Determination of instrument current transformer errors in frequency range up to 1 kHz

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Abstract. Two procedures for determining instrument current transformer (ICT) errors in the specified frequency range are described in the paper. The basis is use of accurate, frequency independent resistors, the ratio of which corresponds to the ratio of measured currents. These resistors are included in the primary and secondary circuit of the measured ICT. The difference in voltage drops across them corresponds to the ratio error and their phase shift to the phase displacement. The evaluation of the real and imaginary component of this difference is performed using a lock-in amplifier, phase-locked at the voltage corresponding to the primary current. In the case of primary currents of 100 A to 1 000 A, the use of resistors in the primary circuit is difficult with respect to their power loss. The procedure using a current transducer is also described.

1. Introduction

Instrument current transformers (ICTs) are mostly used for current measurements in 50 Hz power grids in the range of primary currents of units of amperes to several kiloamperes. The corresponding secondary currents are predominantly 5 A or 1 A, respectively. The basic ICT parameter is the ratio error \( \varepsilon_I \), reported in percent (%) and the phase displacement \( \delta_I \), reported in angle minutes ('). ICT errors at 50 Hz frequency are usually determined by comparison with standard ICT using known procedures [1], [2], [3], etc. In some cases, it is necessary to know error values in the frequency band up to 1 kHz. This is, for example, determination of present higher harmonic frequencies in the distorted course of the measured current induced by the power take-off system. Two procedures for determining errors in the specified frequency range are described in the paper. The basis is use of accurate, frequency independent resistors, the ratio of which corresponds to the ratio of measured currents. These resistors are included in the primary and secondary circuit of the measured ICT. The difference in voltage drops across them corresponds to the ratio error and their phase shift to the phase displacement. The evaluation of the real and imaginary component of this difference is performed using a lock-in amplifier, phase-locked at the voltage corresponding to the primary current [4], [5], [6]. In the case of primary currents of 100 A to 1 000 A, the use of resistors in the primary circuit is difficult with respect to their power loss. The procedure using an IT 400-S ULTRASTAB current transducer, manufactured by LEM [7], is also described.

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2. Determination of ICT error frequency dependence using standard resistors

The layout for measurement of ICT error frequency dependence using standard resistors is shown in Figure 1.

![Figure 1. ICT Calibration in wider frequency range by means of shunts.](image)

The primary circuit of the ICT under test fed by a power amplifier that output is excited from a lock-in amplifier. This provides a reference signal needed to determine the real and imaginary component of the differential voltage component $\Delta U$, which corresponds to transformer errors. The ratio error of the transformer under test may be expressed as

$$
\varepsilon_1 = \frac{p_t \left| \frac{I_2}{I_1} - \frac{1}{I_1} \right|}{p_t} = \frac{\frac{U_{RN2}}{R_{N2}} - \frac{U_{RN1}}{R_{N1}}}{\frac{R_{N1}}{U_{RN1}}} = \frac{\frac{R_{N2}}{R_{N1}} U_{RN2} - U_{RN1}}{U_{RN1}},
$$

where $p_t = I_1/I_2$ is the ICT transformation ratio (A/A), $R_{N1}$ and $R_{N2}$ are values of standard resistors connected to the primary and secondary ICT circuits (Ω), $U_{RN1}$ and $U_{RN2}$ are voltage drops on resistors $R_{N1}$ and $R_{N2}$ induced by currents $I_1/I_2$ (V). Provided that the ratio of resistors $R_{N2}/R_{N1}$ corresponds to $p_t = I_1/I_2$ transformation ratio according to

$$
p_t = \frac{R_{N2}}{R_{N1}},
$$

the ICT ratio error can be expressed as

$$
\varepsilon_1 = \frac{\Delta U}{U_{RN1}},
$$

or the ratio error $\varepsilon_1$ and the phase displacement $\delta_1$ may be expressed as

$$
\varepsilon_1 = 100 \cdot \Re[\Delta U]/U_{RN1} \quad \text{(\%)} \quad \delta_1 = \tan\delta_1 = \frac{\Im[\Delta U]}{U_{RN1}} \quad \text{(rad)}.
$$

The power amplifier is excited by an internal lock-in amplifier generator to provide a reference signal for measuring the real and the imaginary component of the output voltage difference $\Delta U$. The proper setting of the reference signal relative to the measured voltage is performed in the switch position REF, when the voltage $U_{RN1}$ corresponding to the current $I_1$ is applied to the input of the lock-in amplifier. The phase shift of the internal reference of the lock-in amplifier is set so that the voltage $U_{RN1}$ corresponds to the measured real component and the imaginary component is zero.

Note: It should be noted that the resistor $R_{N2}$ used in the secondary ICT circuit must be chosen so that its value must not exceed the ICT rated burden. The detected frequency error dependence then corresponds to the given burden.

3. Determination of ICT error frequency dependence using a standard transformer

Use of standard resistors described in the previous section for ICT error determination can be easily implemented in the range of primary currents up to 100 A. Standard resistors $R_{N1}$ are generally available for this area. For higher primary currents, the possibility of using a combination of a standard ICT with resistors for the current range up to 5 A was verified. An IT 400-S ULTRASTAB current transducer by LEM was used as a standard [7]. It is a ICT-based converter where the secondary current is generated depending on the difference...
between the magnetic voltages of the primary and secondary windings. The zero indication block evaluates this difference, and using an amplifier feeds the secondary winding by a current in such a way that the difference

$$N_1I_1 - N_2I_2 \rightarrow 0,$$

where $N_1I_1$ and $N_2I_2$ are primary and secondary windings and currents.

The transducers are primarily designed for DC current measurement, but they may be used also for AC current measurement up to tens of kHz frequencies. These transducers are determined mainly to measure currents higher than 100 A and so that the primary winding is formed only by one conductor. With a sufficient gain in the feedback loop, the ratio error of tens ppm and phase displacement of tenth of angle minutes can be achieved at the 50 Hz frequency. The transducers are designed for smaller secondary currents than ICTs, so that when measuring the frequency error dependence, it is necessary to use standard resistors to match the secondary currents as in the previous case. However, it is essential that these are standard resistors with resistance values in the range of 0.1 Ω to 10 Ω, which are commonly available. The block diagram for ICT calibration at higher frequency band using a standard current transducer is shown in Figure 2. The primary windings of the standard ICT $T_N$ and the ICT under test $T_X$ are fed by the common primary current $I_1$. The transformation ratios of both transformers and the magnitude of the standard resistors must match the equation

$$I_{2N}R_{2N} = I_{2X}R_{2X} \Rightarrow I_{1}R_{2N}/p_{IN} = I_{1}R_{2X}/p_{IX} \Rightarrow p_{IX}/p_{IN} = R_{2N}/R_{2X},$$

where $p_{IN} = I_1/I_{2N}$ is transformation ratio of the standard ICT $T_N$ and $p_{IX} = I_1/I_{2X}$ is transformation ratio of the ICT under test $T_X$. When condition (6) is fulfilled, errors of the ICT under test can be evaluated analogously to the previous case using the lock-in amplifier and the eq. (3) and (4). In the application described, it should be noted that for both ICTs, the primary current must not differ significantly. The solution assumes that errors of the standard IVT are negligible.

4. Results of ICT error frequency dependence

The above described procedures for measuring ICT error frequency dependence were verified by ICT Metra TL 20 with 100 A/5 A transformation ratio at a real burden of 2.5 VA, accuracy class 0.05. The LEM IT 400-S transducer with transformation ratio 400 A/0.2 A was used as a standard. All measurements were made at the rated the primary current $I_1 = 100$ A and the real burden of 2.5 VA. Determination of errors at the 50 Hz main frequency was performed in the beginning of the experiment. The Tettex 4761 current comparator with set transformation ratio 100 A/5 A was used as a standard and the errors were evaluated using a Tettex 2767 automatic transformer test set. The results are shown in Table 1.

### Table 1. Results of comparison of individual ICTs at 50 Hz frequency.

| ICT under test | Transformation ratio $p_{IX}$ (A/A) | Standard ICT | Transformation ratio $p_{IN}$ (A/A) | Ratio error (%) | Phase displacement (°) |
|----------------|------------------------------------|-------------|-----------------------------------|----------------|------------------------|
| TL 20          | 100/5                              | Tettex 4761 | 100/5                             | -0.0133        | 1.917                  |
| LEM IT 400     | 400/0.2                            | Tettex 4761 | 100/5                             | 0.0026         | -0.103                 |
| TL 20          | 100/5                              | LEM IT 400  | 400/0.2                           | 0.0151         | 1.890                  |
The comparison results at 50 Hz frequency show a difference of 0.02% in ratio error and 2 angle minutes in phase displacement. This difference must be taken into account by measurement of frequency error dependence. In the following part the frequency dependence of the ICT TL20 errors with at the transformation ratio $p_I = 100$ A/5 A using standard resistors according to Fig 1. In the primary ICT circuit, a Tinsley standard resistor $R_{N1} = 0.001$ Ω/700 A was used. In the secondary circuit a Guildline standard resistor $R_{N2} = 0.02$ Ω/100 A in series with a Guildline load resistor $R_0 = 0.1$ Ω/22 A was used for measurement. The voltage differences across the resistors were measured using a SR 830 lock-in amplifier. The results of the frequency dependence of ratio error and the phase displacement calculated according to (4) are plotted in Figures 3 and 4. The frequency dependence of the ratio of standard resistors $R_{N2}/R_{N1}$ at the frequency band of 40 Hz to 1 kHz was measured in serial connection using a Datron 1281 voltmeter at the layout for voltage ratio measurement. The resulting value $R_{N2}/R_{N1} = (19.993 \pm 0.007)$, so the results in Figures 1 and 2 were not to be corrected. The final part of the experiment concerned measurement of the frequency error dependence of TL20ICT using the LEM IT 400-S transducer as a standard. The measurement was carried out in the layout shown in Figure 2. The transformation ratio of the ICT under test TL20 $p_{IX} = 100$ A/5 A, the transformation ratio of the standard LEM $p_{IX} = 400$ A/0.2 A. According to (6), a resistor $R_{N1} = 10 \, \Omega$ is used in the LEM secondary circuit and in the TL20 secondary circuit a resistor $R_{TX} = 0.1 \, \Omega$. Signal evaluation and error calculation is similar as in the previous case. The results of measurement are shown in Figure 3 and 4.

![Figure 3. TL20 ratio error frequency characteristic.](image-url)

![Figure 4. TL20 phase displacement freq.characteristic.](image-url)

5. Conclusion

Two procedures for ICT calibration in wider frequency band were described. Measurement using resistors in ICT primary circuit (see Figure 1) is limited by magnitude of primary current of the ICT under test. Therefore a method using a current transducer LEM as a standard was verified. The advantage of this procedure is use of standard resistors of higher values. A significant difference was obviously caused by a spurious voltage when calibrating using serial resistors. Because the difference of the two voltage with magnitude of 100 mV was measured a spurious voltages came into account. When using the LEM transducer a difference of 500 mV was evaluated which is much more advantageous.

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