Metrological traceability for AC High-Voltage in Inmetro up to 40 kV

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Abstract. This paper refers to a project carried out in Inmetro aiming to provide internal metrological traceability for 60 Hz AC High-Voltage up to 40 kV. It presents details about the method used, its equations and obtained results. A capacitance and tanδ bridge, with a built-in current comparator, was used in combination with two standard capacitors to calibrate a standard potential transformer (PT), both in ratio and phase angle. The results obtained by Inmetro showed good agreement with PTB ones, for the same PT. The maximum estimated uncertainty was 0.0049 % for ratio error and 104 μrad for phase angle error.

1. Introduction

One goal of a National Institute of Metrology (INM) is to provide internal traceability for its standards based on primary references of quantities that comprise its metrological infrastructure.

For voltage quantity in 60 Hz alternating current (AC), Inmetro already has internal traceability up to 1000 V. Recently, a project was carried out in its High Voltage Metrology Laboratory (Lamat), which resulted in the implementation of a method to providing internal traceability for AC High-Voltage (HVAC) up to 40 kV. This paper presents information about this project and the results obtained by Inmetro compared with those obtained by the Physikalisch-Technische Bundesanstalt (PTB).

2. Method used

The measurement principle of the method for traceability in HVAC implemented in Inmetro is shown in figure 1 [1]. A commercial capacitance and tanδ bridge (C and Tanδ bridge), with a built-in current comparator, in combination with two standard capacitors are used to calibrate a standard potential transformer (PT), both in ratio and phase angle.

2.1. Formulation of the method

2.1.1. Equation to obtain the ratio of PT

From figure 1, under bridge balanced conditions ($I_S \cdot N_S = I_X \cdot N_X$), being $C_X$ the value measured by the bridge for $C_{HV}$ and neglecting the voltage drops in the resistances of $N_S$ and $N_X$ windings, we have:

$$j \omega \cdot C_{LV} \cdot U_2 \cdot N_S = j \omega \cdot C_X \cdot U_1 \cdot N_X$$

(1)
Figure 1. Circuit for PT calibration with a C and Tanδ bridge, $C_{LV}$ = standard low voltage capacitor and $C_{HV}$ = standard HV capacitor.

With $U_1/U_2 = a_N$, being “$a_N$” the ratio previously attributed to the PT under calibration, from equation (1), we have:

$$j\omega \cdot \left(\frac{C_{LV}}{a_N}\right) \cdot U_1 \cdot N_S = j\omega \cdot C_X \cdot U_1 \cdot N_X$$

(2)

If we consider $U_1/U_2 = a$, being “$a$” the actual ratio of the PT under calibration, the bridge will measure the actual capacitance $C_{HV}$ ($C_X = C_{HV}$). Therefore, from equation (1), we have:

$$j\omega \cdot \left(\frac{C_{LV}}{a}\right) \cdot U_1 \cdot N_S = j\omega \cdot C_{HV} \cdot U_1 \cdot N_X$$

(3)

With equations (2) and (3), the expression for the PT ratio obtained in the calibration process becomes:

$$a = \left(\frac{C_X}{C_{HV}}\right) \cdot a_N$$

(4)

Where:
- $C_X$ = Capacitance measured by the bridge;
- $C_{HV}$ = Known capacitance of the HV capacitor;
- $a_N$ = Ratio previously attributed to the PT;
- $a$ = Actual PT ratio obtained in the calibration.

Considering the original circuit found in the operating manual of a commercial C and Tanδ bridge, without PT, the capacitor $C_X$ to be measured and the known standard capacitor named $C_S$ are connected directly to the voltage source: $U_1$ in figure 1. In this case, under balanced bridge conditions, we have:

$$j\omega \cdot C_S \cdot U_1 \cdot N_S = j\omega \cdot C_X \cdot U_1 \cdot N_X$$

(5)

The bridge requires the characteristic parameters of $C_S$ (capacitance and tanδ values) as very accurate input data. By comparing equations (2) and (5), it is concluded that the best possible $C_S$ value to be set in the bridge, when using the circuit of figure 1, is given by:

$$C_S = \left(\frac{C_{LV}}{a_N}\right)$$

(6)

With equations (4) and (6), we also obtain “$a$” as function of the relationship between capacitances:

$$a = \left(\frac{C_X}{C_S}\right) \cdot \left(\frac{C_{LV}}{C_{HV}}\right)$$

(7)

2.1.2. Equation for the phase angle of PT
The phase angle (\(\phi\)) of the PT is determined from the diagram shown in figure 2, which represents the voltages and currents of figure 1, resulting in:
\[ \psi = \delta - \delta_X + \delta_S \]  

(8)

Where:
\( \delta \) = Phase angle between \( I_X \) and \( I_S \), measured by the bridge
\( \delta_X \) = Known dissipation factor of \( C_{HV} (\delta_{HV}) \)
\( \delta_S \) = Known dissipation factor of \( C_{LV} (\delta_{LV}) \)

Figure 2. Diagram for determination of the phase angle of the PT under calibration.

3. Equipment used
The C and Tan\( \delta \) bridge used was a 7010B model manufactured by MI – Measurements International. \( C_{HV} \) was a 100 pF/200 kV standard SF\(_6\) insulated capacitor. For \( C_{LV} \), four thermally stabilized [4] units of 1000 pF/750 V N\(_2\) insulated standard capacitors were available, allowing capacitance values of 1000 pF, 2000 pF, 3000 pF and 4000 pF. For the low voltage measurement of \( C_{HV} \) and \( C_{LV} \) and their respective dissipation factors (\( \delta_{HV} \) and \( \delta_{LV} \)), a high accurate capacitance meter AH2700A model, manufactured by Andeen-Hagerling, was used.

The standard PT calibrated during the implementation of the method was a NVRD40 PT model, manufactured by Epro. Nine PT taps were calibrated with rated voltages from 3kV to 40kV. The reasons for choosing this PT were: a) Up to its maximum voltage (40 kV), the variation of \( C_{HV} \) due to its voltage coefficient is less than 1 ppm [2]; b) Its ratio values, combined with \( C_{HV} \) and \( C_{LV} \) available at Inmetro, enable measuring ranges at the bridge with low uncertainties; c) This PT was recently calibrated at PTB (2013), enabling comparison for validation purposes under equivalent conditions.

The C and Tan\( \delta \) bridge was calibrated in Inmetro considering its best operating parameters that lead to minimum contribution to the uncertainty in the PT calibration results, based on the PT, \( C_{HV} \) and \( C_{LV} \) known characteristics. The circuit arrangement in the HV hall of Lamat is shown in figure 3.

4. Corrections and uncertainties
For metrological purposes, it must be considered that the temperature variation (\( \Delta_T \)) and the applied voltage level (U) affect a capacitance (C).

Studies and experiments were performed in Inmetro for \( C_{HV} \) and \( C_{LV} \) capacitors in order to consider the effects of temperature and voltage either for correction purposes or for including them in the uncertainty of the results, together with the contribution due to the uncertainty of the capacitance bridge itself [3].
Figure 3. Circuit arrangement in the HV hall of Lamat.

For the PT phase angle, corrections were applied in equation (8) to consider the effects of stray capacitances and resistances between $C_{HV}$ and $C_{LV}$ capacitors and their respective inputs $C_X$ and $C_S$ in the bridge, as well as the correction of the bridge itself for dissipation factor measurement.

The uncertainty for phase angle result was estimated considering the uncertainties of the corrections and those related to the bridge: resolution, repeatability and its calibration for dissipation factor [3].

5. Results
The results obtained by Inmetro for the PT calibration are shown in tables 1 and 2, together with information about the results obtained by PTB and those given by the manufacturer.

The maximum expanded uncertainty estimated by Inmetro in the PT calibration process was 0.0049 % for ratio error and 104 µrad for phase angle error. The PTB expanded uncertainty was 0.0040 % for ratio error and 44 µrad for phase angle error. The manufacturer gives 0.0050 % for ratio error and 145 µrad for phase angle error.

6. Comments and conclusions
A method for internal metrological traceability of 60 Hz HVAC up to 40 kV, based on a circuit that uses a C and Tanδ bridge with two standard capacitors and a standard potential transformer, was successfully implemented in Inmetro.

By this method, the obtained results for PT ratio and phase angle are linked to the electrical resistance quantity (ohms), obtained from the quantum Hall effect in Inmetro.

The maximum estimated uncertainties obtained by Inmetro were 0.0049 % for ratio error and 104 µrad for phase angle error.

For the PT ratio, the results obtained by Inmetro, both error and uncertainty values, were in good agreement with those obtained by PTB.

Table 1. Discrepancies between Inmetro and PTB for ratio error ($\Delta a$) [$\times 10^{-6}$] and phase angle ($\Delta \phi$) [µrad].

| Tap (%) | 3 kV | 15 kV | 40 kV |
|--------|------|-------|-------|
|        | $\Delta a$ | $\Delta \phi$ | $\Delta a$ | $\Delta \phi$ | $\Delta a$ | $\Delta \phi$ |
| -40    | 00  | 04 | 00  | -13 | -02 | -28 |
| 60     | 09  | 02 | 01  | 00  | 00  | 26  |
| 80     | 09  | -01 | -02 | -14 | 00  | -27 |
| 100    | 06  | -08 | -15 | 00  | -03 | -37 |
| 120    | 07  | -07 | -03 | -15 | -03 | -37 |
Table 2. Inmetro uncertainties for PT error in ratio $U_r(a) \times 10^6$ and phase angle $U_r(\phi) \ [\mu\text{rad}]$.

| Tap (%) | 3 kV | 15 kV | 40 kV |
|---------|------|-------|-------|
|         | $U_r(a)$ | $U_r(\phi)$ | $U_r(a)$ | $U_r(\phi)$ | $U_r(a)$ | $U_r(\phi)$ |
| 40      | 25    | 104   | 46    | 104   | 36    | 104   |
| 60      | 26    | 104   | 46    | 104   | 36    | 104   |
| 80      | 26    | 104   | 46    | 104   | 37    | 104   |
| 100     | 28    | 104   | 47    | 104   | 38    | 104   |
| 120     | 30    | 104   | 49    | 104   | 41    | 104   |

References

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