Uncertainty sources analysis of a calibration system for the accuracy vs. temperature verification of voltage transformers

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Abstract. The paper deals with the investigation of accuracy vs. temperature variation of inductive instrument transformers. There is still a lack of literature on this specific and nowadays very important topic. In previous works, authors presented results on effects of temperature on voltage instrument transformers accuracy. In this paper the study continues with the uncertainty sources analysis which affects the calibration setup previously proposed. To this purpose, the metrological characterization along with the Monte Carlo method have been applied in order to highlight the main positive features of the calibration setup. Results of such procedures are presented.

1. Introduction
In the last years, Instrument Transformers (ITs) [1-3] have experienced a huge revolution under the technological point of view. Such devices, are being replaced by the so-called Low Power Instrument Transformers (LPITs). As the name suggests, LPITs provide outputs with low level signals, ready for being acquired from typical Intelligent Electronic Devices. Such new instrument transformers are lightweight with respect to the inductive ones, and suitable for measuring and protections purposes as well as for the evaluation of high frequency components.

Despite of all the aforementioned, inductive ITs are still used for extremely important applications: the metering for pricing and the legal metrology in terms of power and energy measurements. This is due to the fact that LPIT are still not considered sufficiently reliable, by the electrical utilities, for such delicate purposes. At the light of this, in this paper, authors tackle an issue not faced in the literature yet: the accuracy vs. temperature of the ITs. In particular, the calibration setup proposed in [4], has been metrologically characterized with the aim to underline the more significant uncertainty sources and of proposing the setup as a benchmark for the inductive instrument transformer calibration vs. temperature. Such a study has been carried out according to previous experience gained by authors [5] and of course according to the GUM and its Supplement 1 [6-7].

2. Calibration system
In this Section, the calibration system proposed in [4] and depicted in figure 1 is recalled. Such a system is made by:

- a programmable power source Agilent 6813B, which features up to 300 V RMS, 1750 VA from DC to 1 kHz. It assures a proper stability of input sinusoidal voltage (in term of both amplitude and frequency) to the transformer under test;
3. Uncertainty sources analysis

The uncertainty sources analysis located in the above calibration system can be performed by starting from the rated accuracy specifications of the elements of which it is composed or by exploiting the result of a metrological characterization of such elements. This paper focuses on the latter.

3.1 Metrological characterization

As it is clear from figure 1, ratio and phase errors of the VT under test are computed by properly processing the samples acquired from two channels of the DAQ. Therefore, instead of characterizing each element of the calibration system, it is convenient to consider the chains made by R-C divider + DAQ channel, and R-divider + DAQ, respectively. As far as the voltage R-C divider + DAQ is concerned, the setup shown in figure 2 was used: the divider is fed by the voltage provided by a Fluke Calibrator 6105a (see table 1 for its accuracy specifications @50 Hz) and its waveform is acquired by the DAQ, which is controlled by a personal computer, not reported in the picture. Different RMS voltage levels (1000, 650, 300, 100 V) have been applied.

| Output Voltage | Accuracy (ppm+mV) |
|----------------|-------------------|
| 57             | 42                |
| 100            | 44                |
| 300            | 44                |
| 650            | 60                |
| 1000           | 60                |

Figure 1. Schematic representation of the experimental setup.

- a 0.1/15 kV step-up transformer used to provide the rated voltage for the transformer under test;
- a resistive-capacitive voltage divider (R-C divider) used as a reference. Its rated transformation ratio is 5981:1 with a ratio error < 0.1% and a phase error <0.15 crad (accuracy class 0.1);
- the voltage transformer (VT) under test;
- a thermostatic chamber, which hosted the voltage transformer under test in an environment whose temperature could be varied from +5 °C to +55 °C;
- a resistive voltage divider with a rated ratio of 11:1;
- a 24-bit DAQ NI9239, which acquires the conditioned output voltages of the voltage transformer under test as well as of the reference.
Due to the limitation in voltage of the calibrator, only a maximum voltage of 1000 V RMS was applied; however, according to the calibration certificate of the divider, it exhibits high linearity (non-linearity error lower than $10^{-4}$) up to twice the rated voltage (10 kV). For each voltage level, 100 measurements were performed and tests were repeated for 5 days in order to ensure a certain level of repeatability. The calibrator has been used as a reference for both the amplitude and the phase of the voltage applied to the divider. Then, its actual ratio $k_{RC}$ and phase error $\phi_{RC}$ have been computed as:

$$k_{RC} = \frac{|V_{cal}|}{|V_{RC}|}$$

$$\phi_{RC} = \tilde{V}_{RC} - \tilde{V}_{cal}$$

where $|V_{RC}|$ and $|V_{cal}|$ are the amplitudes of the output voltage of the R-C divider and the calibrator, respectively. $\tilde{V}_{RC}$ and $\tilde{V}_{cal}$ instead, are the phases of such voltages. The results of this first test, considering all the 100x5 measurements, consist in a mean value and a standard deviation of 5983.3 and 0.8, respectively. Moreover, daily variations of the mean value of $k_{RC}$ in the order of 0.004% have been reported. This means that there are some operating conditions that slightly change day by day, for example the ambient temperature. On the contrary, the daily variations of the mean value of $\phi_{RC}$ are compatible with the relevant standard deviations. Nevertheless, mean value and standard deviation computed over the whole set of measurements have been used: 0.22 mrad and 0.08 mrad, respectively.

The second test had the aim to verify the performance of the R-divider + DAQ. The setup used for the measurements is shown in figure 3 and its made by the calibrator, the voltage divider and the DAQ. As it has been done for the R-C divider, 100 measurements have been acquired for five consecutive days by applying 57 V at the voltage divider with the calibrator, thus approximating the output value of the voltage transformer under test ($100/\sqrt{3}$) when the rated voltage at primary side is applied. Measurements results have been used to calculate the actual ratio of the R-divider $k_R$ and its phase error $\phi_R$. Hence, the results of this second test are 11.0024 and $2 \times 10^{-4}$ for $k_R$, $\sigma_{kR}$, and -0.1 mrad and 0.2 mrad for $\phi_R$ and $\sigma_{\phi_R}$, respectively.

The uncertainty affecting all the above values must be computed by considering the relevant experimental standard deviations as well as the contributions due to the calibrator. However, the latter is negligible given that they are at least 10 times lower than the former.

4. Uncertainty evaluation

As it is well known, in accordance with [2], the accuracy of a measuring voltage transformer is expressed by its accuracy class, which defines maximum values for ratio (or voltage) error $\varepsilon$ and the phase error $\Delta\phi$. At the light of this, in this section, the uncertainty affecting $\varepsilon$ and $\Delta\phi$ is computed when results of the metrological characterization are considered as uncertainty sources. Such an evaluation is performed by means of a Monte Carlo (MC) method [7]. For the sake of brevity, uncertainty is computed for just one of the cases obtained in [4] and recalled in table 2.
Starting from the results of the metrological characterization process described in section 2, the uncertainty on \( \varepsilon \) and \( \Delta \phi \) has been evaluated with 100,000 trials of the MC method. With the same notation used in table 2, the relevant results are shown in table 3, where \( \pm L \) refers to the 95%-confidence interval. This leads to conclude that the proposed calibration setup may be used to evaluate \( \varepsilon \) and \( \Delta \phi \) vs. temperature of VTs up to 0.1 accuracy class. Of course, this holds if the random variation of the aforementioned parameters, during their measurements, is negligible, as in the considered case, with respect to the uncertainties due to the calibration system.

| Table 2. Measured ratio and phase error obtained in [4] and used as reference for this study. | Table 3. Results of the MC method application when considering the metrological characterization of the items for the uncertainty evaluation. |
|---|---|
| Mean Value | Standard deviation | Mean Value | Standard deviation | \( \pm L \) |
| \( \varepsilon \) | -7.153e-4 | 7e-7 | \( \varepsilon \) | -7.2e-4 | 8e-5 | -8.4e-4; -5.9e-4 |
| \( \Delta \phi \) (mrad) | -3.3 | 6e-4 | \( \Delta \phi \) (mrad) | -3.6 | 0.1 | -3.8; -3.4 |

5. Conclusions
An experimental setup for calibrating inductive voltage transformers at different temperatures has been recalled. This kind of instrument transformer is still used in metering for tariff and this justify the importance of a setup like the one proposed. In this paper, the effects of the uncertainty sources located in the devices composing the calibration system have been taken into account to provide a complete analysis of the uncertainty affecting the measurement of ratio and phase errors. In particular, the analysis has been performed starting from the information coming from the metrologically characterized of the setup elements. The outcome of this study has been that the proposed calibration system allows the measurement of phase and ratio errors of voltage transformers up to 0.1 accuracy class. Hence, the proposed setup could become a benchmark for this kind of tests.

6. References
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