCTs X, Y, and Z, respectively. They show the ratio errors of all possible test configurations, which include temperature, frequency, and position variations. In particular, each set of columns represent a position, whereas the colors refer to the temperatures: blue, green, and red, for 5, 22, and 40 °C, respectively. From the pictures it is possible to appreciate

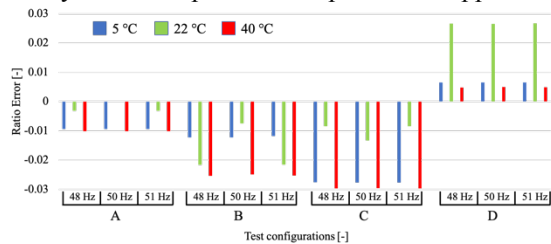


Fig. 14. Ratio Error results for tests concerning all the influence quantities acting on the RUT (Z).

the ε trends due to multiple influence of the varying quantities. As for Fig. 12, it emerges the negative effect of the temperature superimposed to the position B. In fact, the combination of these two influence quantities turns into a ratio around seven times greater than the allowed limit. On the contrary, working at frequency different from the rated one does not result in significant variation of the RUT performance accuracy.

Similar comments on the frequency can be stated also for Fig. 13 and 14. From the Y results in Fig. 13, it can be concluded that positions B and C are particularly critical, whereas the presence of an external conductor (position D) is not affecting at all the performance of Y. Moreover, a low temperature seems to be more critical, in all the performed test, compared to the high one. Interesting results can be drawn also from Fig. 14. As a matter of fact, Z is sensitive to the presence of external cables. However, this sensitiveness seems to be reduced by a working temperature different from the rated one (22 °C). One more time the frequency does not influence the RUT operation, whereas the temperature combined with the position effects result in critical results.

From the abovementioned results it can be concluded that, on the one hand the simultaneously presence of the influence quantities temperature and position causes a severe degradation of the LPCT performance. This is true for all the RUT studied in this work. In addition, such a degradation brings the ratio error out of its bounds, hence, not guaranteeing anymore the manufacturers' given accuracy. On the other hand, the phase error φ seems not to be affected by any of the influence quantities tested in this work.

In addition to the previous comments, the interesting and satisfactory results presented support the authors idea of using the proposed tests as benchmark for the Rogowski coil testing. Then, the study could be completed by assessing the Rogowski

behavior with waveforms affected by all kind of power quality issues (harmonics, interharmonics, dips, etc.)

VI. CONCLUSIONS

This work presents a study on Low Power Passive Current Transformers, in particular the Rogowski type. By starting from their related Standards, new tests have been proposed to assess their accuracy performance under the simultaneously influence of multiple quantities: frequency, position and ambient temperature. Obtained results confirm the authors hypothesis: the passive transformers suffer from the multiple presence of such influence quantities. In particular, all tested device exceeded their accuracy thresholds when temperature and position where varied from the rated one. This holds for the ratio error, whereas the phase displacement is completely insensitive with respect to the influence quantities applied. Along with the results, suggestions and comments on the possible technical solutions to be implemented in order to compensate the obtained results are provided.

In conclusion, the work wants to be a first step towards the idea of testing the accuracy of the LPCTs, not just considering one influence quantity at the time, but multiple ones. In addition, it can be observed that the simultaneously presence of more than one influence quantity does not always turn into a worsen of the accuracy performance of the LPCT. Furthermore, the described tests, in light of the obtained results, might become a starting point for improving the existing Standards.

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