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CHARACTERIZING MAGNETIC MATERIALS USING VIRTUAL INSTRUMENTATION

G. Mahesh [1], *Boby George* [2], *V. Jayashankar* [3], *V. Jagadeesh Kumar* [3]

[1]SAMEER- Centre for Electromagnetics, Chennai - 600113, India.
[2]Institute of Electrical Measurement and Measurement Signal Processing,
Graz University of Technology, Graz-8010, Austria, bgeorge@tugraz.at.
[3]Dept. of Electrical Engineering, Indian Institute of Technology Madras, Chennai - 600036, India.

Abstract – A virtual instrumentation based scheme is developed for the characterization of magnetic materials. The principle used for measurement is derived from the comparison method of testing instrument transformers. A prototype has been developed by suitably modifying an instrument transformer test set. Characterization of magnetic materials at single frequency and multiple frequencies have been carried out. Typical test results obtained are presented in the paper. The developed instrument substantially reduces the testing time associated with magnetic characterization.

Keywords: Instrument transformers, magnetic measurement, watt-loss measurement.

1. INTRODUCTION

One of the largest users of magnetic materials in the form of laminations and toroidal cores is the electric power sector. Power transformers almost always use Si-steel laminations. Current transformers (CTs) are unique in that the magnetic structure is usually of a toroidal form. Depending on the application, CTs use high permeability Ni – Fe or Si – steel cores. Often, composite cores [1] are employed. Designers of CTs require the magnetic characteristics of core in the form of watt-loss and magnetizing ampere turns as a function of the flux density. Instruments with both sinusoidal B and H [2], [3] are available for performing such measurements. In the recent years, the advent of significant power electronic switching devices has meant that the voltage and current waveforms in the power network are not of a single frequency and contain significant harmonics. An instrument transformer test set for meeting this need has been designed [4]. It then becomes necessary to characterize the magnetic materials as a function of frequency. We develop a Virtual Instrumentation (VI) based scheme for this purpose. The new scheme uses a modified Instrument Transformer Test Set (ITTS) for the characterization of magnetic materials. The proposed method also shows a new application for the ITTS, with certain modifications, as an instrument for the characterization of magnetic materials.

2. PRINCIPLE OF MAGNETIC CHARACTERIZATION USING AN INSTRUMENT TRANSFORMER TEST SET

The Ratio Error (RE) and Phase Error (PE) in a CT are principally due to the excitation characteristic of the core and it is known [5] that

$$\%RE = -100\left(\frac{I_m \sin\delta + I_w \cos\delta}{I_{2S}}\right) \tag{1}$$

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

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 and $I_{2\text{S}}$ is the secondary current.

If the load is intentionally made to be unity power factor, equations (1) and (2) results in equations (3) and (4).

$$I_w = \frac{I_{2S}\times RE}{-100} \tag{3}$$

$$I_m = \frac{I_{2S}\times PE}{3438} \tag{4}$$

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

$$H_m = \frac{N_S I_m}{l}\ \text{A/m} \tag{5}$$

and watt loss ampere turns

$$H_w = \frac{N_S I_w}{l}\ \text{A/m} \tag{6}$$

can be evaluated, where l is the mean length of the magnetic path and N_S is the number of secondary turns. If the range of secondary currents and burdens are chosen appropriately the instrument transformer test set can be used for characterizing the performance of the core material. The principal advantage of this method is that the result is in a form, which is directly useful for the CT design [1].

3. A VIRTUAL INSTRUMENTATION SCHEME FOR MEASUREMENT OF ERRORS

A virtual instrument for evaluating the RE and PE of a CT using LabVIEW is developed. The principle of error measurement is based on the comparison method [6], [7]. The schematic of the setup for the comparison method is shown in Fig.1. 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, $\underline{I}_{2S}$ and that of *X*, $\underline{I}_{2X}$ flows through a standard resistance R_d. $\underline{I}_d$ represents the difference current ($\underline{I}_{2X}$ - $\underline{I}_{2S}$), θ the phase difference between $\underline{I}_d$ and $\underline{I}_{2S}$ and R_b the resistance of the burden. The phasor diagram of comparison method of testing a CT is shown in Fig.2.

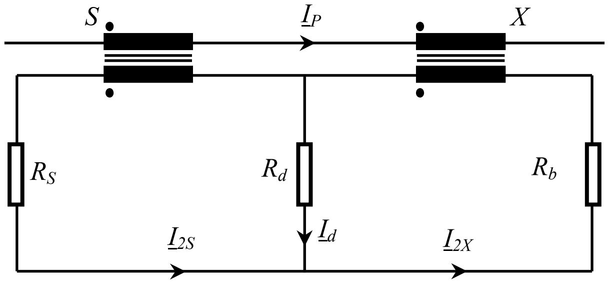

Fig. 1. The comparison method of testing a CT

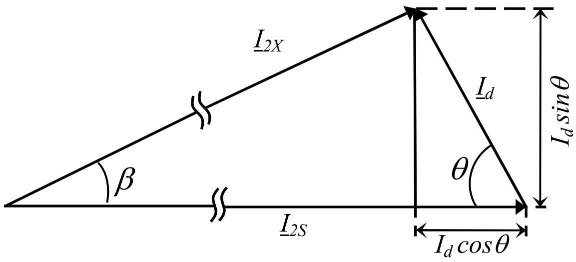

Fig. 2. The Phasor Diagram for comparison method of testing a CT

A 12-bit Data Acquisition Card (PCI 6024 E) from National Instruments [8] forms the heart of the Data Acquisition System (DAS). The input signals, proportional to standard current $\underline{I}_{2S}$ and difference current $\underline{I}_d$, are brought to the two BNC analog input connectors. A programmable gain amplifier is used to amplify the signal to appropriate values. The two channels were simultaneously sampled at 10 kHz, which is sufficient for a system with about 40 harmonics of a 50 Hz power frequency. The data acquisition VI essentially samples the inputs and stores them in an array. If I_{2sj} and I_{dj} represent the acquired samples of $\underline{I}_{2S}$ and $\underline{I}_d$ respectively, then sampling based methods [9] are used to evaluate the errors of the CT as follows:

$$\%RE = \frac{\sum_{j=0}^{N-1} I_{2S\,j} \times I_{d\,j}}{\sum_{j=0}^{N-1} I_{2Sj} \times I_{2Sj}} \times 100 \tag{7}$$

$$PE = \frac{\sum_{j=0}^{N-1} I_{2S[j+N/4]} \times I_{d\,j}}{\sum_{j=0}^{N-1} I_{2Sj} \times I_{2Sj}} \times 3438 \tag{8}$$

Where *N* is the number of samples acquired per cycle. Since the *RE* and *PE* at individual frequencies and dimensions of the core are known, using eqn (3) & (4) I_w and I_m and thus H_w & H_m at individual frequencies can be easily computed for various levels of flux densities.

4. EXPERIMENTAL SET-UP FOR MEASUREMENT AT SINGLE FREQUENCY

A 100/100mA CT is designed with core of size 90mm x 60mm x 20mm of PERMAX from Vacuumschmelze. It has 100 primary and secondary turns. An Arbitrary Function Generator Model 33120A from Hewlett Packard is used to excite the primary of the test and standard CTs. A burden of $R_b = 5\ \Omega$ was connected to the secondary of test CT. *RE* and *PE* measurements and thus the H_w and H_m at individual frequencies were computed using the virtual instrumentation scheme explained in previous section.

5. CHARACTERISATION OF MAGNETIC MATERIALS AT CONSTANT FLUX DENSITY

The method discussed in previous section is valid for single frequency excitation. An alternative viewpoint, which is likely to be more useful to the designer, is to consider error measurement at constant flux operation.

From the basic transformer equation for a sinusoidal input, we know that

$$V_{2s} = 4.44 f N_s A\, B_m s \tag{9}$$

where V_{2s} = secondary induced e.m.f (V), B_m= peak flux density (Wb/m^2), f = frequency(Hz), N_s = No. of secondary turns, A =cross sectional area of core (m^2) and s = space factor As f, N_s, A and s are constants, from equation (9) it can be seen that $V_{2s} \propto B_m$. So, in order to perform measurement at constant flux density, the excitation is varied such that the flux at each frequency is the same. i.e.,

$$\frac{v_1}{f_1} = \frac{v_2}{f_2} = \frac{v_n}{f_n} etc$$

where v_1 is the magnitude of voltage at frequency f_1, $v_2 = 2v_1, \ldots, v_n = nv_1; f_2 = 2f_1$ & $f_n = nf_1$ etc. A stepped sine wave is used for excitation. The data acquisition is modified so that error component proportional to each frequency (ωi) is calculated separately, (i.e)

$$\%RE\Big|_{\omega i} = \frac{\sum_{j=0}^{N-1} I_{2S\,j(\omega i)} \times I_{d\,j(\omega i)}}{\sum_{j=0}^{N-1} I_{2Sj(\omega i)} \times I_{2Sj(\omega i)}} \times 100 \qquad (10)$$

$$PE\Big|_{\omega i} = \frac{\sum_{j=0}^{N-1} I_{2S[j(\omega i)+N(\omega i)/4]} \times I_{d\,j(\omega i)}}{\sum_{j=0}^{N-1} I_{2Sj(\omega i)} \times I_{2Sj(\omega i)}} \times 3438 \text{ min} \qquad (11)$$

Once the RE and PE for a frequency (ωi) is known, H_w and H_m for that frequency can be computed as explained in section 3. Since a stepped sine wave excitation is employed, the H_w & H_m for multiple frequencies are obtained in a single measurement cycle rather than repeating the measurement for each frequency of interest. This achieves a reduction in measurement time for characterizing the magnetic material for multiple frequencies. The details of the experimental set-up, excitation pattern and test results are given in the next section.

6. EXPERIMENTAL SET-UP AND RESULTS FOR MEASUREMENTS AT CONSTANT FLUX DENSITY

The CT explained in section IV is used for measurement. An Arbitrary Function Generator Model 33120A from Hewlett Packard is programmed to give an excitation of the form given below

$\sqrt{2}I_P \sin(2\pi 50t)$ for $t = 0$ to 1s,

$3\sqrt{2}I_P \sin(2\pi 150t)$ for $t = 1$ to 2s and

$5\sqrt{2}I_P \sin(2\pi 250t)$ for $t = 2$ to 3s.

A burden of $R_b = 5.0\ \Omega$ was connected to the secondary of test CT. The ratio and phase errors of the CT under this stepped sine wave excitation are measured using the developed virtual instrument. *RE* and *PE* measurements and thus the H_w and H_m at individual frequencies were computed using the modified VI scheme which enables determination of magnetic characteristics at various excitation frequencies in a single shot measurement. Fig 3 and Fig. 4. show the B Vs H_m and B Vs H_w characteristics for the stepped sine wave excitation.

The results on the stepped sine measurements using the developed instrument have compared with those performed individually at single frequency computed based on sampling based measurements using equations (3) to (8). The comparison of the results is given in table 1 for the H_m and table 2 for *Hw*.

H_m(I) and H_w(I) denotes the values obtained from measurements at single frequencies and H_m(M) and H_w(M) are the results on the stepped sine wave measurement for multiple frequencies. The results were also compared with a watt-loss measurement. These results show the efficacy of the proposed method.

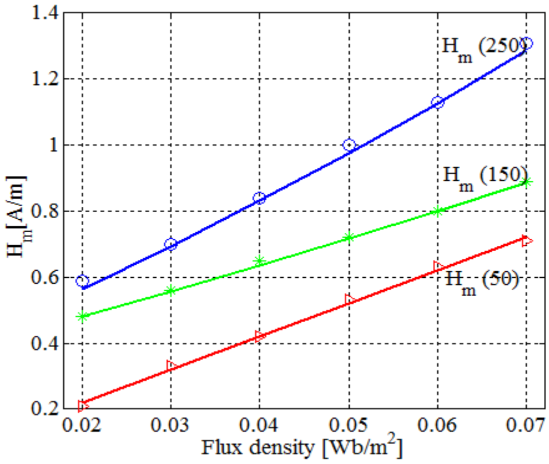

Fig. 3. Magnetizing ampere turns (H_m) observed for different flux densities (B) of the core during stepped sine wave excitation. The core was excited with the fundamental frequency at 50 Hz and its 3rd and 5th harmonics consecutively.

Table 1. Comparison of stepped sine wave measurement of H_m with single frequency measurement. $H_m(M)$ indicates the result for a stepped sine wave excitation while $H_m(I)$ shows the values obtained from single frequency measurement on the same core.

Flux Density B (Wb/m^2)	FREQUENCY OF EXCITATION								
	50Hz			150Hz			250Hz		
	H_m (M)	H_m (I)	% Error	H_m (M)	H_m (I)	% Error	H_m (M)	H_m (I)	% Error
0.02	0.21	0.21	0	0.48	0.48	0	0.59	0.60	-1.6
0.03	0.33	0.33	0	0.56	0.56	0	0.70	0.71	-1.4
0.04	0.42	0.43	-2.3	0.65	0.65	0	0.84	0.83	1.2
0.05	0.53	0.52	-1.9	0.71	0.72	-1.38	1.00	0.99	1.0
0.06	0.63	0.62	-1.6	0.80	0.80	0	1.13	1.14	-0.88
0.07	0.71	0.71	0	0.89	0.89	0	1.31	1.30	0.77

Table 2. Comparison of stepped sine wave measurement of H_w with single frequency measurement. $H_w(M)$ indicates the result for a stepped sine wave excitation while $H_w(I)$ shows the values obtained from a single frequency measurement.

Flux Density B (Wb/m^2)	FREQUENCY OF EXCITATION								
	50Hz			150Hz			250Hz		
	H_w (M)	H_w (I)	% Error	H_w (M)	H_w (I)	% Error	H_w (M)	H_w (I)	% Error
0.02	0.38	0.39	-2.5	0.52	0.51	1.9	0.70	0.71	-1.4
0.03	0.48	0.47	2.1	0.61	0.60	1.7	0.82	0.83	-1.2
0.04	0.55	0.55	0	0.67	0.68	-1.5	1.00	0.98	2.0
0.05	0.63	0.64	-1.5	0.75	0.76	-1.3	1.19	1.18	0.8
0.06	0.75	0.74	1.4	0.85	0.85	0	1.38	1.41	-2.1
0.07	0.83	0.82	1.2	0.92	0.93	-1.1	1.64	1.62	1.2

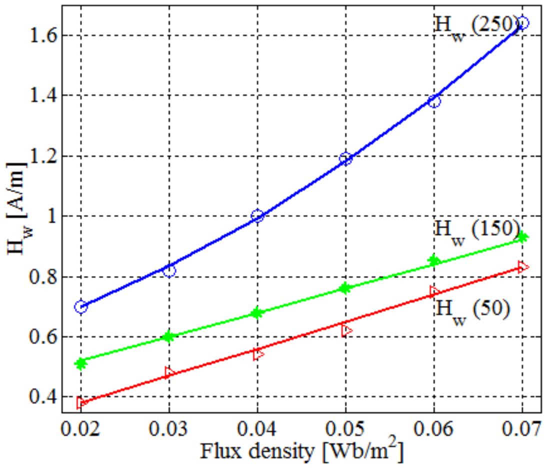

Fig. 4. Watt loss ampere turns (H_w) for different flux densities (B) for stepped sine wave excitation.

7. CONCLUSION

A virtual instrumentation scheme, which is based on comparison method of testing of Instrument transformers, is developed for characterizing magnetic materials as a function of frequency. The experimental results show the effectiveness of the scheme for characterization of magnetic materials. The stepped sine excitation substantially reduces the measurement time for characterizing the magnetic material for multiple frequencies.

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