Accurate Measurement of the Air-Core Inductance of Iron-Core Transformers With a Non-Ideal Low-Power Rectifier

Francisco de León, *Senior Member, IEEE*, Saeed Jazebi, *Student Member, IEEE*, and Ashkan Farazmand

Abstract—The air-core inductance of power transformers is measured using a nonideal low-power rectifier. Its dc output serves to drive the transformer into deep saturation, and its ripple provides low-amplitude variable excitation. The principal advantage of the proposed method is its simplicity. For validation, the experimental results are compared with 3-D finite-element simulations.

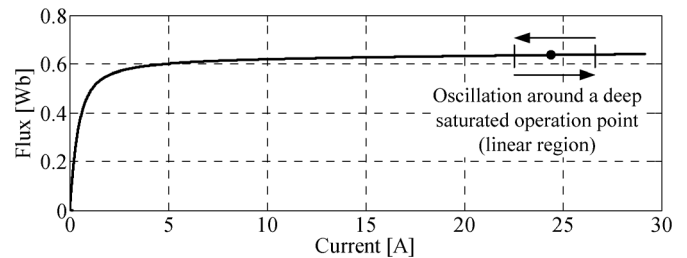*Index Terms*—Air-core inductance, core deep saturation, inrush currents, transformers.

Fig. 1. Positive part of the saturation curve and operation of transformer with a dc-biased ac excitation.

I. INTRODUCTION

TRANSFORMER energization may draw large inrush currents because the iron core could go into deep saturation. The most important factors that determine the magnitude of the inrush currents are: winding resistance, angle of energization, core residual flux, and the air-core inductance. Air-core inductance is the most important parameter needed for the accurate modeling of transformers involving deep saturation (e.g., inrush currents, ferroresonance, and geomagnetic-induced currents [1]). However, it is not easy to measure in the field or laboratory because a very large ac power source (more than 10 times larger than the transformer rating) is needed. This is so because high voltage is needed to push the core into saturation while it draws large currents when it saturates. In addition, the high voltage that is necessary to apply, may damage the windings and the interlamination insulation.

Methods to estimate the deep saturation characteristics of transformers have been proposed (in [2] and [3]) using recorded inrush voltage and current waveforms. In [4], a stepwise changing dc supply with a constant frequency is proposed. This method is regarded as a very low frequency ac excitation. The amplitude and frequency of the applied voltage are selected in such a way that the corresponding current reaches steady state before the voltage changes polarity. In [5], the magnetizing characteristics are measured based on the transient response of the transformer during energization with a dc source. In this method, the ripples of the voltage cause error and when the winding resistance changes with temperature and frequency, the accuracy of the method is reduced.

Reference [6] examined several methods for the determination of the magnetizing characteristics of electromagnetic devices. In [6], the application of an ac source with a dc bias was introduced to capture the entire hysteresis characteristics of a magnetic device. The hysteresis cycle was obtained as linear piece-wise sections applying the hybrid method repeatedly hundreds of times. The conclusion of [6] was that the application of the method of [4] (a stepping changing dc) was the most adequate.

In this paper, an improvement of [6] is proposed to measure the air-core inductance of transformers. The method relies on a nonideal rectifier with the appropriate test setup. Simple rectifiers naturally give a set of ac harmonics with a dc bias. The device is readily available and easy to implement. In fact, the natural ripple caused by the nonideal power converter is the key feature of our method.

Different from other methods in the literature, our method does not need demagnetization, zero crossing switching, or synchronization between measuring and switching devices; the experiment runs in steady state and is free from the uncertainties imposed by transients.

II. UNDERLYING THEORY AND LABORATORY EXPERIMENTS

A dc-biased ac source could be used to measure the air-core inductance. The dc component forces the transformer into saturation with a small voltage, while the ac component sweeps on the linear part of the magnetizing characteristic around the dc operating point (see Fig. 1). Alternatively, as proposed in this paper, a dc voltage source (obtained from a simple static uncontrolled rectifier) with ripple is appropriate.

Fig. 2 depicts the proposed test setup. The variable resistor R_v is added to control the current and to protect the source when testing transformers with small winding resistances. The primary ac current and the secondary ac voltage are measured. Note that the secondary voltage contains only ac components (valuable data for inductance measurements) and the dc component is filtered out. By measuring the voltage on the secondary side, in addition to capturing the incremental flux, the
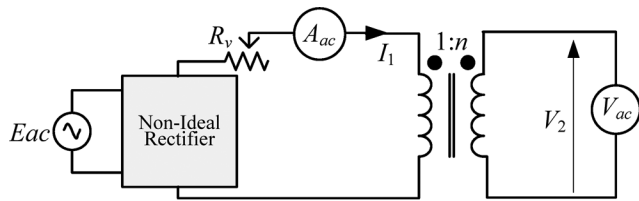
Fig. 2. Circuit diagram of the experimental setup.

Fig. 3. Current of the innermost winding and voltage of the inner winding of T1.

winding and the source resistances are eliminated from the calculations. Hence, possible discrepancies caused by variations in resistance, as in the method of [5], are avoided. The measured signals are usually polluted with electromagnetic noise and integration methods may cause large errors. Therefore, the fast Fourier transform (FFT) is used to obtain quantities to substitute in the following expression:

$$L_{\rm Air} = \frac{V_{2f}}{2\pi f \, n \, I_{1f}} \tag{1}$$

where $L_{\rm Air}$, n, f, V_{2f}, and I_{1f} are the air-core inductance, turns ratio, nominal frequency, amplitude of secondary fundamental voltage, and amplitude of primary fundamental current, respectively. The voltage and current were recorded in the lab with high precision (0.2% of reading), using a PZ4000 Yokogawa power analyzer.

Theoretically, all harmonic components could be substituted in (1) for the calculation of air-core inductance. This is because measurements are performed in the linear region of the magnetizing characteristic. The three-phase half-wave uncontrolled rectifier used in this study produces dominant harmonics of order $3k$, $k = 1, 2, \ldots n$. Higher accuracies are obtained using the fundamental and the dominant frequencies. Note that the inductance of the iron core is frequency dependent due to eddy current effects [1]. Hence, it is recommended to compute the air-core inductance with frequencies where the penetration depth is larger than the lamination thickness. In our experiments, calculations with the triplen harmonics up to the 18th give accurate results.

III. RESULTS AND VALIDATION

Four single-phase transformers were selected for laboratory measurements. T1 is a shell-type standard transformer with four separate (layer) windings, and T2, T3, and T4 are toroidal transformers. The primary current measured for the innermost winding and the secondary voltage measured at the inner winding of T1 are shown in Fig. 3. Fig. 4 illustrates the voltage at the rectifier terminals before and after connecting the transformer. In Table I, the measured air-core inductances are compared with the 3-D finite-element simulations using Maxwell v14.0. Windings are numbered from the innermost to the outermost.

From Table I, one can see that most inductances are measured with acceptable engineering accuracy (less than 5%). Note that the required power is considerably lower than that of the conventional open-circuit test.

Each time the transformer is excited with the rectifier, it goes into deep saturation on the positive side of the $\phi - i$ curve. Therefore, the result is accurate with any remnant flux, and the
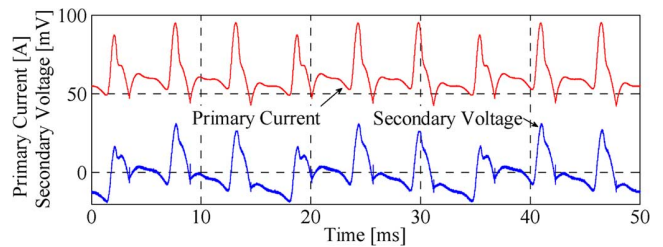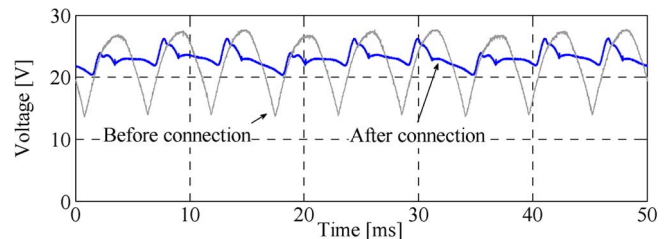

Fig. 4. Voltage of the source before and after connecting to the transformer.

TABLE I
COMPARISON OF MEASUREMENTS AND FINITE-ELEMENT SIMULATIONS

Code	Winding	Number of turns	Power (VA)	$L_{Air}(\mu H)$ (FEM)	$L_{Air}(\mu H)$ (Exp.)	Diff. (%)
T1 (1 kVA)	1	108	3,996	645	640	0.8
	2	108	3,527	850	894	5.1
	3	108	3,453	1,069	973	8.9
	4	108	2,511	1,300	1,267	2.5
T2 (1 kVA)	1	196	2,388	316	314	0.6
	2	196	2,753	383	374	2.3
T3 (4 kVA)	1	81	176	75.2	81	7.7
	2	82	183	119.6	118	1.3
T4 (25 kVA)	1	26	138	51.7	50	3.3

method does not need predemagnetization. Moreover, with dc excitation, iron losses are also eliminated, which is not the case during the traditional no-load test.

The results of Table I indicate that for larger transformers with lower per-unit resistance, the required power with respect to the transformer rating is lower. This is because the dc current necessary to saturate the core is limited by the winding resistance. Although the current drawn by the larger transformers is higher, the required voltage is smaller. Therefore, for higher power-rating transformers, the voltage source should be able to supply large currents, but the source can be low power.

IV. CONCLUSION

This letter has shown that the air-core inductance of transformers can be conveniently measured with high precision using simple low-power static rectifiers.

REFERENCES

[1] F. de León, P. Gómez, J. A. Martinez-Velasco, and M. Rioual, "Transformers," in *Power System Transients: Parameter Determination*. Boca Raton, FL, USA: CRC, 2009, ch. 4, pp. 177–250.
[2] C. G. A. Koreman, "Determination of the magnetizing characteristic of three-phase transformers in field tests," *IEEE Trans. Power Del.*, vol. 4, no. 3, pp. 1779–1785, Jul. 1989.

[3] S. Abdulsalam, W. Xu, W. L. A. Neves, and X. Liu, "Estimation of transformer saturation characteristics from inrush current waveforms," *IEEE Trans. Power Del.*, vol. 21, no. 1, pp. 170–177, Jan. 2006.

[4] E. P. Dick and W. Watson, "Transformer models for transient studies based on field measurements," *IEEE Trans Power App. Syst.*, vol. PAS-100, no. 1, pp. 409–418, Jan. 1981.

[5] S. Calabro, F. Coppadoro, and S. Crepaz, "The measurement of the magnetizing characteristics of large power transformers and reactors through D.C. excitation," *IEEE Trans. Power Del.*, vol. PWRD-1, no. 4, pp. 224–234, Oct. 1986.

[6] G. Stumberger, B. Polajzer, B. Stumberger, M. Toman, and D. Dolinar, "Evaluation of experimental methods for determining the magnetically nonlinear characteristics of electromagnetic devices," *IEEE Trans. Magn.*, vol. 41, no. 10, pp. 4030–4032, Oct. 2005.