The Instrument Transformer Bridges for Testing and Characterizing, for Harmonic Measurements, Instrument Transformers

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Abstract - The modern development of electric power systems is increasingly demanding for high improvements in the accuracy of metering and testing methods in both HV and high current, namely, in testing the instrument transformers. The necessity of determining if the existing instrument transformers are usable for harmonic measurements is, at present, also required. The illustrated Instrument transformer bridges implement the, at present, used ratio transformer bridge to testing the instrument transformers and their usability for harmonic measurements. The illustrated bridges uses two ratio transformers, an instrument transformer and a decade ratio transformer. The use of the instrument transformer allows to supply the reference standard ($S$) at its secondary low rating and extends the bridges’ range without extending the dynamic range of both $S$ and decade ratio transformer. Thus the illustrated bridges undeniably appears innovative of the, at present, used ratio transformer bridge technique that in the illustrated form could find wider use. The uncertainty of 0.5 ppm, of the used ratio transformer has been achieved in the absolute and relative test of both voltage and current transformers by experimental bridges.

I. Introduction

The modern development of electric power systems is increasingly demanding for high improvements in the accuracy of metering and testing methods in both HV and high current. Such strict exigencies are particularly, at present, in (i) the test of instrument transformers (IT’s), almost invariably involved in measurements of large amount of electric energy. Resolution of 10 ppm is usually satisfactory; (ii) the necessity of determining if the existing IT’s are usable for harmonic measurements [1]. The widespread use of non-linear solid-state devices in electrical and electronics appliances is the main cause of this harmonic distortion in load/line voltages and currents. For accurate harmonic measurements [2], the current and voltage transducers must have sufficient operating frequency bandwidth and negligible nonlinearity errors. More accurate testing methods are then required for calibrating IT in the whole frequency bandwidth. The denoted, “Instrument transformer bridges with inductively coupled ratio arms” (IBI), in its two structures, the "HV admittance potential transformer bridge with current comparator" (HPBC) and "Four-terminal impedance current transformer bridge with inductively coupled ratio arm" (FCBI) are illustrated. IBI uses two ratio transformers, an IT and a decade ratio transformer. IT allows to supply the reference standard ($\bar{S}$) at its secondary low rating and extends the bridges' range without extending the dynamic range of both $\bar{S}$ and decade ratio transformer. Moreover the application for calibrating and characterizing IT is illustrated as well. The prototypes of the new bridges, which have been developed are illustrated and obtained experimental results in testing IT’s are shortly discussed. An uncertainty equal to that of 0.5 ppm of the used decade transformer is achieved. For characterizing the instrument transformers for harmonic measurements the same uncertainty can be maintained to at least 10-20 kHz.

Fig. 1. Block diagram of the basic (a) and equivalent (b) circuit of IBI. D is the null detector. IT is the instrument transformer. $\bar{X}$ and $\bar{S}$ are the unknown and standard components. $R$, and $R_I$ are respectively, the re-phasing component and the ratio inductive detector in zeroing, $s_i$ is the equivalent of IT.
II. Basic Principle of IBI

The schematic diagram of the basic principle of IBI is illustrated in Fig. 1 (a). $\overline{X}$, $\overline{S}$, and $R_e$ and RI are the: compared components, re-phasing component and ratio inductive detector in zeroing. $X$, $S$, and $R_e$ and $RI$ are the: supplied with the primary and secondary quantities, $\overline{x}^p$ and $\overline{x}''$ of IT; The output quantities - $y_x$ and $y_s$ are passed through the re-phasing block $R_e$ its outputs - $y_x$ and $y_s$ in phase, are entered $RI$ having adjustable ratio, $\rho$. $\rho$ of $RI$, and $\pm \Delta \Phi$ by $R_e$ balance IBI. At balance, $\rho = \frac{y_s}{y_x}$. In the ideal case ($X$, $S$, pure and similar elements, no error neither quantity absorbed by $RI$ and $R_e$) is, $X = \rho st S$. Where $st$ is the inverse of the nominal ratio $r_t$ of IT ($st = \frac{r_t}{r_t}, s_t = \frac{t}{t\epsilon}$, $\eta_t$ is the ratio error and $\epsilon_t$ the phase angle of IT. In the real case. The equivalent circuit of Fig. 1(b) can evaluate the equilibrium conditions. The equivalent block $Sst$ substitutes IT and $S$ in Fig. 1 (a). At balance is,

$$\overline{X} = \rho \overline{S}, \overline{S}$$
$$X = \rho st S$$
$$\Phi_x = \Phi_s + \epsilon_s \pm \Delta \Phi$$
$$\eta_t = \frac{r_t X}{\rho S} - 1$$
$$\epsilon_t = \frac{1}{2} \Delta \Phi + \Delta \Phi'$$

III. Accuracy

Is: $X \propto \rho st S$. $\rho$ can be calibrated almost without any uncertainty and $st$ determined within 0.5 to a few ppm. To obtain $\frac{X}{S}$, $st$, $\eta$, and $\epsilon$ as function of $\rho$, $\Phi$, and $\Delta \phi$ the only the interchange method can be used. With this method two balances of IBI must be reached with in the second balance, all the connections of $\overline{X}$ and $\overline{S}$ interchanged and assuming that $r_e$ and $x'$ maintain the same values as in the first balance. If: $\rho$ and $\Delta \phi$, $\rho'$ and $\Delta \phi'$ are the first and second balance values is,

$$X = \sqrt{\frac{\rho}{\rho'}} \text{ and } s_t = \sqrt{\frac{1}{\rho \rho'}}$$
$$\eta_t = \frac{r_t}{\sqrt{\rho \rho'}} - 1$$
$$\Phi_x = \Phi_s + \frac{1}{2} (\Delta \Phi - \Delta \Phi')$$
$$\epsilon_t = \frac{1}{2} \Delta \Phi + \Delta \Phi'$$

IV. Applications of IBI in Testing IT’s

This Section is devoted to illustrating how IBI may be used in accurate testing and characterizing of IT’s.

A. Absolute Test

In Fig. 1 (a) - IT is the under test IT, ITx; $\overline{X}$ and $\overline{S}$ are similar nearly pure components $\eta$, and $\epsilon$ are evaluated according with (4) and (5). By the interchange method, (7, and 8) still hold.

B. Relative Test

In Fig. 1 (a) IT is the reference standard. The primary of the under test IT, ITx replaces $\overline{X}$; ITx supplies with its output $\overline{x}''$ an $S$ like $\overline{S}$. ITx and IT are supplied with the same $x'$ and $S$ respectively with their secondary
outputs $x^u_x$ and $x^u_y$. The connections of $\overline{X}$ with $R_e$ illustrated in Fig. 1 are replaced by that of $\overline{S'}$. With:

$$\overline{X} = \overline{s_x S} \times \overline{x} \times S'$$

and, $\Phi_x = \Phi_x^' + \epsilon_x$ from (4) and (5)

$$\eta_x = r'_x \rho \frac{S}{S'} - 1 \quad (9)$$

$\epsilon_x = \epsilon_x^' + \Phi_x - \Phi_x^' \pm \Delta \Phi \quad (10)$. By the interchange method with, (i) interchanged $S'$ and $S$; (ii) constant $x'$, $r'_x$, and $r_x$, is,

$$\eta_x = s_x, r_x, \sqrt{\rho \rho'} - 1 \quad (11)$$

$$\epsilon_x = \epsilon_x^' + \frac{1}{2} \left( \Delta \Phi + \Delta \Phi' \right) \quad (12)$$

- Uncertainty - The Uncertainty of IBI in testing IT’s appears from (11) and 12). $\eta_x$ and $\epsilon_x$ can nearly be determined with the same uncertainty with which $\rho$, $s_x$, or $\eta_t$ and $\epsilon_t$ are known.

V. IBI an Innovative Ratio Transformer Bridge Form

The use in IBI of IT allows to supply the reference standard, S, at its secondary low rating and extends the bridges' range without extending the dynamic range of both S and decade ratio transformer. Thus IBI undeniably appears innovative of the current ratio transformer bridge technique that in IBI form could find wider use (see Section 10. A).

VI. The HPBC

The schematic diagram of the basic principle of HPBC, with necessary screening and shielding, is shown in Fig. 3. RI of Fig. 1 is a current comparator that has ratio $\rho_c = \eta_x / \eta_t$. IT is a potential transformer (PT), $T_p$, $Y_x$ and $Y_s$ must be admittances of the same or dual kind. Even so there will inevitably be a small quadrature out-of-balance in the m.m.f. of the current comparator. In Fig. 3 a decade conductance G is used to adjust this quadrature out-of-balance. $\rho_c$ and G balance HPBC. If $Y_x$ and $Y_s$ are represented by their equivalent parallel parameters at balance is,

$$\Phi_x = act \frac{B_x}{(G_x + G)} \quad or \quad \Phi_x = act \frac{B_x}{G} \quad (14)$$

where, $+ \Delta \Phi = act \frac{\rho_c B_x}{G}$

$$G_x = \rho_c s_p (G_x + G) \quad or \quad G_x = s_p (\rho_c G_x - G) \quad (16)$$

$$G_x \eta_p = \frac{r_p B_x}{\rho_c B_x} - 1 \quad (17)$$

$$G_x \epsilon_p = \Phi_x - \Phi_x^' + \Delta \Phi \quad (18)$$

$$G_x \rho_c \frac{B_x}{G} \quad or \quad \Phi_x = act \frac{B_x}{(\rho_c G_x - G)} \quad (19)$$

$$G_x \rho_c \frac{B_x}{G} \quad where, \quad + \Delta \Phi = act \frac{B_x}{G} \quad ; \quad or \quad - \Delta \Phi = act \frac{\rho_c B_x}{G} \quad (20)$$

Fig. 2. Circuit of HPBC. Fig. 3 Photo of an experimental HPBC.
VII. HPBC an Innovative HV Current Comparator Bridge Form

Let us now outline that the basic bridge circuit of HPBC is an extension of HV current comparator bridges [3-5] and, in consequence, it may appear similar to a bridge circuit shown in [5], as a proposal for testing PT’s. However HPBC, if compared with this similar bridge circuit, is both a simpler and more general bridge form. In fact, it does not need [5]: for balancing the in-phase current in the sample, a feedback amplifier, (which may introduce troublesome noises), a variable conductance and a third ratio winding having variable turns number in the current comparator (which requires the adoption of a special current comparator). Moreover the HPBC may be used in a very wide number of applications (see Section 10).

VIII. The FCBI

The schematic basic diagram of FCBI, with necessary screening and shielding, is shown in Fig. 4. IT of Fig. 1(a) is a current transformer (CT) and RI a voltage decade ratio transformer. These dividers with their high input low output impedance, provide a very significant reduction of the current drown from the potential terminals of $Z_x$ and $Z_z$ without significant loss of sensitivity. This drown current is further on reduced when, by the capacitor $C_p$, an LC parallel resonance is achieved. The ratio $Z_x/Z_z$ must be nearly real. Even so, there will inevitably be a small out-of-balance in the bridge. The decade capacitor $C_i$ is used to adjust this quadrature out-of-balance. The null detector $D$ is connected to the variable tapping point TP on the divider and to the common tape (CT) through the resistor $R_i$. $C_i$ is connected from the detector end of $R_i$ to the switch; SW. $C_i$ is used to draw a small amount of current through $R_i$, which in turn causes a small quadrature voltage drop. The high gain detector $D$ is isolated from the bridge by a 10:1 step-up screened and shielded detector transformer. FCBI is supplied with the primary current $I'$. The deflection of $D'$ is reduced to a minimum by $C_p$ (LC parallel resonance). $D'$ is shorted. $\rho$, and $C_i$ balance FCBI. The equilibrium conditions under the assumption that $Z_x$ and $Z_z$ are, $Z_x=R_v\Phi_x\Phi'_x + \Delta\Phi_v$, and $Z_z=R_v\Phi_x\Phi''_x + \Delta\Phi_v$, where, $\Delta\Phi_v=\rho R_i C_i$, at balance is,

$$\eta_x = \frac{r_x Z_x}{\rho Z_x} - 1 \quad (21); \text{ and } \epsilon'_x = \Phi'_x - \left(\Phi'_x + \Delta\Phi_v\right) \quad (22).$$

- **Uncertainty** - The considerations on the class B errors for IBI still hold. Sources of possible class A errors due to: mutual coupling, environmental temperature, and frequency. Two factors of major importance involving the layout of the bridge are the inductive coupling between the potential and current circuits and the capacitive coupling of those portions or circuits where currents forming a ratio are defined. Inductive coupling may be reduced by using either, coaxial go-and-return leads from small junction boxes both in the current circuit, which is the principal source or interfering flux, and in the potential circuit where induced voltages must kept to a minimum, or shielded and twinned in pairs conductors; moreover astatic reference standard vectorial operator $\overline{S}$ must be adopted and in CT tests the bridge circuit must be kept at a distance of 4÷10 m from CT and its connection. Capacitive coupling’s effects may be controlled by the use of grounded screens and fixing the circuit potentials, with respect to ground, as illustrated in Fig. 2 and 4. It will be noted that the central point of the current comparator, Fig. 2, and the variable tapping point, TP, Fig. 4 of the decade ratio transformer are kept at earth potential. As others have shown this is generally the most effective earth point because the stray earth impedances either directly connect shields to earth.
and the comparator windings are not interested by the earth currents or directly shunts the ratio windings, which inherently have low leakage impedance, or the null detector. Frequency and environmental temperature affect $\bar{S}$ according with its frequency and thermal characteristic that must be enclosed with the bridge. Moreover their influence did not affect our measurement accuracy because the respective coefficients are very small (f.i. 150 ppm/°C) and it is easy to keep frequency and environmental temperature constant for a series of experiment. No loading may affects $\bar{S}$ and the remaining bridge arms; they are supplied with the secondary low rating $x''$ of IT.

**IX. Applications of FCBI on the Test of CT’S**

This Section is devoted to illustrating how FCBI may be used in accurate testing and characterizing CT’s.

**A. Absolute Test**

The components in Fig. 4 are: - T is the under test CT, CTs - $\bar{Z}_x$ and $\bar{Z}_s$ are a nearly pure shunt S s and resistance standard Rs, $\eta_x$ and $\eta_s$ are evaluated with (21), (22). By this procedure $\eta_x$ is a function of $S_x/R_s$. By the interchange method with (i) interchanged $S_x$ and Rs (ii) constant $\Gamma'$ and $x''$, $\eta_s$ and $\varepsilon_s$ are as in (11), (12).

**B. Relative test**

In this application, the procedure is that illustrated in Section 4. B. - $T_x = T_x$ is the under test CT, CTs - $\bar{I}_T = T$ is an accurate CT standard (it may be $r_p r_{x''} S = R_s$ and $S = r_p' R_s'$, are two nearly pure resistance standard. With $Z_x \Rightarrow R_x$, $\Phi_x = \Phi_{x''} + \varepsilon_x$, $Z_s = = R_s$, and, $\Phi_s = \Phi_{s''} + \varepsilon_s$ from (21), (22) is,

$$\eta_s = r_x \frac{\rho_x s_x^2 R_s}{R_x} - 1 \quad (23) ; \quad \varepsilon_x = 2 \varepsilon_s + \Phi_s - \Phi_{s''} \pm \Delta \Phi_v \quad (24).$$

By the interchange method with (i) interchanged $R_x'$ and $R_s'$; (ii) constant $\Gamma'$, $r_{x''}$, and $r_{s''}$, $\eta_x$ and $\varepsilon_s$ have the values by (7) and (8).

**X. Proof of the Claimed Uncertainty and Performances of IBI, Test Results**

Accuracy of the method. In the illustrated applications (testing and characterizing IT’s) the only factors that can affect the measurements’ result are, $s_0$ or $\eta_s$ and $\varepsilon_s$. The first factor can be detected by a checkout test within at least 0.5 ppm. The influence on the test results by an error of the ratio $\rho$ can be nearly eliminated by the interchange procedure (see Section 2)

**A. Test of PT’s by HPBC**

A prototype of an HPBC has been developed; see the photo in Fig. 5. This prototype has been used in carrying on the following tests and measurements: (i) typical tests of PT’s; (ii) HV high Q shunt reactors; (iii) voltage apparatus’s tests on exercise.

- (a) **Absolute Test** - A PT submitted to an international comparison of test methods [7] (it was calibrated at NBS, NPL, PTB, IENGF, and IEI laboratories) has been submitted to an absolute test with the prototype of an HPBC. This transformer has been a step-down transformer [8]. Its primary winding was in 4 sections each of ratio $r_p = 200$. The interlaboratory calibration results were within a band of 0.5 ppm. The influence on the test results by an error of the ratio $\rho$ can be nearly eliminated by the interchange procedure.

- (b) **Relative Test** - It can be performed as illustrated for IBI (see Section 4. B). In order to proof the accuracy of IBI in this application tests have been carried on, both with HPBC and FCBI, with connected as current divider.
respectively of $I_x$ and $I_t$ an auxiliary decade transformer (ADT). By ADT, it has been possible to change the apparent value of $r_x$ of 0.1% known within 0.1 ppm, one fifth of the one claimed for our IBI’s, to be proved. By HPBC during a relative test of the same PT used during the absolute test having $r_x = 800$ this imposed variation of $r_x$ has been detected at $V' = 20$ kV, namely with the lower sensitivity of the test. The results were within the linearity of 0.5 ppm with which $\rho_c$ has been known.

- (b) Absolute and relative tests of CT’s by FCBI - A prototype of an FCBI has been developed, see the photo in Fig. 5. CT’s having $r_x$ ranging from 1 to 23000/5 have been tested. In order to proof the accuracy of FCBI in the test of CT’s, both an absolute and relative test of CT’s was performed on a CT of class 0.1%, having $r_x = 23000/5$ at a primary current ≅ 4 kA and burden ≅ 150 VA cos $\phi = 0.8$. With connected as illustrated in Section 7. (b) at its secondary an ADT. By means of the absolute and relative test it was possible to detect the fictitious imposed variation of $r_x$, by ADT, within an uncertainty equal to that of 0.5 ppm with which $\rho_c$ was known. Finally a test was carried on which has involved the absolute and relative test of CT’s. Two CT’s, $T_x$ and $T_2$, having ratio $r_x = 23000/5$ were submitted, with the same components of FCBI; to an absolute test then on $T_x$, a relative test was carried on by assuming $T_2$ as standard. The difference of the ratio $\eta_x/\eta_t$ obtained in the absolute and relative tests, at a primary current ≅ 4 kA has been within the same uncertainty of 0.5 ppm with which $\rho_c$ was known. These test results have demonstrated the accuracy and utility of FCBI in the tests of high precision CT’s and validates its utility in factory tests of CT’s at very high primary current.

- (c). Voltage Dependent Capacitance Variations of Compressed-Gas Capacitor This application has been earlier developed [6]. The same uncertainty of 0.5 ppm has been achieved.

XI. Conclusions

The developed bridges by the use of an instrument transformer allows to supply the reference standard ($\tilde{S}$) at its secondary low rating and extends the bridges' range without extending the dynamic range of both $\tilde{S}$ and decade ratio transformer. Thus the illustrated bridges undeniably appears innovative of the, at present, used ratio transformer bridge technique that in the illustrated form could find wider use. The uncertainty of 0.5 ppm, of the used ratio transformer has been achieved in the absolute and relative test of both voltage and current transformers by experimental bridges and may be extended to a frequency of 10-20 kHz. Thus they appear highly useful to respond to the necessity of determining if the existing instrument transformers are usable for harmonic measurements, at present, required.

References