# A SENSORLESS METHOD FOR THE IDENTIFICATION OF ASYMMETRIC HYSTERESIS LOOPS OF FERROMAGNETIC MATERIALS

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**Abstract** – *The sensorless determination of the dynamic hysteresis loop of the magnetic materials, and in particular those of magnetic plates, can be obtained under ac symmetric conditions in a relatively simple way. This paper proposes a new digital method and instrument for the sensorless determination of the dynamic hysteresis loop under ac asymmetric conditions, in the presence of a dc flux polarization. The method is based on the determination of the parameters of a simplified linear circuital model of the magnetic circuit, which shows an energy equivalence. The results of some experimental work are provided in order to validate the proposed method.*

**Keywords** – Magnetic measurements. Sensorless measurement systems. Virtual Instruments. Digital Signal Processing.

## 1. INTRODUCTION

The identification of the dynamic hysteresis loops drawn by a ferromagnetic material under cyclic magnetization represents an important challenging problem of the measurement science. It is well known that many important properties of the ferromagnetic materials, such as the normal magnetization characteristic, the total losses, the saturation level as to list the most important ones, can be directly obtained by the analysis of the loop. All above listed properties are of utmost importance in designing and sizing all equipment that make use of magnetic materials.

The main problem in the experimental determination of the dynamic hysteresis loops is the measurement of the magnetic flux inside the core, that can be a suitable test core or the magnetic core in the actual working conditions. The determination of the magnetic flux under whatever working condition requires the use of proper sensors. Presently, Hall-effect sensors are available at a reasonable cost, and feature, after calibration, an accuracy of 0.2%, which is quite appropriate for most applications. However, sensors must be inserted in the magnetic path of the core under test: this requires the use of materials with built-in sensors (which is an expensive solution and does not allow for using normal materials in the fabrication of the magnetic cores) or the insertion of an air-gap in the core under test (which may modify the material working conditions intolerably). Moreover, Hall-effect sensors subtend a very small cross section and a great number of sensors must be used if information is needed on the flux distribution across the core, or the average flux.

On the contrary, the measurement of the magnetic flux under symmetric cyclic conditions can be obtained in a much simpler way, by integrating the signal coming from a search coil, both when test cores are used [1, 2], or when measurements are performed directly on the material in its working conditions [3]. The basic structure of the measurement device, based on a digital structure, that has proved to be very effective to characterize the material in a test core [2] is reported in Fig. 1.
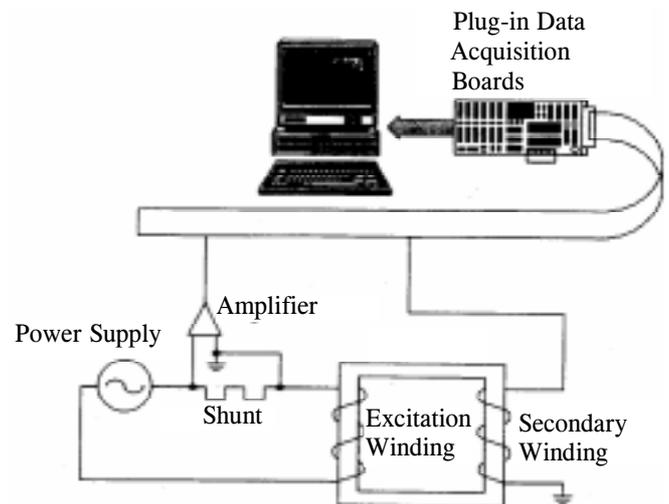


Fig. 1. Architecture of a digital measurement system for the determination of the hysteresis loop.

This method, however, fails when the dynamic hysteresis loop is no longer symmetric. Since the electromotive force induced in the search coil represents the derivative of the magnetic flux inside the test core, the information related with the dc component of the magnetic flux cannot be retrieved from the integration of the electromotive force any longer.

An alternate approach is based on the identification of the parameters of the dynamic hysteresis loop by means of measurements performed under symmetric conditions [4, 5]. These parameters are then used to model the behavior of the material under asymmetric cyclic magnetization. However, this solution proved to be not effective, due to the scarce knowledge of the physical phenomenon of the hysteresis and the consequent inadequacy of the mathematical tools used to model the hysteresis itself.

This paper proposes a method that overcomes this

problem by means of the identification of the parameters of an equivalent elliptic hysteresis loop. The theoretical background is reported, and finally the results of the experimental work are reported that prove the validity of the proposed method.

## 2. THEORETICAL BACKGROUND

It is possible to prove that [6] the hysteresis behavior of a magnetic material can be represented, from the point of view of the energy balance, by an elliptic loop with the same area as the original hysteresis loop. If $H_m$ and $B_m$ are the main axes, in the $B$-$H$ plane, of the elliptic loop, and $\alpha$ is the loss angle, the equivalence between the two loops is represented by:

$$\oint H dB = \pi B_M H_M \sin\alpha \tag{1}$$

The above assumption leads to identifying the linear equivalent circuit of the magnetic structure under test shown in Fig. 2. If the magnetizing current $i(t)$ is sinusoidal, it can be written as:

$$i(t) = \sqrt{2} Re\left\{ A e^{j\omega t} \right\} \tag{2}$$
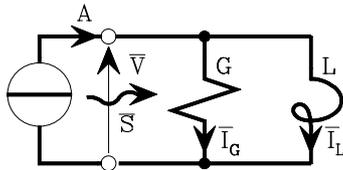


Fig. 2. Linear equivalent circuit modelling an elliptic hysteresis loop

where the rms value $A$ must be the same as the rms value of the actual magnetizing current in order to ensure the equivalence from the energy point of view [6]. Under these assumptions, the electrical quantities in Fig. 2 can be obtained as:

$$\begin{cases} \bar{I}_L = \dfrac{1}{1+j\omega LG} A = \dfrac{A}{\sqrt{1+(\omega LG)^2}} e^{-j\tan^{-1}(\omega LG)} = I_L(\omega)e^{-j\vartheta(\omega)} \\ \bar{I}_G = \dfrac{j\omega LG}{1+j\omega LG} A \\ P = EI_G = EA\sin\vartheta \\ Q = EA\cos\vartheta \end{cases} \tag{3}$$

where $E$ is the rms value of the sinusoidal equivalent electromotive force across the excitation winding and is supposed to be the same as the rms value of the actual electromotive force [6].

From these equations, the parametric equations of the elliptic loop in the current-flux plane can be written as:

$$\begin{cases} i(t) = \sqrt{2} \cdot Re\left\{ A e^{j\omega t} \right\} \\ \psi(t) = \sqrt{2} \cdot Re\left\{ LI_L e^{j(\omega t - \vartheta)} \right\} \end{cases} \tag{4}$$

and, taking into account (3), as:

$$\begin{cases} i(t) = \sqrt{2} \cdot A \cos(\omega t) \\ \psi(t) = \sqrt{2} \cdot \dfrac{LA}{\sqrt{1+(\omega LG)^2}} \cos\left(\omega t - \tan^{-1}(\omega LG)\right) \end{cases} \tag{5}$$

The area of this elliptic loop is given by:

$$\Theta = 2\pi \frac{LA^2}{\sqrt{1+(\omega LG)^2}} \sin(\omega LG) \tag{6}$$

Since the area of the elliptic loop is the same as the area of the actual hysteresis loop, and can be obtained by the measurement of the total core loss, the above equations, together with the assumption that the rms value $A$ of the sinusoidal equivalent magnetizing current and the rms value $E$ of the sinusoidal equivalent electromotive force on the excitation winding are the same as the actual rms values, the above equations lead to the straightforward determination of the $L$ and $G$ parameters of the equivalent circuit in Fig. 2.

If a dc polarization is present in the magnetizing current, the superposition principle can be applied to the linear equivalent circuit in Fig. 2 and the parametric equations (5) of the elliptic equivalent loop become:

$$\begin{cases} i(t) = A_o + \sqrt{2} \cdot A \cos(\omega t) \\ \psi(t) = L \cdot A_o + \sqrt{2} \cdot \dfrac{LA}{\sqrt{1+(\omega LG)^2}} \cos\left(\omega t - \tan^{-1}(\omega LG)\right) \end{cases} \tag{7}$$

The equivalent circuit parameters are the same as in the case of pure ac conditions [6], and can be therefore evaluated starting from the ac component of the voltage and current signals.

The parametric equations (7) represent the same elliptic loop as in pure ac conditions, but the loop center is shifted from the axes origin to the point with $(A_0, LA_0)$ coordinates. The magnetic flux value $LA_0$ can be therefore taken as the dc component of the flux and added to the ac component obtained by integration of the search coil electromotive force in order to obtain the actual hysteresis loop.

## 3. THE METHOD

According to the theoretical considerations shortly recalled in the above section, the method being proposed in this paper develops according to the following steps.

- The magnetizing current of a test core is acquired together with the electromotive force induced on a search coil.
- The core total loss are evaluated from these signals. Since the total loss depends only on the cyclic magnetization, the determined loss is the actual core loss, even if the dc component of the flux is not taken into account.
- The ac component of the magnetizing current is extracted from the acquired current and its rms value is determined.
- The rms value of the electromotive force is determined starting from the voltage signal acquired at the terminals
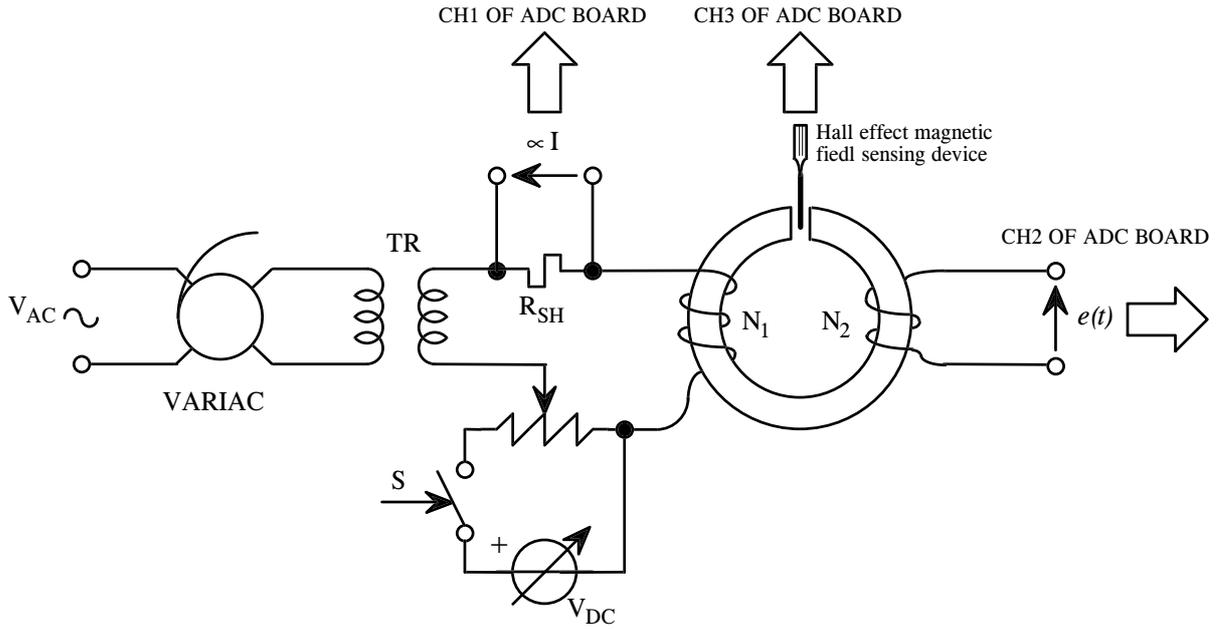
Fig. 3. Schematic of circuit implemented for measurement.

of the search coil.

- The parameters of the linear equivalent circuit are determined, according to (3) and (6).

- Having determined the equivalent inductance $L$, the dc component of the magnetic flux is determined as $\psi_0 = LA_0$.

- This dc component is added to the ac component obtained by integrating the electromotive force acquired by the search coil and finally the actual hysteresis loop under asymmetric cyclic magnetization is obtained.

## 4. EXPERIMENTAL RESULTS

In order to validate the proposed method, the experimental set-up shown in Fig. 3 has been employed.

A toroidal core with rectangular cross section, obtained with a wound ferrosilicon sheet, has been employed as a test core. A 1 mm air gap was created in order to insert a reference magnetic probe. The length of the obtained magnetic path was 408.5 mm and its cross section was 600 mm$^2$. A magnetizing winding of 180 turns has been wound around the whole magnetic path, and a probe winding of 50 turns has been also wound around a small portion of the core.

The signals have been acquired by an Analog-to-Digital conversion board featuring 12-bit resolution, 8 input channels with simultaneous sampling and a maximum sampling rate of 500 kHz on a single channel. Since all tests have been performed under 50 Hz cyclic magnetization, a sampling rate of 25.6 kHz has been set, and an observation interval of 4 periods of the input signals has been considered. The algorithm developed to apply the proposed method has been implemented in a VI structure, under LabView environment.

In order to have a reference value of the magnetic flux inside the test core to compare with the values provided by

the proposed method, an Hall-effect flux probe has been inserted in the air gap. The employed probe is a solid-state Hall effect magnetic field sensing device, whose magnetic sensitivity may vary in a 0.5 ÷ 1.4 VT$^{-1}$ range, according to the specifications of the manufacturer.

Due to this wide variation range, in order to have a significant comparison between the measurement results given by the proposed method and those given by the probe, the probe must be calibrated.

The implemented VI was already proved to feature a relative accuracy, in the evaluation of the magnetic flux under pure ac conditions, in the ±2 % range [2]. Therefore this same VI was used to calibrate the probe. The maximum induction values measured by the VI have been plotted against the maximum output values of the probe, as shown in Fig. 4. The probe behavior is fairly linear, as expected, and the probe gain has been evaluated to be 2.433 VT$^{-1}$. The same measurements have been repeated adding a constant dc
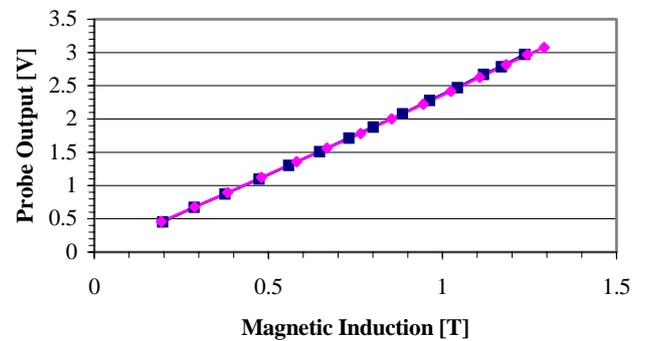


Fig. 4. Measured maximum induction values by the implemented VI versus the probe maximum output values under ac conditions (■) and ac conditions with a dc polarization (▲).
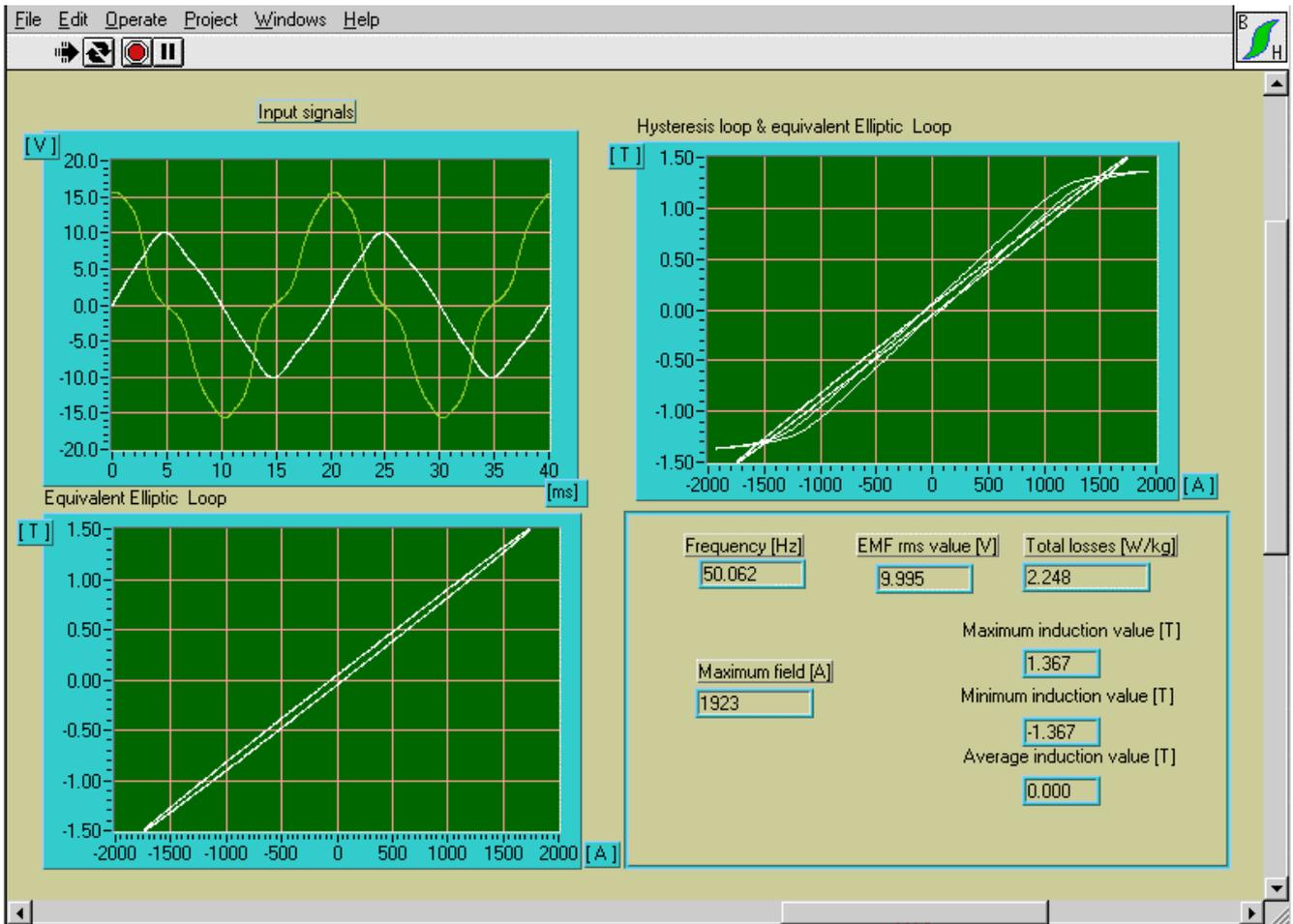
Fig. 5. Front Panel of the Virtual Instrument under symmetric AC magnetization.

polarization to the ac magnetizing current and the obtained diagram is shown in Fig. 4 as well. The plot is still linear, and a gain coefficient of 2.398 $VT^{-1}$ has been evaluated in this condition, with a relative deviation of 1.44 % with respect to the calibration value. The linear behavior of the two plots in Fig. 4 and the good agreements between the gain coefficient values show that the proposed method is capable of evaluating also the dc component of the magnetic flux with an estimated relative uncertainty lower than 5 %.

Fig. 5 end 6 show the front panel of the implemented VI in the actual working conditions. The plots on these panels show the input signals, the determined equivalent elliptic loop and the actual hysteresis loop. The measured values of the dc flux component, the minimum and maximum induction values and the total losses are also reported.

## 5. CONCLUSION

An experimental method has been proposed in order to determine the dynamic hysteresis loop of a magnetic material under asymmetric cyclic conditions.

The proposed method is still based on the integration of the electromotive force induced on a search coil, for the evaluation of the pure ac component of the magnetic flux, and the determination of a suitable linear equivalent circuit, for the evaluation of the dc polarization component of the flux itself.

The method proved itself quite accurate and the experimental results of measurements performed under pure ac conditions and dc polarized cyclic conditions are in perfect agreement with the results of measurements coming from an Hall-effect flux probe.

The method accuracy is good enough for using this method in many industrial applications, especially in transformer and rotating machine manufactures, where the actual behavior of the magnetic plates under polarized cyclic magnetization must be investigated in order to better evaluate the machine performance.

## REFERENCES

[1] A. Brandolini, E. Carminati, A. Ferrero: "A completely microprocessor-based measurement of magnetic properties", *IMAC 84 Conference*, Tokyo, Japan, 1984.
[2] E. Carminati, A. Ferrero, "A Virtual Instrument for the measurement of the characteristics of magnetic materials", *IEEE Trans. Instr. Meas.*, vol. 41, n. 6, 1992.
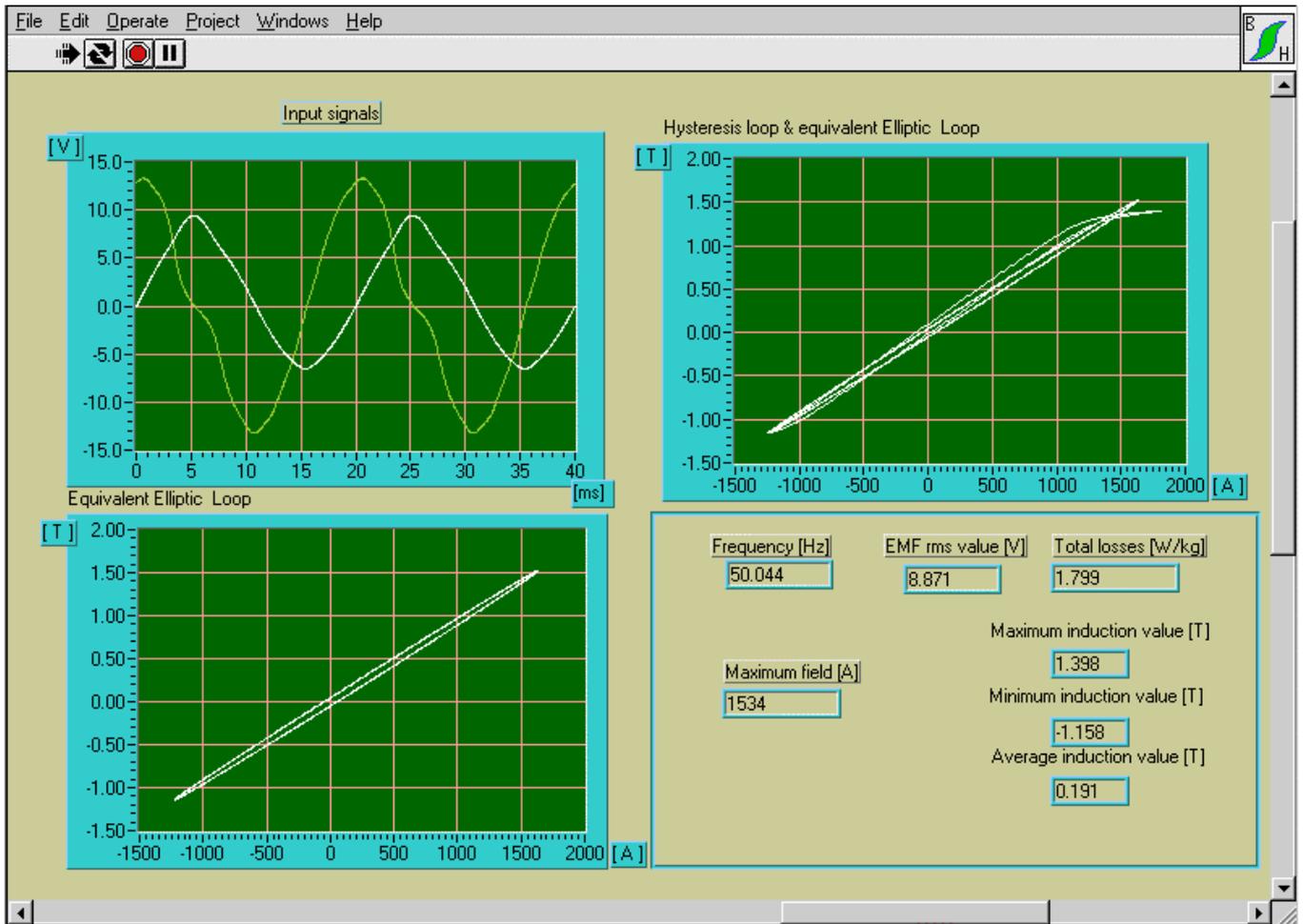
Fig. 6. Front Panel of the Virtual Instrument under polarized AC magnetization.

[3] A. Ferrero, A. Raciti, "A digital method for the determination of the magnetic characteristic of variable reluctance motors". *IEEE Trans. Instr. Meas.*, vol. 39, n. 4, 1990.

[4] L. D'Alessandro, A. Ferrero, "A method for the determination of the parameters of the hysteresis model of magnetic materials". *IEEE Trans. Instr. Meas.*, vol. 48, n. 4, 1994.

[5] A. Salceanu, L. Breniuc, O. Ciobanu, "Programs and virtual hysteresisgraph for scalar Preisach modelling", *IMEKO TC4 Symposium*, Napoli, Italy, 1998.

[6] S. Leva, A. P. Morando, "Topological transition from magnetic networks to the electric equivalent ones when iron losses are present", *43rd MWSCAS Conference*, Lansing, USA, 2000.