Automatic instrumental platform for the measurement of the characteristics of ferromagnetic materials based on LabVIEW

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Abstract: In this paper, we propose a complete automation of the different measurements of ferromagnetic materials dynamic characterization according to the CEI60404-6 standard. The measurement bench consists of two major parts: hardware and software. The hardware part comprises a programmable function generator MTX-3240, an electronic card for the magnetic induction’s waveform control, and an NI PCI-6225 acquisition card. The software part is developed in the LabVIEW environment to enable the generator and the acquisition card control. It also allows for the processing of obtained experimental records and the correction of static errors. The identified characteristics are mainly the first magnetization curve, the static and the differential permeability, the hysteresis loop characteristics, and the core loss measurements.

Key words: Experimental design, hysteresis loop, magnetic properties, ferromagnetic losses, data acquisition, virtual instrument, LabVIEW, synchronous detection

1. Introduction

In electrical engineering, it is required to identify the magnetic characteristics of a ferromagnetic material in order to optimize its design economically and technically. The functioning of the classic electrical devices such as engines, alternators, or transformers depends on its magnetic circuit characteristics.

With the major progress in digital technology and computer-aided design, several automated magnetic measuring systems have been developed. Novikov et al. proposed an instrument where the coordinates of the hysteresis loop points are converted with an analog-digital converter into coupled digital code pairs stored and processed in a microprocessor [1]. Others developed instruments that are based on the ferrometric approach consisting of phase-sensitive rectification of signals from the magnetizing and measuring coils of the ferromagnetic sample. Subsequent averaging is applied to find the instantaneous field intensity and magnetic induction [2]. Krokhin and Sushchev proposed a digital compensating ferrometer that uses a modification of the ferrometric method [3]. With the progress of virtual instrumentation, Pölik and Kuczmann and other research groups developed different computer-controlled measurement systems applying the National Instruments NI-DAC Data Acquisition Card and the National Instruments LabVIEW software package [4].

Our efforts in this field concern the improvement of an automatic instrumental platform for the measurement of the characteristics of ferromagnetic materials. We apply an accuracy measurement converter called a synchronous detector, usually used in the field of instrumentation and digital signal processing. Our method

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is inspired by the modified ferrometric method and the system is controlled by the NI-DAC and LabVIEW software.

In this paper, we present the design of a test bench for the automatic magnetic characterization of a ferromagnetic sample such as a first magnetization curve, static and differential permeability, hysteresis loop, remanent induction, saturation induction, coercive field, and total losses.

The measurement principle is based on the electromagnetic induction law. The measurement of the magnetic characteristics is performed on a thin ferromagnetic ring sample in the dynamic regime with a sinusoidal magnetic induction conforming to the international standard CEI60404-6 [5].

2. Architecture of the measurement system

The essential parameters characterizing a magnetic material, such as coercivity field $H_c$, magnetization at remanence point $B_r$, saturation induction $B_s$, static permeability $\mu_{stat} (H_m)$, differential permeability $\mu_d (H_m)$, iron losses $P_{HF} (B_m)$, and features that allow the quantification of losses in the material for a definite stimulus, are deduced from the hysteresis loop [6]. Figure 1 shows an example of a hysteresis loop with the essential parameters that can be derived from this characteristic.

![Figure 1. Hysteresis loop.](image)

The measurements of the magnetic characteristics of a ferromagnetic sample are based on the identification of the hysteresis loop. The identification of magnetic properties of ferromagnetic material requires the use of a closed magnetic circuit to prevent submitting the sample to an internal demagnetizing field, which might be the origin of an error source difficult to quantify [7]. For this reason it is recommended to use certain types of circuits [8]. Moreover, the proposed measures are based on the induction law. The measurement circuit has two windings, one for excitation and one for measurement. The magnetic flux variation can be obtained by measuring the induced voltage in the secondary coil [9].
However, considering the nonlinearity of electromagnetic phenomena and the need of measurement standardization of ferromagnetic materials’ characteristics in the dynamic regime, it is necessary to take measures for a sinusoidal waveform according to the CEI60404 standard. For this purpose, and in order to have the same operating conditions of an electrical machine and to ensure the reproducibility of measurements, the control of the waveform requires the presence of feedback. The synoptic plan and the general structure of the characterization bench of ferromagnetic materials are presented in Figures 2 and 3.

**Figure 2.** Synoptic plan of the automatic bench for ferromagnetic characterization of ferromagnetic materials.

**Figure 3.** Block diagram of automatic bench for ferromagnetic materials characterization with the stabilization system of the ferromagnetic sample’s magnetic state.

Figure 4 illustrates the constitution of the test bench of ferromagnetic materials characterization. This system is controlled by a PC via a functional user interface in the LabVIEW environment and it consists of an
NI-PCI-6225 acquisition card [10] and a programmable function generator, MTX-3240, with the electronic card that controls the wave’s form and keeps the sinusoidal form of the magnetic induction $B(t)$.

![Test circuit and hardware architecture of the automatic hysteresis measurement system.](image)

**Figure 4.** Test circuit and hardware architecture of the automatic hysteresis measurement system.

The LabVIEW measurement software controls the MTX-3240 generator in terms of amplitude and frequency via an optic serial port RS232 [11]. This generator can achieve a peak-to-peak amplitude of 20 V with an automatic calibration and a frequency range from 0.1 Hz to 5.1 MHz. Starting with a sinusoidal signal set, the servo card keeps the sinusoidal shape of the magnetic induction to ensure measurement standardization. The voltage representing the magnetic induction $V_B$ and the voltage image of the magnetic excitation $V_H$ are acquired thanks to the NI-PCI 6225 acquisition card.

After the design and implementation of an electronic control card corresponding to the sinusoidal magnetic induction form presented in Figure 5, the output signals obtained are shown in Figure 6. Obtained data will be processed using the LabVIEW environment and allow calculation of the characteristics of the ferromagnetic ring-shaped sample mounted on the test bench. The acquisition card is connected to the outputs $V_B$ and $V_H$ of the electronic servo card. It has 80 analog input channels, an analog-digital converter with a resolution of 16 bits, and a sampling frequency of 250 kHz.

### 3. Automation of magnetic measurement in the LabVIEW environment

The control of the signal generator MTX-3240, the acquisition card NI PCI-6225, and the measurement processing are performed in the LabVIEW environment.

The LabVIEW program for controlling the generator is shown in Figure 7. It consists of Vis for the initialization of the RS232 communication parameters and configuration settings of the output signal.
Figure 5. Electronic control card of the magnetic sinusoidal induction form.

Figure 6. Output signals from the control card.
The control program of the acquisition card is shown in Figure 8. It allows acquiring N samples for a sampling frequency Fe and saving them in a file database. The value of sampling frequency Fe is deduced from the signal frequency generated by the MTX3240 generator, which provides us with a constant number of samples N. The magnetic field and magnetic induction are calculated from data obtained by respectively applying Eqs. (1) and (2).

\[ H(t) = \frac{N_i(t)}{I_{moy}} \]  

(1)
Here, $N_1$ and $N_2$ are respectively the number of turns of the excitation coil and the sensing coil, $l_{moy}$ is the average length of the ring-shaped sample, $i(t)$ is the excitation current measured through the noninductive low-value resistance $R_N$, $S$ is the section of the sample, and $V_B(t)$ is the induced EMF in the sensing coil terminals. The calculation of the integral in Eq. \((2)\) requires the determination of integration constants that are not easy to obtain. Thus, the solution is to use the method of synchronous detection as long as $V_B(t)$ satisfies the conditions of periodicity and antisymmetry relations given by Eq. \((3)\).

\[
\begin{aligned}
x(t) &= -x(t + \frac{T}{2}) \\
x(t) &= x(t + T)
\end{aligned}
\]  

\(T\) is the signal period.

The instantaneous value of the original signal is known by applying the conversion function of a synchronous detector, which is given by Eq. \((4)\).

\[
\overline{X} = \frac{1}{T} \int_{t_i}^{t_i+\frac{T}{2}} x(t)dt = -\frac{2}{T} X(t_i) = -2f X(t_i)
\]

\(x(t)\) is the derivative of \(X(t)\).

According to this principle, the magnetic induction is given by Eq. \((5)\).

\[
\frac{1}{T} \int_{t_i}^{t_i+\frac{T}{2}} \frac{dB(t)}{dt}dt = -\frac{2}{T} B(t_i) = -2f B(t_i)
\]

\(t_i\) varies from 0 to \(T\).

The program for the conversion function of synchronous detection is shown in Figure 9.

Knowing \(H(t)\) and \(B(t)\), it is possible to define all the standard magnetic parameters of the ring-shaped sample:

- The first magnetization curve $B_m(H_m)$, from which static $\mu_{stat}(H_m)$ and differential permeability $\mu_d(H_m)$ can be inferred through the implementation of Eqs. \((6)\) and \((7)\):

\[
\mu_{stat} = \frac{B_m}{H_m}
\]
\[
\mu_d = \frac{\Delta B_m}{\Delta H_m}
\]

- The network of hysteresis loops $B(H)$ for different amplitudes of $B_m$, which then allows to identify the iron losses $P_{HF}(B_m)$ according to the maximum induction through Eq. \((8)\) \[12\]:

\[
P_{HF} = \frac{f}{\rho} \int_{cycle} H \cdot dB = \frac{f}{\rho} \int_{cycle} B \cdot dH \quad [W/Kg]
\]

Here, $\rho$ [Kg/m$^3$] is the volumic mass of the ferromagnetic material.
4. Results

The test bench for the automatic magnetic characterization has been tested for the ferromagnetic toroidal sample and for the sinusoidal excitation voltage with a frequency variation from 20 Hz to 400 Hz.

The front panel of the magnetic measurement program is shown in Figure 10. It has 13 display areas for numerical results, such as $B_r$ - remanent induction, $H_c$ - coercive excitation, $B_{sat}$ - saturation induction, $P_H$ - hysteresis losses, and $P_{HF}$ - core losses.

It has also nine areas of graphic display. In this group, the signal curves $V_B$ and $V_H$ can be seen at the top left side. The calculated signals $H(t)$ and $B(t)$ together with the spectral analysis are plotted at the bottom left. The curves of static and differential relative permeability and the first magnetization curve, as well as the all-measure hysteresis loop, appear at the bottom right, and 16 control areas can be seen at the top right side, such as the parameters of the magnetic sample, the magnetic stabilization system, and save location.

Gradually increasing the excitation voltage with a step $\Delta V$, we can evaluate the maximum values of $H(t)$ and $B(t)$ corresponding to each increase. The first magnetization curve is obtained when these points $B_i(H_i)$ on the graph are linked. Figure 11 shows the practical result of the first magnetization curve of a toroidal core sample of ferromagnetic material (Steel E42). Static permeability $\mu_{stat}(H_m)$ and differential permeability $\mu_d(H_m)$ are inferred from the first magnetization curve and illustrated by Figure 12.

5. Evaluation of measurement errors

The error in magnetic measurements depends on the sum of measuring channel error and the primary transducer error. Measuring channel error contains a variety of independent errors such as resolution error, mainly consisting of the reference voltage and the DAC converter, the sampling error, electronic amplifiers gain errors, error due to numerical calculation, and other factors.
Figure 10. Front panel of LabVIEW measurement software for the automatic characterization bench of ferromagnetic materials.

Figure 11. The measurement result of the first magnetization curve and hysteresis loops.

Figure 12. The measurement result of the static and differential permeability. Red graph B (H): The first magnetization curve. Blue graph $\mu_{stat} (H)$: Static relative permeability. Green graph $\mu_d (H)$: Differential relative permeability.
By applying the method of error propagation, the total error is evaluated by this expression:

$$\sigma_{total} = \sqrt{\sum_i \sigma_i^2}$$  \hspace{1cm} (9)

Here, $\sigma_i$ represents each independent error.

In this automatic magnetic induction and field measurements, the measuring channel error does not exceed 0.1%.

The primary transducer error is composed of the error due to counting number of turns for the magnetizing and measuring winding, the error of measuring the cross-sections, and area and length of the mean magnetic force line of the studied sample, and usually this error is evaluated at 1%.

The total error of magnetic measurements is governed mainly by the primary transducer error.

6. Conclusion

An automatic characterization bench for ferromagnetic materials is successfully achieved. It can automatically measure various characteristic parameters of a toroidal sample in the dynamic regime according to the latest CEI60404-6 standard.

This system is simple with autocalibration. It is equipped with a control loop in order to reduce distortion of the induction caused by the nonlinearity of the phenomenon and with a subprogram self-correcting systematic errors. The involvement of virtual instrumentation provides the possibility to add new measurement features. The recorded measurement data can be exported to other environments such as MATLAB. The automatic characterization bench may be used for identification of hysteresis mathematical models. The operator is thus relieved from the onerous conventional tasks of measurements and calculations.

Despite having an operational instrument, there is still room for improvements such as:

- The complete automation by automatic search of the bandwidth of ferromagnetic material in terms of frequency.
- The preliminary identification of saturation parameters.

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