An Experimental Method for Predicting the Magnetic Properties of Ferromagnetic Materials Subjected to Harmonic Excitation

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Abstract. *Probably a new method for the full description of ferromagnetic material was tested and verified. It is based on the approximation of waveforms in the time domain by the use of the Fast Fourier Transform (FFT). Usually 10 waveforms give a perfect approximation. In order to predict the waveform or a hysteresis loop, experiments were performed using systematically increasing harmonic excitation. The most important harmonics were selected and their dependence on the applied input voltage was approximated. Thus the waveform can be created from values of harmonics for any voltage. If the voltage step in the experiment is 10 V or lower, a good prediction can be obtained even in the case of strong excitation.*

Keywords: Ferromagnetic Material, Hysteresis Loop Approximation, Harmonic Analysis, FFT

1. Introduction

Non-linearity and hysteresis are typical phenomena of ferromagnetic materials, which make their complete description extremely difficult. Therefore, more or less exact models must be used. The simplest models use several well-known material parameters, but more precise models need a lot of parameters in order to match experimental results.

Two types of model are used: theoretical and experimental. Theoretical models are based on the magnetic domain structure. The well-known Preisach model [1] uses ideal small volume magnets and exhibits all the basic properties of the material. In principle, experimental models approximate the measured characteristics, especially the hysteresis loop. Very often the hysteresis loop is approximated using a high degree polynomial [2], but a combination of other analytical functions is possible [3]. To our knowledge, the approximation of waveforms in a time domain is less well-known. Our approach is based on the approximation in the time and frequency domain. Since the waveforms are periodic (or harmonic), the use of the Fourier series is well suited for this type of approximation.

2. Subject and Methods

The goal of the measurements and the special processing of the measured results is to get a system that makes it possible to predict the time domain waveforms or the hysteresis loops for harmonic excitation. The solution consists of two parts: experimental and theoretical or computational.

The ferromagnetic parameters of UI core transformers were measured and recorded. The laboratory setup for a no-load transformer test is shown in Fig. 1a. The transformer under test (T) was fed from a programmable power supply (PS) Kikusui PCR-2000 LA. The output offset of the power supply was in the range of tens of mV and the produced DC current influenced hysteresis loop symmetry. Therefore, the testing circuit contained a serial capacitor (C) of 3.4 mF in order to stop the DC current flow. Voltages and the primary current were measured by a Norma 5000 power analyzer. The sampling frequency of the analyzer was 1 MSPS. All the instruments were computer controlled. The scanned voltage and current waveforms were downloaded directly to the computer; typical waveforms are in Fig. 1b.

The theoretical part applies time and frequency domain theory. The transition between the domains is achieved using the Fast Fourier Transform (FFT). It must be applied to an integer number of periods. Where the ascending section of the waveforms crossed the *x* axis was used as the criterion of the period start and finish, as shown in Fig. 1b. All the mathematical operations were performed on these well-defined waveforms. The correct numeric integration of the secondary voltage is necessary in order to get the magnetic flux used for the construction of the hysteresis loop.

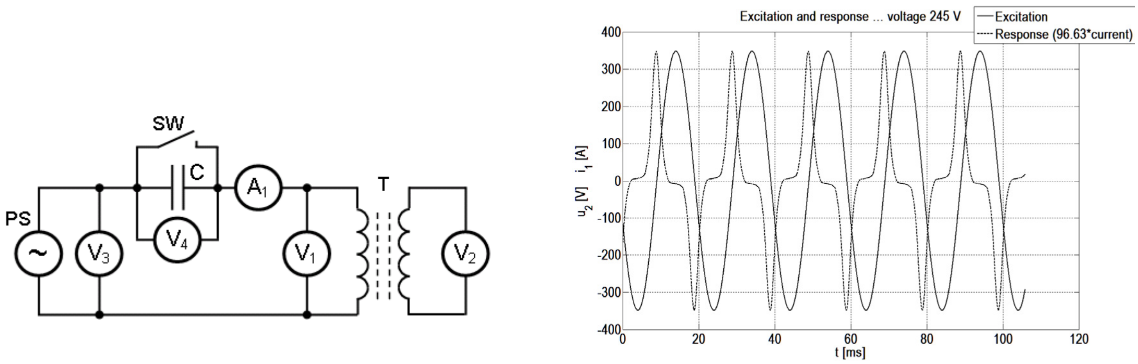

Fig. 1. Experimental part. a) Fully automated laboratory setup, b) Scanned primary current and secondary voltage waveforms.

The waveform spectrum was obtained using FFT. The most important spectral lines were used for the waveform and hysteresis loop approximation. The criterion was a fraction of the most important harmonics; practically, it varies from 1 to 0.1 %. In order to predict the waveform or hysteresis loop the experiment was repeated many times using a slightly higher input voltage on each iteration. From this, the dependence of the most important harmonics on the input voltage was determined. If the dependence is well approximated for every harmonic used, then the waveform or the hysteresis loop for the selected voltage can be produced with a high degree of accuracy. The simplest form of harmonic approximation is achieved using interpolation or polynomial regression.

3. Results

A lot of curves were produced, both from the experimental and theoretical data processing. Therefore, only representative and typical results are shown here in the thematic order: experiment, approximation and prediction. The systematic measurements were made on a soft ferromagnetic material with losses of 1.65 W/kg used as the UI core transformer of windings 360:360 and open circuited secondary winding, see Fig. 1a. The frequencies were 6, 12, 25, 50, 100 and 300 Hz. The amplitude of the input voltage was increased in steps of 2.5 V at 50 Hz or bigger steps at other frequencies. Magnetic field strength and hysteresis loop in Fig. 2 are for every eighth applied voltage in order to be seen clearly. The average curves for one period are shown (see explanation in previous part).

By applying the FFT to waveforms like those in Fig. 2a we get a spectrum. The spectrum lines dependence on the applied voltage is shown in Fig. 3. In Fig 3a several starting odd harmonics are shown. Higher harmonic values are multiplied by a suitable constant to have approximately the same maximum. Fig. 3b shows the 13th harmonic in detail. A harmonic change of order six corresponds to a voltage change from 2.5 to 250 V (order two).

The effect of frequency is presented in Fig. 4. Circuit parameters are used, primary current i and integral u_{int} of secondary voltage, which corresponds to the total Magnetic flux in the core. The width of the loop increases, since the losses increase with frequency.

An approximation was made by the selection of the most significant harmonics. The level of significance is a fraction of the first harmonic; the used fractions were 10, 3, 1, 0.3 and 0.1 %. The results are given in Fig. 5. The criterion of 1% gives an almost perfect approximation.
The goal of this work is the prediction of waveforms and hysteresis loops. The necessary methodology involves the description of the dependence of each harmonic on the input voltage. As shown in Fig. 3, the dependence is very complicated as well as the selection of harmonics to be used in the calculation. Cubic interpolation and fixed harmonics after their sorting were used. The details for the experiment which used a step of 20 V have been omitted as it gave the worst results as shown in Fig. 6. The deviation between the calculation and neighboring experimental curves is visible only in the details.

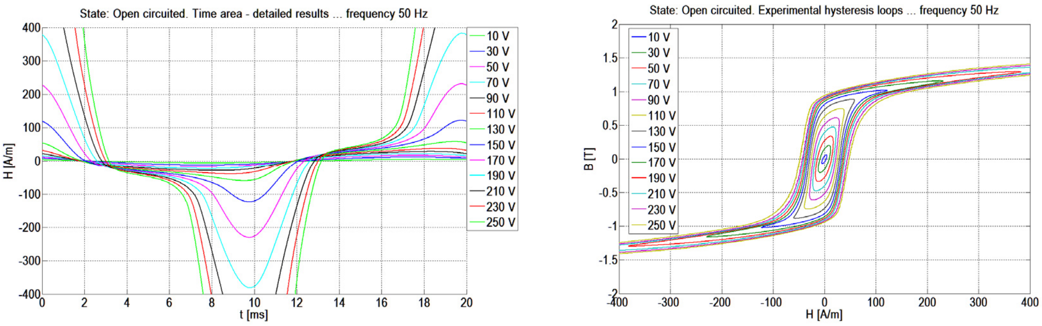

Fig. 2. Experimental results at frequency of 50 Hz. a) Details of field strength waveform. b) Centre part of hysteresis loop.

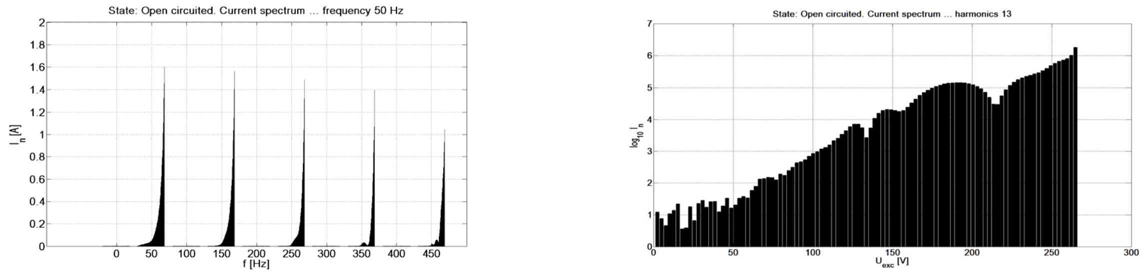

Fig. 3. Waveform spectrum at frequency of 50 Hz. a) First nine harmonics in linear scale. b) Details for 13th harmonics in logarithmic scale.

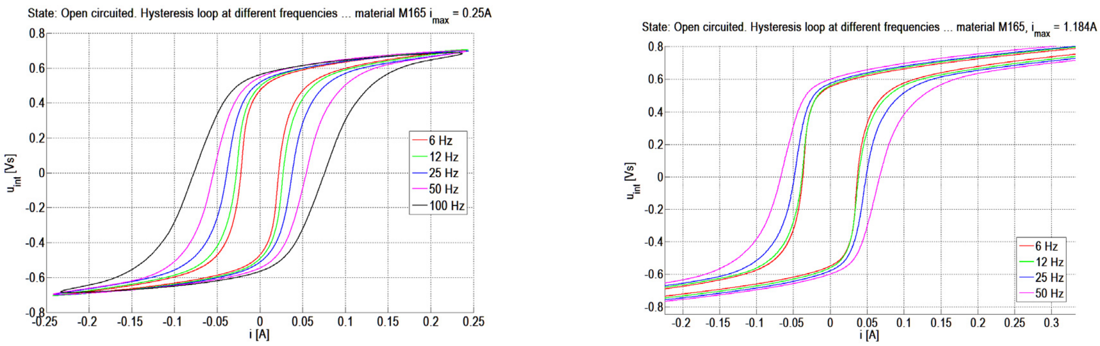

Fig. 4. Effect of frequency. a) Low excitation. b) High excitation, only the central part of hysteresis loop is shown.

4. Discussion and conclusions

In practice, the exciting quantity is the voltage, although the hysteresis loop experiment assumes a harmonic current. The reason is that good current sources are expensive. Among many other models for experimental data processing, the use of harmonic analysis is a natural approach, since each component has its physical significance and the method is a basic one in circuit theory. We have shown that the hysteresis loop is well defined by about 15 parameters, depending on the applied voltage. Therefore, the three main material parameters defined in a hysteresis loop are not sufficient, which is confirmed by literature [3].

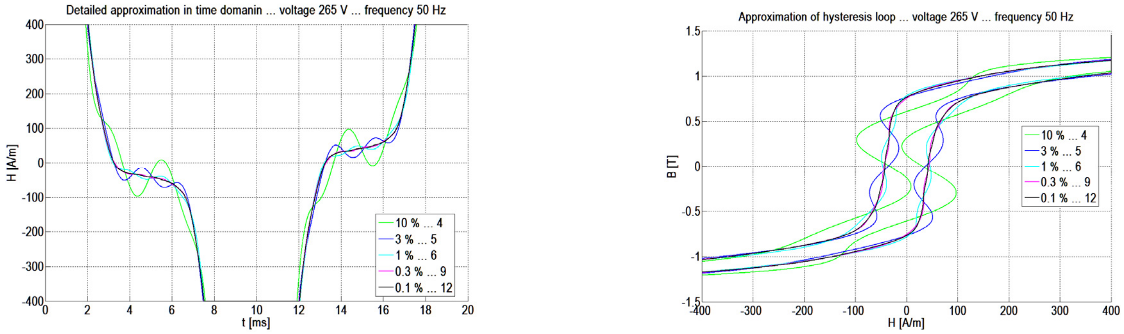

Fig. 5. Approximation. a) Time area. b) Hysteresis loop. The legend shows the importance criterion and number of used harmonics.

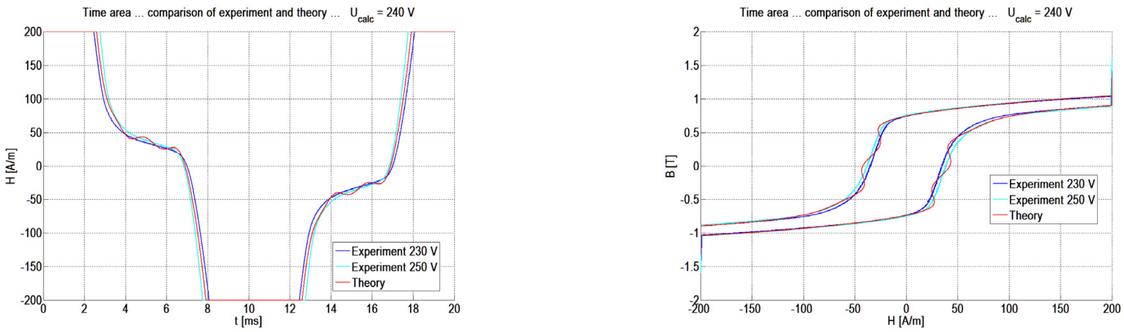

Fig. 6. Comparison of prediction and experiment. a) Detail in time area. b) Central part of hysteresis loop.

Good prediction of waveform and hysteresis loop assumes the knowledge of dependence of harmonics on the applied voltage, which is very complicated. The popular regression method cannot be used because of the complexity of the task and the change of 6 orders among other things. The interpolation method was found to be acceptable. A general rule is valid: The smaller the step in experimental voltage, the better the interpolation. Good results can be obtained for steps of 10 V. The full description of the material needs about 4 thousand parameters.

The next task requires the automated processing of all the experimental data in order to get a file of parameters and then the application of a simple algorithm that includes the file into circuit theory.

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