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

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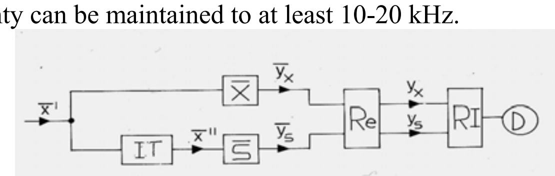
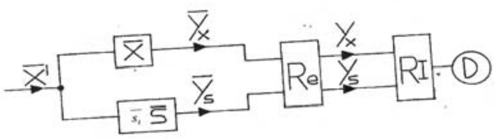
Abstract - The modern development of electric power systems is increasingly demanding for high improvements in the accuracy of metering and testing methods in both HV and high current, namely, in testing the instrument transformers. The necessity of determining if the existing instrument transformers 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 ($\overline{S}$) at its secondary low rating and extends the bridges' range without extending the dynamic range of both $\overline{S}$ 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 ($\overline{S}$) at its secondary low rating and extends the bridges' range without extending the dynamic range of both $\overline{S}$ 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.



(a)



b)

Fig. 1. Block diagram of the basic (a) and equivalent (b) circuit of IBI. D is the null detector. IT is the instrument transformer. $\overline{X}$ and $\overline{S}$ are the unknown and standard components. *R,* and RI are respectively, the re-phasing component and the ratio inductive detector in zeroing, $\overline{s_t}$ 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. - $\overline{X}$ and $\overline{S}$ are respectively supplied with the primary and secondary quantities, $\overline{x'}$ and $\overline{x''}$ of IT; - The output quantities - $\overline{y_x}$ and $\overline{y_s}$ are passed through the re-phasing block R_e its outputs - y_x and y_s in phase, are entered RI having adjustable ratio, ρ. ρ of RI, and ±ΔΦ by R_e balance IBI. At balance, $\rho = \frac{y_x}{y_s}$. In *the ideal case* ($\overline{X}$, $\overline{S}$, pure and similar elements, no error neither quantity absorbed by RI and R_e) is, $X=\rho s_t S$. Where s_t is the inverse of the nominal ratio r_t of IT ($\overline{s_t} = \frac{\overline{x''}}{\overline{x'}} = \frac{1}{r_t}$, $\overline{s_t} = \frac{(1+\eta_t)}{r_t e^{j\varepsilon_t}}$), η_t is the ratio error and ε_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 $\overline{s_t}\,\overline{S}$ substitutes IT and $\overline{S}$ in Fig. 1 (a). At balance is,

$$\overline{X} = \rho \overline{s_t}\,\overline{S} \qquad (1)$$

$$X=\rho s_t S \qquad (2)$$

$$\Phi_x=\Phi_s+\varepsilon_t \pm\Delta\Phi \qquad (3)$$

$$\eta_t = \frac{r_t X}{\rho S} - 1 \qquad (4)$$

$$\varepsilon_t = \Phi_x - \Phi_s \pm \Delta\Phi \qquad (5)$$

III. Accuracy

Is: $X \propto \rho s_t S$. ρ can be calibrated almost without any uncertainty and s_t determined within 0.5 to a few ppm. To obtain $\frac{X}{S}$, s_t, η_t, and Φ_x, and ε_t as function of ρ Φ_s and $\Delta\phi$ 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_t and x' maintain the same values as in the first balance. If: ρ and $\Delta\phi$, ρ' and $\Delta\Phi'$ are the first and second balance values is,

$$\frac{X}{S} = \sqrt{\frac{\rho}{\rho'}} \text{ and } s_t = \sqrt{\frac{1}{\rho\rho'}} \quad (6),$$

$$\eta_t = r_t \sqrt{\frac{1}{\rho\rho'}} - 1 \quad (7),$$

$$\Phi_x = \Phi_s + \frac{1}{2}(\Delta\Phi - \Delta\Phi'); \ \varepsilon_t = -\frac{1}{2}\,\Delta\Phi+\Delta\Phi') \quad (8).$$

By the interchange method the uncertainty of IBI nearly equals that with which the ratio ρ is known.

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, IT_X; - $\overline{X}$ and $\overline{S}$ are similar nearly pure components η_x and ε_x 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, IT_x, replaces $\overline{X}$; IT_x supplies with its output $\overline{x''_x}$ an $\overline{S'}$ like $\overline{S}$. IT_x and IT are supplied with the same x' and $\overline{S'}$ and $\overline{S}$ respectively with their secondary outputs $\overline{x}''_x$ and $\overline{x''}$. The connections of $\overline{X}$ with R_e illustrated in Fig. 1 are replaced by that of $\overline{S'}$. With: $\overline{X} = \overline{s}_x \overline{S}$, $X=s_xS'$ and, $\Phi_x=\Phi'_s+\varepsilon_x$ from (4) and (5)

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

and $\varepsilon_x = \varepsilon_t + \Phi_s - \Phi'_s \pm \Delta\Phi$ (10).

By the interchange method with, (i) interchanged $\overline{S'}$ and $\overline{S}$; (ii) constant x', r_x, and r_t, is,

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

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

- *Uncertainty* **-** The Uncertainty of IBI in testing IT's appears from (11) and 12). η_x and ε_x can nearly be determined with the same uncertainty with which ρ, s_t or η_t and ε_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 $\rho_c = N_s/N_x$. IT is a potential transformer (PT), T_p, $\overline{Y_x}$ and $\overline{Y_s}$ 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. ρ_c and G balance HPBC. If $\overline{Y_x}$ and $\overline{Y_s}$ are represented by their equivalent parallel parameters at balance is,

$$B_x = \rho_c s_p B_s \quad (13);$$

$$\Phi_x = act\frac{B_s}{(G_S + G)} \text{ or } \Phi_x = act\frac{B_s}{G} \quad (14)$$

$$\text{where, } +\Delta\Phi = act\frac{\rho_c B_s}{G} \quad (15)$$

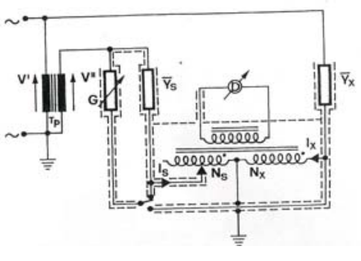
$$G_x = \rho_c s_p (G_s + G) \text{ or } G_X = s_p(\rho_c G_s - G) \quad (16)$$

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

$$G_x \; \varepsilon_p = \Phi'_x - \Phi'_s \pm \Delta\Phi \quad (18)$$

$$G_x \text{ or } \Phi_x = act\,\rho_c B_s/(\rho_c G_s - G) \quad (19)$$

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



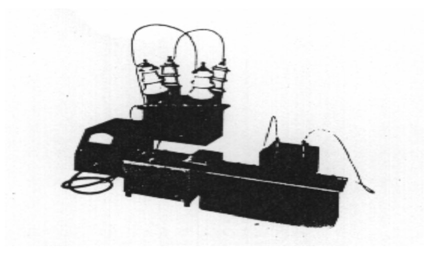


Fig. 2. Circuit of HPBC. Fig. 3 Photo of an experimental HPBC.

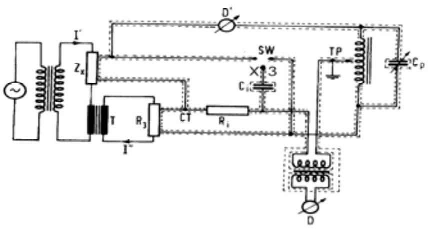


FIG. 4. Circuit of FCBI

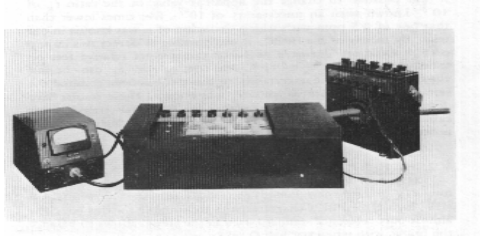


Fig. 5 Photo of an experimental FCBI.

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 $\overline{Z}_x$ and $\overline{Z}_z$ 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_s 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 Ri to the switch; SW. C_i is used to draw a small amount of current through Ri, 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 shortened. ρ_v and C_i balance FCBI. The equilibrium conditions under the assumption that $\overline{Z}_x$ and $\overline{Z}_s$ are, $Z_x=s_s R_s$, $\Phi_x=\Phi'_s+\varepsilon_t \pm \Delta\Phi_v$, and $Z_s=s_t R_s$, $\Phi_s=\Phi''_s+\varepsilon_t \pm\Delta\Phi_v$, where, $\Delta\Phi_v=\omega R_i C_i$, at balance is,

$$\eta_t = \frac{r_t Z_x}{\rho_v Z_X} - 1 \quad (21); \text{ and } \varepsilon_t = \Phi_x - (\Phi_s \pm \Delta\Phi_v) \quad (22).$$

- *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 lay-out 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-retum 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 $\overline{S}$ 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 $\overline{S}$ 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, CT_x - $\overline{Z_x}$ and $\overline{Z_s}$ are a nearly pure shunt S_r and resistance standard R_s. η_x and □X are evaluated with (21), (22). By this procedure η_x is a function of S_r/R_s. By the *interchange method* with (i) interchanged S_r and R_s (ii) constant I' and r_x. η_t and ε_t are as in (11), (12).

B. Relative test

In this application, the procedure is that illustrated in Section 4. B. - $IT_x = T_x$ is the under test CT, CT_x – IT = T is an accurate CT standard (it may be $r_t \neq r_X$) $S=R_s$ and $S'=R'_s$ are two nearly pure resistance standard. With $Z_x = s_x R'_s$, $\Phi_x = \Phi'_s + \varepsilon_x$, $Z_s = s_t R_s$ and, $\Phi_s = \Phi''_s + \varepsilon_t$ from (21), (22) is,

$$\eta_x = r_x \frac{\rho_v s_t^2 R_s}{R_s^{'}} - 1 \quad (23); \quad \varepsilon_x = 2\varepsilon_t + \Phi_s - \Phi'_s \pm \Delta\Phi_v \quad (24).$$

By the *interchange method* with (i) interchanged R'_S and R_s; (ii) constant I', r_x , and r_t , η_x and ε_x have the values by (7) and (8).

X. Proof of the Clamed 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_t or η_t and ε_t. 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 ρ 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 dependent capacitance variations of compressed-gas capacitor [6] power 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 trans-former [8]. Its primary winding was in 4 sections each of ratio $r_p = 200$. The interlaboratory calibration was made, by a resistive voltage divider, while its high voltage windings were connected in parallel and, at NBS; the result was compared, by an absolute electrometer [9], while the four sections were series connected obtaining a nearly exact correspondence. The interlaboratory calibration results were within a band of ± 10 ppm with data resolution of 5 ppm. Our test has been carried on (as illustrated in Section 4. A) at, 60 kV and r_p=800. As C_x and C_s have been respectively used, a sphere gap (25 cm diameter) and 0.1 and a 0.1 μF TETTEX capacitance standard (in a double-walled sealed gap container standard form with in the inter-wall a thermal shield) have been used. Firstly the ratio $\rho'_c = C_X/C_S$ has been detected by the current comparator of HPBC with C_x and C_s, parallel supplied at 500 V. Secondly HPBC has been balanced at V′=60 kV; from the obtained values ρc' and ρc", $\eta_x = r_p \rho c'/\rho c'' - 1$. The difference between the detected η_x and the one from the interlaboratory test results has been within the resolution of the interlaboratory data namely, 5 ppm. This result allows one to conclude the HPBC satisfies the requirements of this application. High accuracy is generally attained at the cost of increased time and effort. There is the necessity for combining accuracy with the simplicity that makes for reliability. The *reliability* by HPBC is proved by comparing, the absolute test procedure of PT's by HPBC and the achieved uncertainty (0.5 ppm) with the outlined method used at NBS.

- (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 $\overline{I_x}$ and I'' 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 us-ed 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 ρ_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 cosφ=08̃. 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 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, 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 as standard. The difference of the ratio η_x/η_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 ρ_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 ($\overline{S}$) at its secondary low rating and extends the bridges' range without extending the dynamic range of both $\overline{S}$ 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.

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