Instrument Transformer Performance Under Distorted Conditions

G. Mahesh, Boby George, V. Jayashankar and V. Jagadeesh Kumar.

Abstract-- **Current Transformers (CT) and Voltage Transformers (VT) are the primary sensing elements in electric power systems. While their performance at a single frequency is well known, it is necessary to analyze the performance of CTs and VTs for harmonic excitation. A single virtual instrument that can be used for performance measurements of Instrument Transformers (IT) in addition to analyzing the magnetic characteristics of cores is proposed. Experimental results are shown to validate the proposed method.**

Index Terms-- **Instrument transformers, Network harmonics, virtual instrument.**

I. Introduction

ELECTROMAGNETIC current transformers and voltage transformers are constructed in the main using ferromagnetic materials in toroidal form and stacked laminations respectively. The performances of such Instrument Transformers are specified in Standards such as IEC-60185 and IEC-60186. These specifications seek conformance of ratio and phase errors at various values of primary excitation and burdens. Typically the performance is sought at a single frequency, viz, the power frequency. It is known that the errors depend mainly on the watt loss and magnetic components of the material used for construction. Procedures are known for the estimation of errors of CTs using single or composite cores [1]. With the proliferation of networks that contain significant voltage and current harmonics it would be instructive to analyze the performance of the ITs with non-sinusoidal excitation. Saturation of the core also causes significant harmonics in the secondary [2], [3]. We initially show that conventional transformer bridges or Instrument Transformer Test Sets (ITTS) can be used for characterizing the magnetic properties of cores. We then devise an instrument for performance analysis of instrument transformers under distorted conditions.

G. Mahesh is with SAMEER Centre for Electromagnetics, Chennai, 600113, India. (e-mail: mahesh@sameer.org.in).

Boby George is with the Electrical Engineering Department, Indian Institute of Technology Madras, Chennai, 600 036, India. (e-mail: ee03d001@ee.iitm.ernet.in).

V. Jayashankar is with the Electrical Engineering Department, Indian Institute of Technology Madras, Chennai, 600 036, India. (e-mail: jshankar@ee.iitm.ernet.in).

V. Jagadeesh Kumar is with the Electrical Engineering Department, Indian Institute of Technology Madras, Chennai, 600 036, India. (e-mail: vjk@ee.iitm.ernet.in).

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II. Preliminary Observations

The Ratio Error (RE) & Phase Error (PE) of a CT at x% of the rated primary current are given by [4].

$$\%RE = -100\left(\frac{I_m \sin\delta + I_w \cos\delta}{x I_{sn}}\right) \quad (1)$$

$$PE \approx \tan^{-1}\left(\frac{I_m \cos\delta - I_w \sin\delta}{x I_{sn}}\right) \times 3438 \text{ min} \quad (2)$$

where

I_m is the magnetizing component of exciting current,
I_w is the watt loss component of exciting current,
δ is the secondary power factor angle,
I_{sn} is the rated secondary current.

These errors are usually measured using an ITTS. The expressions above show that the errors of the CT are intrinsically due to the magnetic characteristics of the cores used. In effect, the errors of the CT quintessentially reflect the behavior of the core. If the load is intentionally kept at unity power factor, it follows that

$$I_w = \frac{x I_{sn} RE}{-100} \quad (3)$$

$$I_m = \frac{x I_{sn} PE}{3438} \quad (4)$$

This implies that the measurement of RE and PE in a transformer test bridge can enable a determination of I_m and I_w. If the dimensions of the core are available, magnetizing ampere turns $H_m = \frac{N I_m}{l}$ A/m and watt loss ampere turns $H_w = \frac{N I_w}{l}$ A/m can be evaluated, where l is the mean length of the magnetic path and N is the number of secondary turns. The flux density can be measured from the voltage across an auxiliary coil in the same core. If the range of secondary currents and burdens are chosen appropriately the ITTS can be used for characterizing the complete B-H curve of the core material.

III. A Virtual Instrument For The Performance Analysis OF IT

Conventional transformer bridges evaluate the performance of a CT at a single frequency, as standards require only such characterization. The front ends [5], [6] of such ITTS usually involve a Phase Sensitive Detector (PSD). The features of the PSD that make it useful as a front end are that it has a very high signal to noise ratio and the fundamental component alone can be extracted. The PSD in [5] and [6] is implemented using analog electronics. With the advent of fast A/D converters it can also be implemented using digital principles. The block diagram of a PSD is shown in Fig.1. The input signal $A_m\cos(\omega t+\phi)$ and the reference signal $B_m\cos\omega t$ are multiplied and the average value of this multiplied signal ($AB\cos\phi$) is the PSD output. The output will be ($AB\sin\phi$), if the reference is replaced by $B_m\cos(\omega t+90)$, where A_m and B_m are the maximum amplitudes of the signals, A and B are its root mean square values and ϕ is the phase difference.

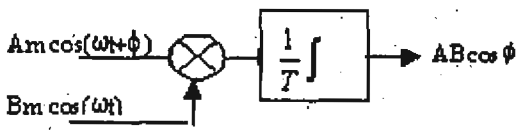

Fig. 1. Principle of the phase sensitive detection

We propose an extension of this instrument to characterize the performance at harmonic excitations. The block diagram of the extended PSD is shown in Fig.2.

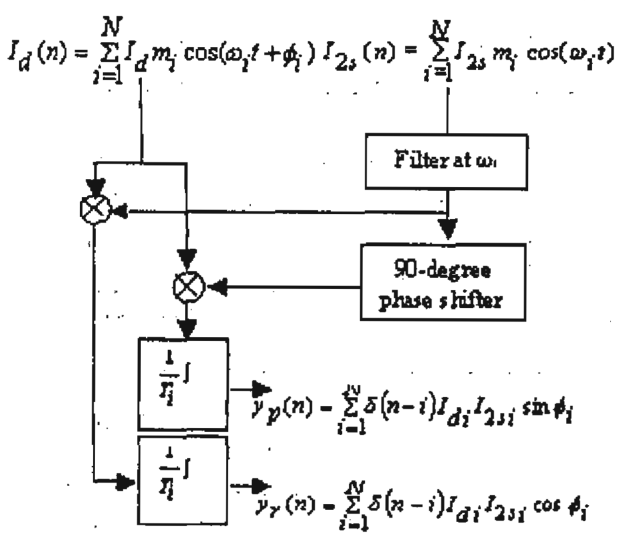

Fig. 2. Schematic of an extended PSD for error measurements.

The input excitation I_d and I_{2s} contains N number of harmonics, so 2N numbers of PSDs are required to obtain the ratio and phase errors.

A virtual instrument for evaluating the errors of an IT is designed on the following basis: The comparison method [5] is the principle of error measurement. The comparison method is the common technique employed for the determination of the ratio and phase errors of an instrument transformer. It involves the comparison of the test transformer with a standard transformer of the same ratio specifications with known, very low errors. The schematic of the setup for the Comparison method is shown in Fig.3. As can be seen, the primaries of the test current transformer X and the standard current transformer S are connected in series, so that the same current flows through them. The secondaries are so connected that the difference between the current in the secondary of S, I_{2s} and that of X, I_{2x} flows through a standard resistance, R_d. A similar arrangement can also be made for VTs but is not shown. For VTs the expressions relating to ratio and phase errors as computed using (5) and (6) are the same, one has to only replace current (I) by voltage (V).

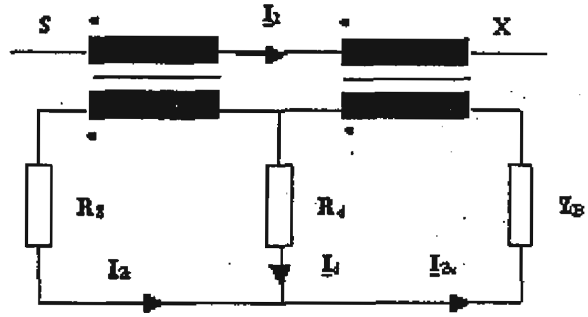

Fig. 3. The Comparison method of testing a CT

The input section of the test setup has isolating transformers to help to derive voltages proportional to I_{2s} and I_d and compatible with the Data Acquisition System (DAS). A 12-bit Data Acquisition Card (PCI 6024 E) from National Instruments [7] forms the heart of the Data Acquisition System. The two channels are simultaneously sampled at 10 kHz, which is sufficient for a system with about 40 harmonics of a 50 Hz power frequency. If I_{2sj} and I_{dj} represent the acquired samples of I_{2s} and I_d respectively, then sampling based methods are used to evaluate the errors of the CT as follows [8].

$$\%RE = \frac{\sum_{j=0}^{N-1} I_{2sj} I_{dj}}{\sum_{j=0}^{N-1} I_{2sj} I_{2sj}} \times 100 \tag{5}$$

$$PE = \frac{\sum_{j=0}^{N-1} I_{2s(j+N/4)} I_{dj}}{\sum_{j=0}^{N-1} I_{2sj} I_{2sj}} \times 3438 \min \tag{6}$$

This method is being extended to the case with harmonic excitation. Here we consider that

$$I_p = \sum_{i=1}^{N} A_i \sin(\omega_i t + \phi_i) \qquad (7)$$

$$I_{2s} = \sum_{i=1}^{N} a_i \cos(\omega_i t + \phi_j) \qquad (8)$$

where I_p is the primary current and I_{2s} is the secondary current of the test CT .

For example, if the fundamental and first two odd harmonics are known to exist, a Low Pass Filter (LPF) and two Band Pass Filters (BPF) are used, to extract the fundamental, third and fifth harmonics. The LPF cut-off frequency is just above the fundamental frequency whereas the BPFs are centered at each harmonic. These filters are implemented digitally in the virtual instrument. The error components of the individual harmonics are evaluated as follows:

$$\% \mathrm{RE}\,|\,\omega_i = \frac{\sum_{j=0}^{N-1} I_{2sj} I_{dj}}{\sum_{j=0}^{N-1} I_{2sj} I_{2sj}} \times 100 \qquad (9)$$

$$PE\,|\,\omega_i = \frac{\sum_{j=0}^{N-1} I_{2s(j+N/4)} I_{dj}}{\sum_{j=0}^{N-1} I_{2sj} I_{2sj}} \times 3438 \text{ min} \qquad (10)$$

One problem with the measurement of errors of each frequency is the possibility of interharmonics, especially if the core goes into saturation. In order to check for this condition, the composite error (CE) is also evaluated as given in equation (11).

$$CE = \frac{\sqrt{\sum_{j=0}^{N-1} I_{dj}^2}}{\sqrt{\sum_{j=0}^{N-1} I_{2sj}^2}} \qquad (11)$$

If the composite error exceeds the vector error, ie if

$$CE > 1.05\sqrt{(RE)^2 + (PE)^2} \ ,$$

the CT is in saturation. The value 1.05 is a conservative value based on the standard definition of composite error exceeding 10% to be indicative of saturation. One of the advantages of this instrument is that even at a single frequency excitation, the composite error will also be measured and displayed. Existing instruments do not have this feature, which makes it difficult to judge if the CT is saturated or not. Using the ratio and phase errors of the fundamental component, the core would then become non-linear and interharmonics are likely to occur.

IV. Experimental Results

A 100mA/100mA CT is designed with core of size 90mm x 60mm x 20mm of PERMAX from Vacuumschmelze. It has 100 primary and secondary turns and tapings every 25 turns for different turns ratio. An Arbitrary Function Generator Model 33120A from Hewlett Packard is programmed to give an excitation of the form given below:

$$I_1 \sin(2\pi 50t) + 0.33 I_1 \sin(2\pi 150t) + 0.2 I_1 \sin(2\pi 250t)$$

(These are the first three harmonics of a square wave with I_1 as the fundamental). The errors of the CT under harmonic excitation are measured using the proposed virtual instrument.

Table 1 shows the ratio and phase errors for each frequency at different percentages of full primary current rating. This would enable one to fix the maximum value of each harmonic current to 100%. From this result the I_w and I_m are computed using (3) and (4) and subsequently corresponding H_w and H_m values are obtained The B-H_w and B-H_m curves of the core at each frequency are shown in Fig. 4 and Fig. 5 respectively. H_m and H_w are the magnetizing and core loss components of the exciting ampere-turns.

TABLE I
ERRORS OF CT UNDER HARMONIC EXCITATION MEASURED USING A VIRTUAL INSTRUMENT

% Im	%RE at 50 Hz	%RE at 150 Hz	%RE at 250 Hz	PE (min) at 50 Hz	PE (min) at 150 Hz	PE (min) at 250 Hz	% CE
20	-1.09	-0.40	-0.29	50.97	42.71	39.10	2.11
50	-0.83	-0.38	-0.25	38.53	30.63	27.59	1.42
80	-0.69	-0.35	-0.19	32.49	22.4	19.74	1.15
90	-0.67	-0.33	-0.18	30.81	20.78	17.57	1.09
100	-0.65	-0.31	-0.17	29.92	19.53	16.25	1.06

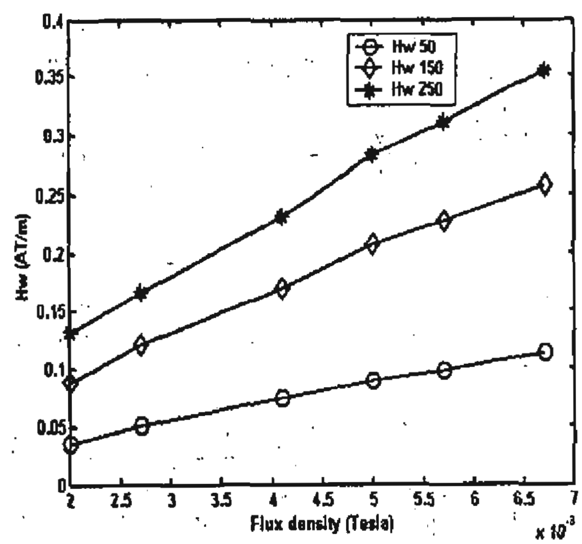

Fig. 4. B-Hw characteristic of core at 50, 150 and 250 Hz magnetization.

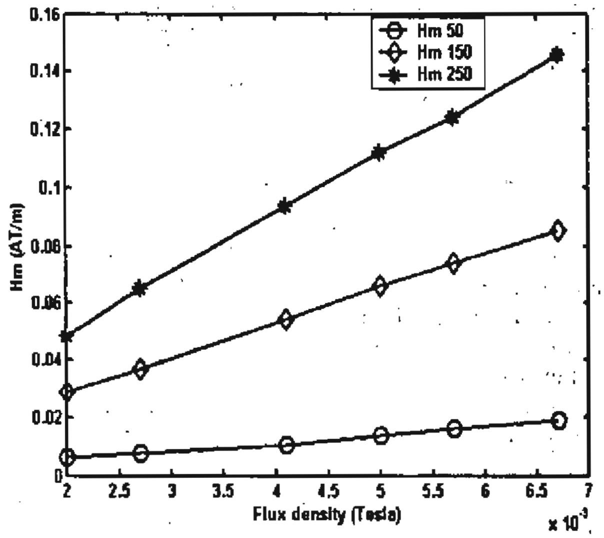

Fig. 5. B-Hm curve of core at 50, 150 and 250 Hz magnetization.

V. Conclusion

The behavior of an instrument transformer under distorted conditions can be predicted if the magnetic characteristics of the core at all frequencies are known. A convenient virtual instrument has been developed that serves the functions of measuring errors at harmonic frequencies as well as characterizing the cores. Experimental results on a core show the utility of the proposed scheme.

VI. Appendix

The front panel of the developed instrument is shown in Fig.A1.It has three sections. The top right portion shows the time domain signal of I_d & I_{2s}. The top left portion shows the frequency domain component of I_{2s}. The setting parameters are sampling rate and number of samples. A tabular column shows the errors in the third section.

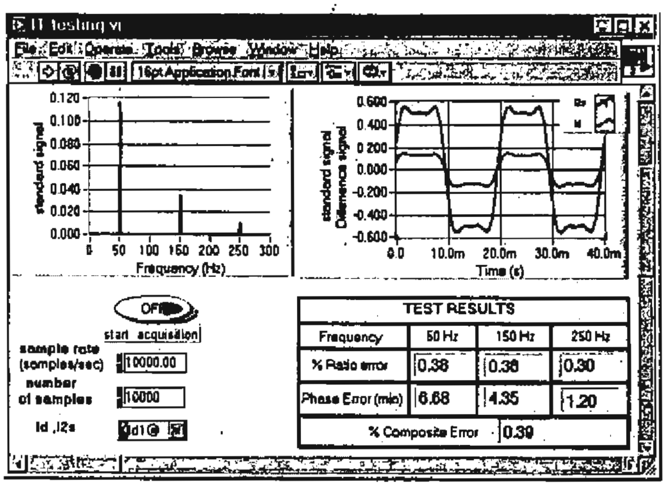

Fig. A1. Virtual Instrument front panel

VII. References

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