Calibration of Instrument Current Transformers at Low Currents Using Lock-In Amplifier

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***Abstract*—A system for evaluating instrument current transformer errors using a lock-in amplifier is described in the paper. The difference between the standard and the transformer under test is evaluated as the ratio error and the phase displacement. The attention is focused to measurement of errors at the range of primary currents less than 20% of the nominal value. The measurement accuracy of current and energy in smart grids is important particularly at the time when the majority of appliances are in the standby mode.**

Keywords—instrument current transformer; lock-in amplifier, calibration, ratio error, phase displacement

I. Introduction

Calibration of instrument current transformers (ICTs) is performed using a comparative method. A passive compensated current comparator (CCC) by Custers or current transformers with electronic error compensation (e.g. Tettex 4764 & Tettex 4761 current comparators) serve as standards. A difference of secondary currents of the ICT under test and the standard $\boldsymbol{I}_{2X}$ and $\boldsymbol{I}_{2N}$ are evaluated using an automatic transformer test set (e.g. Tettex 2767, Zera WM 303-I, etc.). The ratio error and phase displacement are displayed on the screen.

The following part of the paper is devoted verification of a possibility to evaluate the difference between errors of the standard and ICT under test using a lock-in amplifier. It is presumed that the transformation ratios of the standard and ICT under test are identical. The difference of the secondary

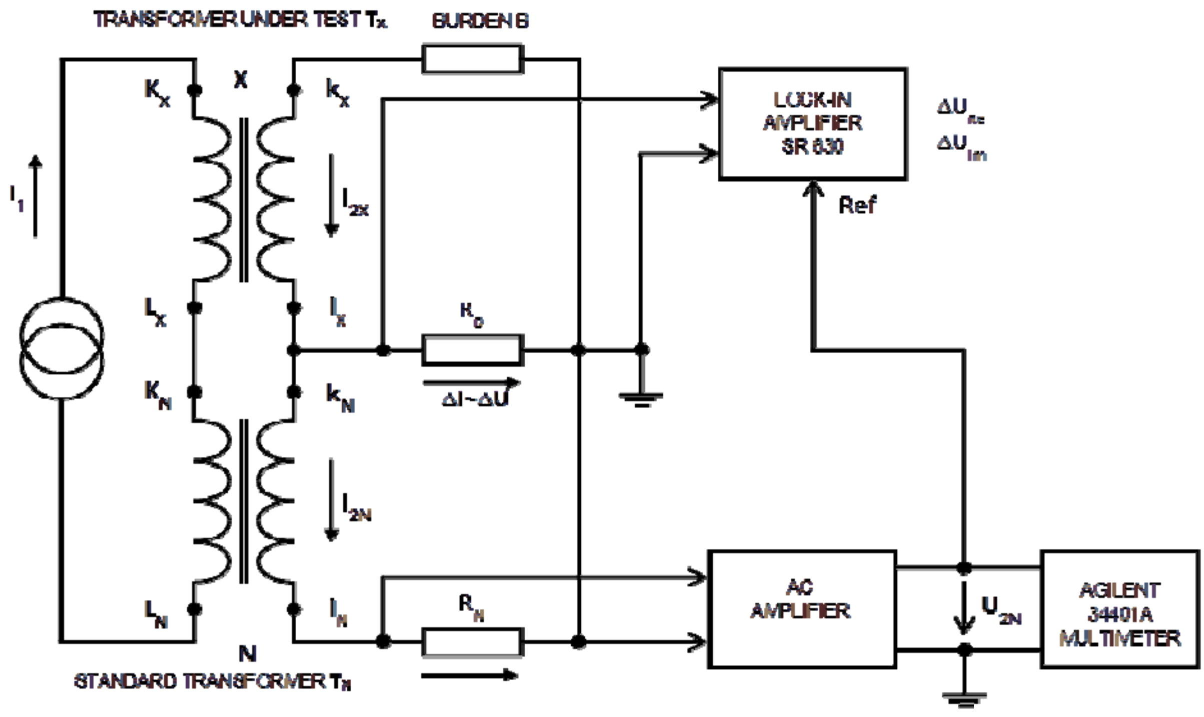

Fig. 1. Layout for ICT error evaluation using a lock-in amplifier.

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currents $\Delta \boldsymbol{I}$ is evaluated using a differential resistor as a voltage difference $\Delta \boldsymbol{U}$. The real and imaginary components of the voltage $\Delta \boldsymbol{U}$ are measured using a SR 830 lock-in amplifier and the ratio error and phase displacement are calculated from the voltage drop $\Delta \boldsymbol{U}$.

II. The Procedure for ICT Error Evaluation Using a Lock-in Amplifier

The block diagram of the layout for ICT error evaluation using a lock-in amplifier is shown in Fig. 1. The ICT under test T_X, loaded by a burden $\boldsymbol{B}$ in the secondary circuit is compared with a standard T_N. The primary winding of both transformers is fed by a common current $\boldsymbol{I}_1$ and a difference of the secondary currents

$$\Delta \boldsymbol{I} = \boldsymbol{I}_{2X} - \boldsymbol{I}_{2N} . \qquad (1)$$

is evaluated in the secondary circuit.

As it is apparent from the phasor diagram of the secondary currents in Fig. 2, the error difference between the standard T_N and the ICT under T_X) may be expressed as

$$\varepsilon_{ID} = \varepsilon_{IX} - \varepsilon_{IN} = \frac{\boldsymbol{I}_{2X} - \boldsymbol{I}_{2N}}{\boldsymbol{I}_{2N}} 100 = \frac{\Delta I_{Re}}{I_{2N}} 100 , \qquad (2)$$

$$\delta_{ID} = \delta_{IX} - \delta_{IN} \doteq \mathrm{tg}\,\delta_{ID} = \frac{\Delta I_{Im}}{I_{2N} - \Delta I_{Re}} , \qquad (3)$$

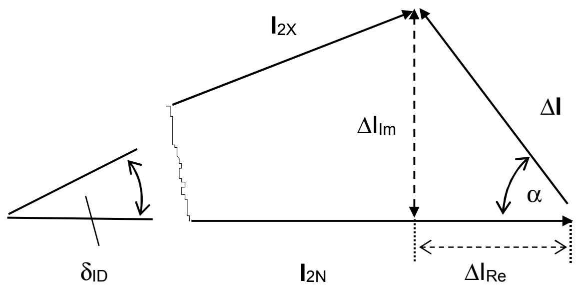

Fig. 2. Phasor diagram of secondary currents.

where ε_{IX} and ε_{IN} are ratio errors of the standard and the ICT under test (%), δ_{IX} and δ_{IN} are phase displacements of the standard and the ICT under test (rad), $\boldsymbol{I}_{2X}$ and $\boldsymbol{I}_{2N}$ are secondary currents of the standard and the ICT under test (A), ΔI_{Re} and ΔI_{Im} are magnitudes of rectangular components of the phasor of the differential current $\Delta \boldsymbol{I}$ referred to $\boldsymbol{I}_{2N}$ (A).

Equations (2) and (3) or their simplifications are valid only by an assumption if errors of the standard are very small (e.g. $\varepsilon_{IN} \leq 0.01\%$) and

$$\Delta I \ll I_{2N}, \quad \Delta I_{Re} \ll I_{2N} , \ \Delta I_{Im} \ll I_{2N} . \qquad (4)$$

Resulting errors of the ICT under test may be expressed as

$$\varepsilon_{IX} = \varepsilon_{ID} + \varepsilon_{IN} , \ \ \delta_{IX} = \delta_{ID} + \delta_{IN} . \qquad (5)$$

When evaluating signals corresponding according to (2) and (3) to errors of the ICT under test, the voltages

$$\Delta \boldsymbol{U} = R_d \, \Delta \boldsymbol{I} , \ \ \boldsymbol{U}_N = R_N \, \boldsymbol{I}_{2N} , \qquad (6)$$

where R_d and R_N are resistors connected in the secondary circuits of the two transformers (Ω) – see Fig. 1.

The voltage $\Delta \boldsymbol{U}$ is applied to the lock-in amplifier input which reference voltage $\boldsymbol{U}_{2N}$ is picked-up in the secondary current circuit of the standard using a standard resistor R_N. The lock-in amplifier evaluates the real and imaginary components of the voltage $\Delta \boldsymbol{U}$ that may be according to Fig. 2 expressed as

$$\Delta U_{Re} = R_D \, \Delta \boldsymbol{I} \cos \alpha = R_D \, \Delta I_{Re} ,$$

$$\Delta U_{Im} = R_D \, \Delta \boldsymbol{I} \cos(90 - \alpha) = \mathrm{R_D} \, \Delta I_{Im} . \qquad (7)$$

The error difference between the standard and the ICT under test may be expressed according to (2) to (7) as

$$\varepsilon_{ID} = \varepsilon_{IX} - \varepsilon_{IN} = \frac{\boldsymbol{I}_{2X} - \boldsymbol{I}_{2N}}{\boldsymbol{I}_{2N}} 100 = \frac{\Delta I_{Re}}{I_{2N}} 100 = = \frac{R_N}{R_D} \frac{\Delta U_{Re}}{U_N} = \frac{R_N}{R_D} \frac{A \Delta U_{Re}}{U_{2N}} 100 \quad (\%) , \qquad (8) \; (3)$$

$$\varepsilon_{IX} = \varepsilon_{IN} + \frac{R_N}{R_D} \frac{A \Delta U_{Re}}{U_{2N}} 100 \quad (\%) \qquad (9)$$

$$\delta_{ID} = \delta_{IX} - \delta_{IN} \doteq \mathrm{tg}\,\delta_{ID} = \frac{\Delta I_{Im}}{I_{2N} - \Delta I_{Re}} = = \frac{1}{R_D} \frac{\Delta U_{Im}}{\frac{U_{2N}}{A R_N} - \frac{\Delta U_{Re}}{R_D}} (\mathrm{rad}) , \qquad (10)$$

where A is the gain of the AC amplifier in the arm for measurement of the voltage $\boldsymbol{U}_N$ (-).

If the ratio error ε_{IX} of the ICT under test is less than 5% then $\Delta U_{Re} << U_{2N}$ and eq. (10) for phase displacement expression may be simplified to the form

$$\delta_{ID} = \frac{R_N}{R_D} \frac{A \Delta U_{Im}}{U_{2N}} \quad (\mathrm{rad}) ,$$

$$\delta_{IX} = \delta_{IN} + \frac{R_N}{R_D} \frac{A \Delta U_{Im}}{U_{2N}} \quad (\mathrm{rad}) . \qquad (11)$$

III. Determination of the ICT Error Uncertainty Using Lock-In Amplifier

The type B uncertainties of the ratio error ε_{IX} and phase displacement δ_{IX} determination may be using (9) and (10) expressed as

$$u(\varepsilon_{IX}) = \sqrt{u(\varepsilon_{IN})^2 + u(\varepsilon_{ID})^2} \ ,$$

$$u(\delta_{IX}) = \sqrt{u(\delta_{IN})^2 + u(\delta_{ID})^2} \ , \qquad (12)$$

where

$$u(\varepsilon_{ID}) = \frac{\varepsilon_{ID}}{100}\sqrt{u(R_N)^2 + u(R_D)^2 + u(A)^2 + u(U_N)^2 + u(\Delta U_{Re})^2} \qquad (13)$$

$$u(\delta_{ID}) = \frac{\delta_{ID}}{100}\sqrt{u(R_N)^2 + u(R_D)^2 + u(A)^2 + u(U_N)^2 + u(\Delta U_{Im})^2} \qquad (14)$$

where $u(\varepsilon_{IX})$ (%) and $u(\delta_{IX})$ (') are absolute values of uncertainties of ratio error and phase displacement of the ICT under test, $u(\varepsilon_{IN})$ (%) and $u(\delta_{IN})$ (') are absolute values of uncertainties of ratio error and phase displacement of the standard, ε_{ID} (%) and δ_{ID} (') are measured error differences between the ICT under test and the standard, $u(\varepsilon_{ID})$ (%) and $u(\delta_{ID})$ (') are absolute values of uncertainties of measurement of the differences of ratio error and phase displacement, $u(R_N)$, $u(R_D)$, $u(A)$, $u(U_N)$, $u(\Delta U_{Re})$ and $u(\Delta U_{Im})$ are relative values of uncertainties of individual coefficients in eq. (9) and (11).

Assuming that the maximum deviations from the true value of individual variables in (12) and (13) are: $\delta(R_N)$ = 0.1%, $\delta(R_D)$ = 0.1%, $\delta(A)$ = 0.5% , $\delta(U_N)$ = 0.5% and $\delta(\Delta U_{Re}) = \delta(\Delta U_{Im})$ = 1.5% and applying the uniform distribution of errors, we get according to (12) and (13) the relative value of the expanded uncertainty of ratio error and phase displacement measurement $\delta(\varepsilon_{IX}) = \delta(\delta_{IX})$ = 2% RDG.

When measured errors approach zero, interference voltages apply and worsen the measurement accuracy, especially accuracy of measurement of the differential voltages ΔU_{Re} or ΔU_{Im}, respectively. A reduced accuracy of the voltage ΔU_{Re} and ΔU_{Im} is assumed for ratio errors $\varepsilon_{IX} \leq 0.1\%$ or phase displacements $\delta_{IX} \leq 3'$, respectively. In this case it is assumed that the maximum deviation from the true value of the real or imaginary component $\delta(\Delta U_{Re}) = \delta(\Delta U_{Im})$ = 3 % or 15 ppm for ratio error and 0.05′ for phase displacement. The larger of the two values is always valid. When using rectangular distribution of errors, we get from (12), and (13) the relative value of the expanded measurement uncertainty fault current $U(\varepsilon_{IX}) = U(\delta_{IX})$ = 3.5% of reading or 17 ppm for error current, respectively 0.057 for error angle. Always the larger of the two values is valid. When using the rectangular distribution of errors we get according to (12) and (13) the relative value of expanded uncertainty for ratio error and phase displacement measurement $U(\varepsilon_{IX}) = U(\delta_{IX})$ = 3.5% RDG or 17 ppm for ratio error and 0.057′ for phase displacement. Always the larger of the two values is valid.

IV. Results of Calibration

The comparison of results of ICT calibration using a lock-in amplifier and a Tettex 2767 transformer test set was performed using a ICT with transformation ratio of 50 A/1 A; class 0.5; burden 15 VA; cos β = 0.8.

The transformer was in both cases loaded by an electronic burden Tettex 3691. A lock-in amplifier SR 830 and resistors R_D = 1 Ω and R_N = 0.1 Ω were used for error evaluation – see Fig. 1.

An AC amplifier with a gain A = 100 was used for evaluation of the voltage U_N and a lock-in amplifier reference. Ratio error and phase displacement were calculated according to (9) and (11) of the errors of the standard were neglected. Uncertainties of ratio error and phase displacement were calculated using eq. (12) up to (14). A transformer with electronic error compensation (current comparator Tettex 4761) served as the standard in both cases. Its maximum deviation from the true value of the transformation ratio (ratio error) $\Delta\varepsilon_{IN} \leq 0.001\%$, and of the phase displacement $\Delta\delta_{IN} \leq 0.05'$. The errors were measured in the range of primary currents (0.5 up to 20)% I_N. This area of measured current is important because the Tettex 2767 automatic transformer test set has here reduced accuracy and unstable reading of errors.

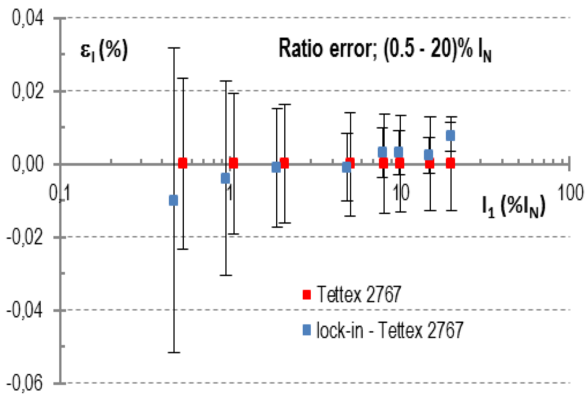

Fig. 3. Results of ICT calibration using a SR 830 lock-in amplifier and a Tettex 2767 transformer test set; range (0.5 – 20)% I_N; ratio error.

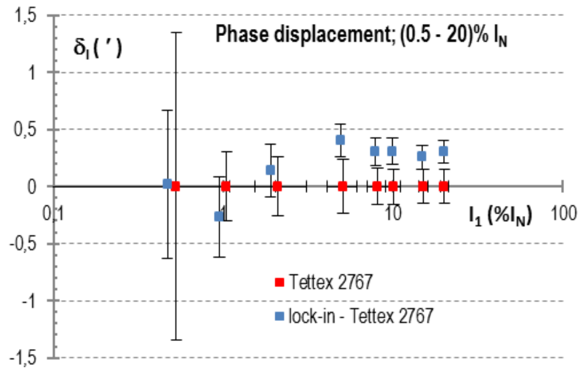

Fig. 4. Results of ICT calibration using a SR 830 lock-in amplifier and a Tettex 2767 transformer test set; range (0.5 – 20)% I_N; phase displacement.

The results are shown in Figs. 3 and 4. On the horizontal axis are plotted points at which was the calibration performed, values of the measured current I_1 (% I_N). On the vertical axis are plotted differences between errors measured using lock-in amplifier and the Tettex 2767 system.

V. CONCLUSION

From the results shown in the Figs. 3 and 4 it is obvious that in the current range below 20% I_N are calibration results using lock-in amplifier in accordance with results obtained using the Tettex 2767 test set. Measurement of errors in the current range below 10% I_N when using the Tettex 2767 test set exhibits greater instability of measured quantity than when using a lock-in amplifier. The correct determination of measurement uncertainties using a lock-in amplifier requires its calibration in the range of measured voltage of 0.1 mV to 100 mV. This calibration may be performed e.g. using an inductive divider. A proper calibration of the lock-in amplifier enables a substantial reduction in the uncertainty of measurement errors in the range of ICT currents less than 10% of rated value.

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