Hysteresis loss analysis of magnetic materials with data acquisition system

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Magnetic materials are widespread in many fields of the electronics and electrical engineering. The most of them take place in the constructions of transformers, coil cores, electromagnets, measurement sensors etc. Thus, their parameters and characteristics are important to be studied precisely and within the whole operating range. Due to the nonlinear behavior of the characteristics of the magnetic materials it is crucial point to be obtained hysteresis parameters such, as saturation points and loss in the material. One advanced way to discover characteristics of the magnetic materials is usage of data acquisition system (DAQ). In this manner many tasks required precise and reliable solution can be executed. This paper represents the variant of the well-known oscilloscope's method via DAQ system. For obtaining hysteresis loop and programmable calculation of the loss the capabilities of the sampling of the DAQ measurement channels are used. With the software program, the instantaneous values of the studied voltages in real time are measured. The dynamic hysteresis cycle of the magnetization process is visualized.

***Keywords* – (data acquisition system, hysteresis loss, magnetic material).**

Изследване загубите от хистерезис на магнитни материали чрез система за сбор на данни (Ивайло Й. Неделчев). *Магнитните материали са широко разпространени в много области на електрониката и електротехниката. Повечето от тях намират място в конструкциите на трансформатори, сърцевини на бобини, електромагнити, измервателни датчици и т.н. Важно е да се изследват точно в целия работен диапазон техните параметри и характеристики. Поради нелинейния характер на характеристиките на магнитните материали от голямо значение е намирането на параметрите на хистерезината крива: точки на насищане и загубите в материала. Подходящ съвременен метод за това е използването на система за сбор на данни (DAQ). По този начин могат да бъдат решени задачи изискващи точно и надеждно решение. Тази статия представя вариант на добре познатия осцилоскопен метод за изследване на загуби в магнитните материали чрез използването на DAQ система. За получаването на хистерезисната крива и софтуерното изчисление на загубите са използвани възможностите за дискретизация на входните канали за измерване на DAQ модула. Чрез програмата LabVIEW, в реално време се представят, както моментите стойности на измерените напрежения по време на процеса, така и изчислените загуби в материала.Визуализира се и динамичната хистерезисна крива.*

Introduction

In our practice and daily life, we use equipment, consisting magnetic materials. Every transformer, inductor, electromagnet, most of the sensors and medicine equipment include magnetic material in its construction. Due to the large usage in many fields of the practice, the magnetic materials parameters are important in the engineering science. Their main parameters and characteristics are frequency dependent and thus it is important to be studied within the whole operating frequency range. Due to the level of magnetization dependence of the magnetic materials, they manifest nonlinear behavior. Therefore it is crucial point to be obtained parameters such as saturation points and loss in the material [1], [2]. The effect of hysteresis during cyclically magnetization is a crucial reason for appearing the loss in materials [3] [4]. One advanced way to discover characteristics of the magnetic materials is usage of data acquisition system (DAQ). This paper represents one study over the hysteresis loss of the magnetic materials via DAQ system. It is used the oscilloscope's method for obtaining hysteresis loop and also programmable calculation of the loss. The method can be applied for small by sizes parts of the tested magnetic materials, as well as for the big specimens with appropriate conditioning equipment - transducers and amplifiers. The program code based on LabVIEW software, calculates directly the loss in the material, using dynamic hysteresis loop. In real time instantaneous value of the studied voltages, as well as the hysteresis cycle of the dependence between magnetic flux density (*B*) and magnetic field strength (*H*) are measured and visualized.

Theoretical background of the method

In the oscilloscope's method the hysteresis curve of the magnetic material is obtained. The curve gives information for the hysteresis loss in the magnetic materials and for the main magnetic parameters such, as saturation points, retentivity and coercivity [1] [3] [5]. Fig. 1 shows the basic electrical diagram of the oscilloscope's method [1].

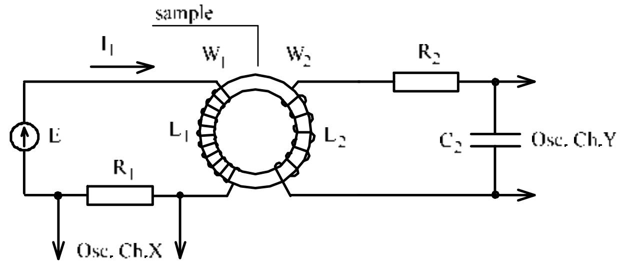

Fig.1. Electrical diagram of the oscilloscope's method.

In order to obtain hysteresis curve on the screen of the oscilloscope, it is necessary to have information for the magnetic flux density *B* and the magnetic field strength *H.* The magnetic quantities have to be connected with the electrical voltages, which could be measured easily with oscilloscope, adjusted to operate in XY mode. In order to work in sinusoidal magnetic flux density regime, the next condition has to be fulfilled: $R_1 << \omega L_1$ [1].

On the X channel of the oscilloscope voltage u_x is applied, which is in relation of the magnetization current i_1. According the Ampere's law (1) magnetic field strength *H* depends on the magnetization current i_1.

(1) $$H_t.l_{AV} = w_1.i_1 ,$$

where H_t is the instantaneous value of the magnetic field strength, l_{AV}, is the average length of the magnetic line into the specimen's core, w_1 is the number of the turns in the primary coil.

Using the Ohm law, magnetization current can be represented as a drop of the voltage on the known resistance (R_1). Thus, the applied voltage on the X plates of the oscilloscope is measured as the drop of the voltage on the resistance R_1 (u_{R1}) in the primary circuit of the experimental set. In this manner it could be made relation with the magnetic field strength instantaneous value H_t.

(2) $$u_x = u_{R1} = R_1.i_1 = \frac{R_1.l_{AV}}{w_1}.H_t .$$

The voltage applied on the Y plates of the oscilloscope is obtained after integration circuit, formed with the resistor R_2 and capacitor C_2 and can be expressed as:

(3) $$u_y = u_{C2} = \frac{1}{C_2}.\int i_2 dt ,$$

where i_2 is the current in the secondary circuit, C_2 is the capacity of the integration unit. According the KVL, the electromotive voltage in the secondary coil is [2] [3]:

(4) $$e_2 = -w_2.S.\frac{dB_t}{dt} = i_2.R_2 + L_2.\frac{di_2}{dt} + \frac{1}{C_2}.\int i_2 dt ,$$

where *S* is the cross section of the core, w_2 is the number of the turns of the secondary coil, B_t is the instantaneous value of the magnetic flux density, L_2 is the inductance of the secondary coil.

The components of the secondary circuit are chosen to be with the following relations:

$$R_2 >> \omega.L_2 ,\ R_2 >> \frac{1}{\omega.C_2} ,$$

where ω is the angular frequency. Thus, the expression (4) can be written as:

(5) $$e_2 = -w_2.S.\frac{dB_t}{dt} \approx i_2.R_2 .$$

According expressions from (3) to (5) can be found the drop of the voltage on the capacitor C_2 – u_{C2} and respectively voltage u_y is:

(6) $$u_y = u_{C2} = -\frac{w_2.S}{R_2.C_2}.B_t .$$

The scale of the obtained hysteresis curve depends on the constants (C_X and C_Y) of the X and Y channel of the oscilloscope [1]. Therefore, the scale coefficients (C_B and C_H) are:

(7) $$C_H = \frac{C_X . w_1}{R_1 . l_{AV}},$$

(8) $$C_B = \frac{C_Y . R_2 . C_2}{w_2 . S}.$$

It is known, that energy for cyclically magnetization of the specimen can be expressed as the contour integral by hysteresis closed curve, obtained by the oscilloscope's method. This integral is proportional of the area of the closed loop. The proportional coefficient depends on the scale coefficients (C_H and C_B), found in the equations (7) and (8) above. Then, the energy can be expressed as:

(9) $$E_H = \oint H dB = C_H . C_B . S_H,$$

where S_H is the hysteresis curve area. Therefore the specific hysteresis loss can be calculated as [1] [3]:

(10) $$P_H = \frac{f}{\rho} . E_H = \frac{C_H . C_B . f . S_H}{\rho},$$

where f is the magnetization current frequency, ρ = 7800 kg/m^3 is the volumetric mass density of the magnetic material. There is one more component of the specific loss in the magnetic materials – the Eddy current loss. The Eddy current loss can be expressed as [5]:

(11) $$P_E = \frac{\pi^2 . \sigma . f^2 . \tau^2 . B_{max}^2}{6},$$

where σ = 2,174.10^6 S/m is electrical conductivity of the material, τ is the thickness of the plate, B_{max} is the amplitude of the magnetic flux density. For the experiment $B_{max} < 0,3$ T.

The total loss is sum of the Eddy current loss (11) and hysteresis loss (10). The calculation by the parameters above shows, that by frequencies in the span of 60 ÷ 140 Hz, for small thickness of the specimen's plate and low levels of magnetization, the Eddy current loss (P_E) can be neglected ($P_H >> P_E$).

Measurement equipment. Setting of the experiment

The main components of the study are: magnetic material specimen, DAQ system, software program.

Experimental specimen

For the magnetic material specimen, the core of the laminated cold-rolled electrical steel plates is used. The experiment is conducted with E - core shaped specimen with plate thickness (τ = 0,1 mm.). The physical dimensions of the core are shown on the Fig. 2. The main sizes are: a = 20 mm, b = 20 mm, c = 5 mm, d = 3 mm. The average length of the magnetic lines (l_{AV}), is assumed to be located in the middle of the magnetic branches of the E - core (dashed lines in Fig. 2). Then, according the sizes (a, b, c, d) given above, the total length path of the magnetic lines is: l_{AV} = 94 mm. and the cross section of the central branch is: $S = c.d$ = 30 mm^2. The windings of the coils have the following parameters: primary - w_1 = 1400 turns, secondary - w_2 = 1400 turns.

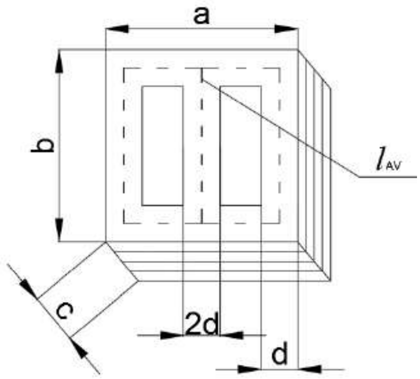

Fig.2. Shape and dimensions of the specimen.

DAQ system

For the experiments DAQ system model NI - 6211 of the National Instruments company is used. Data acquisition system type NI – 6211 contains 8 differential or 16 single ended analog inputs (AI), 2 analog outputs (AO), 4 digital inputs/outputs. The main parameters of NI – 6211 are [6]:

- Sampling rate (fs) 250 kS/s;
- Resolution 16 bits;
- Maximum working voltage for analog inputs (AI), Vi ±10 V.

The application of the DAQ system in the measurement method makes the experiment more precise in order to obtain clear dynamic hysteresis curve and simplify calculation of the scale coefficients (C_H and C_B) during the measurement. Their value is directly proportional to the measurement voltages received by the both input channels included in primary and secondary side of the experimental set. In this case, if the specimen has small sizes and experimental set doesn't need any transducers for measurement channels, C_X = 1, C_Y = 1 (in eq. (7) and (8)). This simplifies the calculation and increases the accuracy of the measurement during the dynamic changes of the specimen magnetization current. In other hand, the obtained results are with high resolution, due to the high sampling frequency rate (f_s = 10 kHz) of the measurement signals. They can be

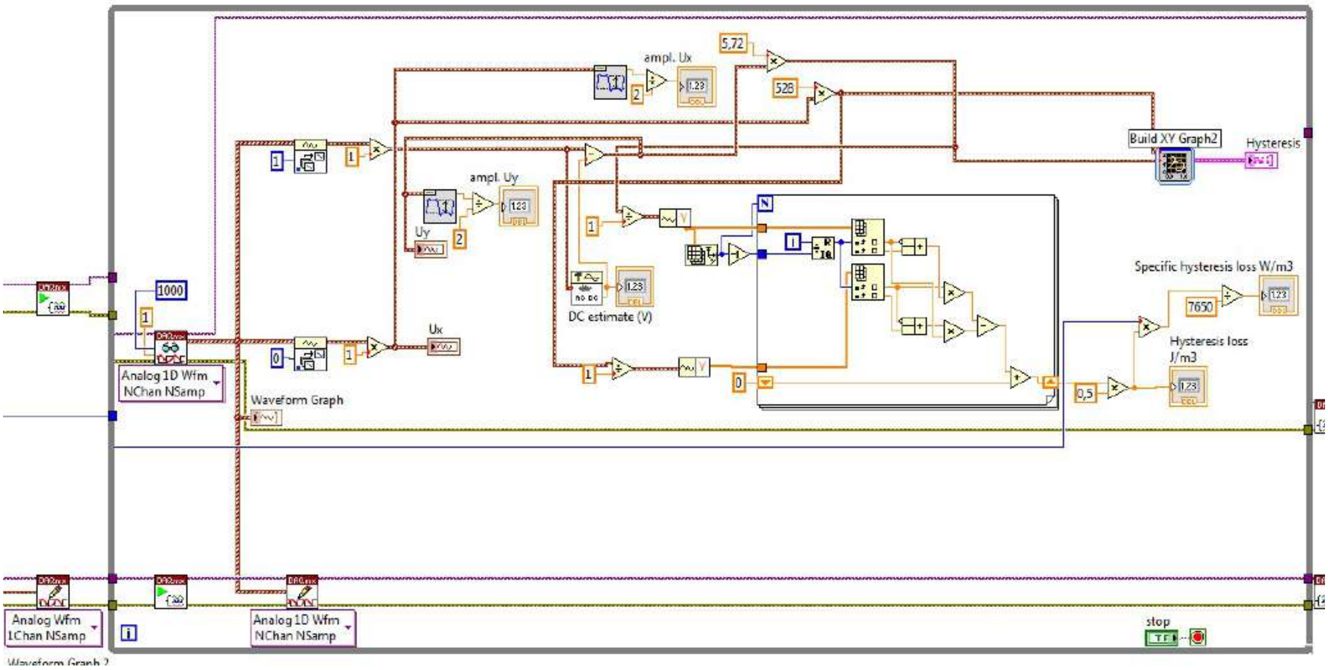

Fig.3.The part of the graphic code of the program.

represented in any form textual or graphical in real time. The hysteresis loss can be calculated and represented immediately during the measurement.

Software program

During the measurements, obtaining and calculation of the hysteresis curve, the LabVIEW software of the National Instruments company is used. It is a visual programming language, based on the graphically manipulating between program elements. The part of the graphic code is shown on the Fig. 3. The control panel of the program is shown in the paragraph of the obtained results, below.

Connection diagram of the experimental set

The inbuilt two analog output channels in NI - 6211 can generate signals with different types and shapes. For the experiment is used output AO 1, generating sinusoidal voltage, which peak to peak value vary between 1 - 10V depending on the magnetization of the specimen and the frequency of the magnetization is in the span of 60 ÷ 140 Hz. In the experiment are involved two input channels AI 1 and AI 4 for measurement the value of the magnetization current in primary coil and output voltage of the secondary coil. The used output and input channels of the NI – 6211, are adjusted to be in a differential mode [6]. The experimental electrical diagram is shown on the Fig. 4.

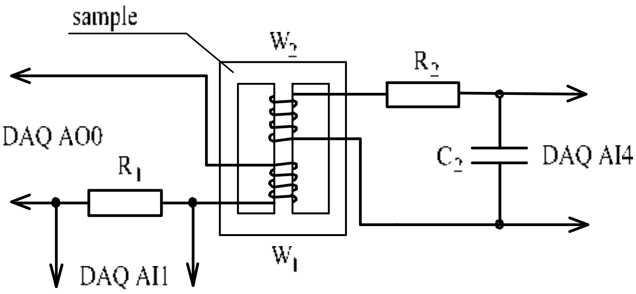

Fig.4. Electrical diagram of the measurement.

The nominal value of the electrical components are: capacitor C_2 = 100 nF, R_2 = 1,2 MΩ, R_1 = 52 Ω.

Estimation of the hysteresis loop area S_H

According (9) the energy for magnetization of the specimen E_H can be calculated by the area of the hysteresis loop S_H and scale coefficients C_B and C_H. One way for estimating the area S_H is to apply the Green's theorem [7]:

$$(12)\qquad \oint_H (u_x dx + u_y dy) = \iint_{S_H} \left(\frac{du_x}{dx} - \frac{du_y}{dy} \right) dxdy\,,$$

where u_x and u_y are voltages which gives the area S_H if is fulfilled the following condition:

$$\frac{du_x}{dx} - \frac{du_y}{dy} = 1\,.$$

Due to the sampling of the received voltage signals (u_x, u_y) with NI – 6211, the hysteresis loop can be represented as a polygon, consisting of n number of edges. The number n depends on the frequency sampling rate (f_s) of the measurement signals. Actually, the measurement data represent a multiplicity of points with Cartesian coordinates ($u_{x(i)}$, $u_{y(i)}$), which forms a two dimensional array. Then the Gauss's area formula (13) could be applied [7]. The expression (13) is a modification of the Green's theorem:

(13)

$$S_H = \left| \sum_{i=1}^{n-1} u_{x(i)}.u_{y(i+1)} + u_{x(n)}.u_{y(1)} - \sum_{i=1}^{n-1} u_{x(i+1)}.u_{y(i)} - u_{x(1)}.u_{y(n)} \right|,$$

where $u_{x(i)}$, $u_{y(i)}$, are the coordinates of the obtained curve, i.e. each sample of the measured voltages u_x and u_y.

Results

The magnetization of the specimen is conducted via output channel AO 1 of the NI – 6211. Maintained range of the output channel is ± 10 V. The control of the amplitude, form and frequency of the magnetization current is driven by software program. The program consists of control and connecting diagram panels. On the Fig. 5 is shown the control panel, which represents the manner of the driving measurements by supplying and receiving the voltages through the output (AO 1) and input (AI 1, AI 4) channels of the DAQ module. On the control panel the regulators for amplitude and frequency and the main diagram of the hysteresis curve are obvious, as well as the time-domain diagrams of the measured voltages in primary and secondary coil via analog channels AI 1and AI 4. On the top right position in the field of panel area are visible fields, which show calculation of the hysteresis loss by E_H and P_H in real time, obtained by Gauss's area expression (13).

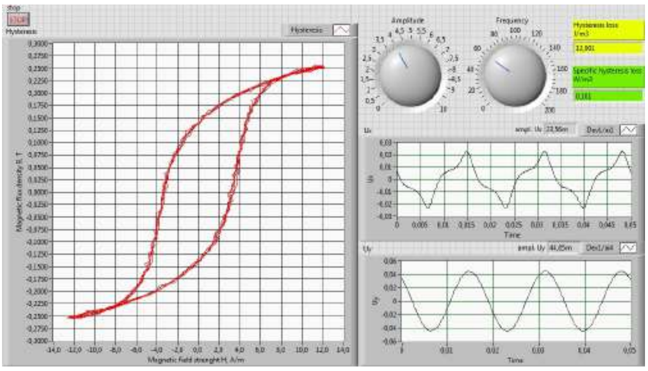

Fig.5.Control panel of the program.

For obtaining the magnetic parameters in broad operating span, the magnetization could be controlled by frequency and amplitude in order family of the characteristics to be built. For the experimental set, the output voltage frequency from AO 1, varies between 60 and 140 Hz, and its amplitude (by constant frequency) is changing in the range 3 V ÷ 10 V. Due to the real time graphical information and numeric representation of the main parameters of the measurement voltages, the experiment could be driven to the point of saturation, reaching the border hysteresis curve. This is visible either in the hysteresis curve diagram or in the time – domain diagram of the non – sinusoidal voltage u_x, which is related with the magnetic field strength H.

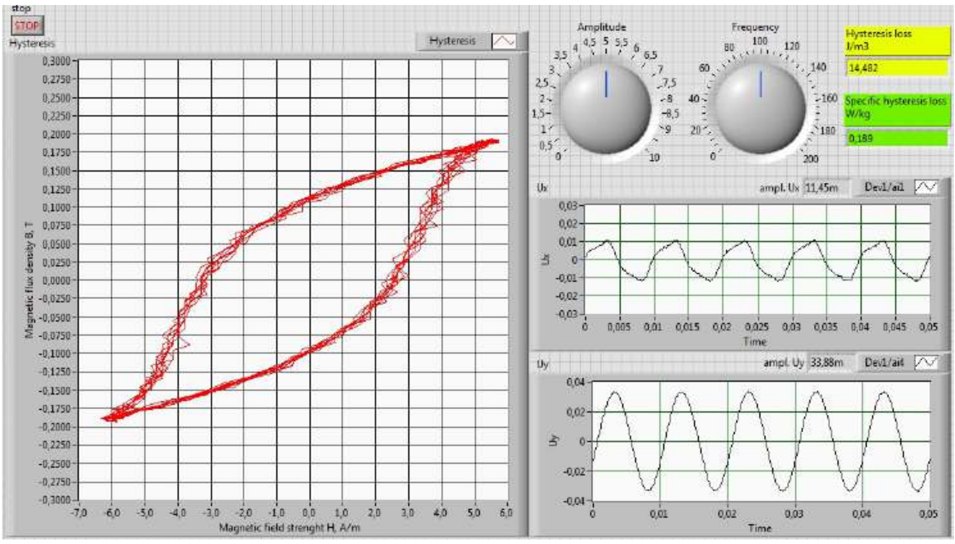

Fig.6. Control panel of the program by output voltage from channel AO 1 - U_{pp} = 5V, f = 100Hz.

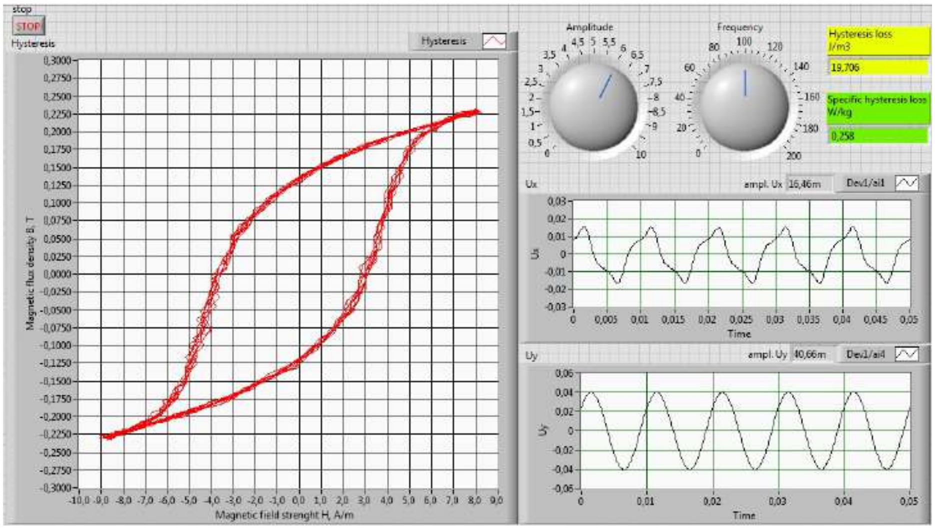

Fig.7. Control panel of the program by output voltage from channel AO 1 - U_{pp} = 6V, f = 100Hz.

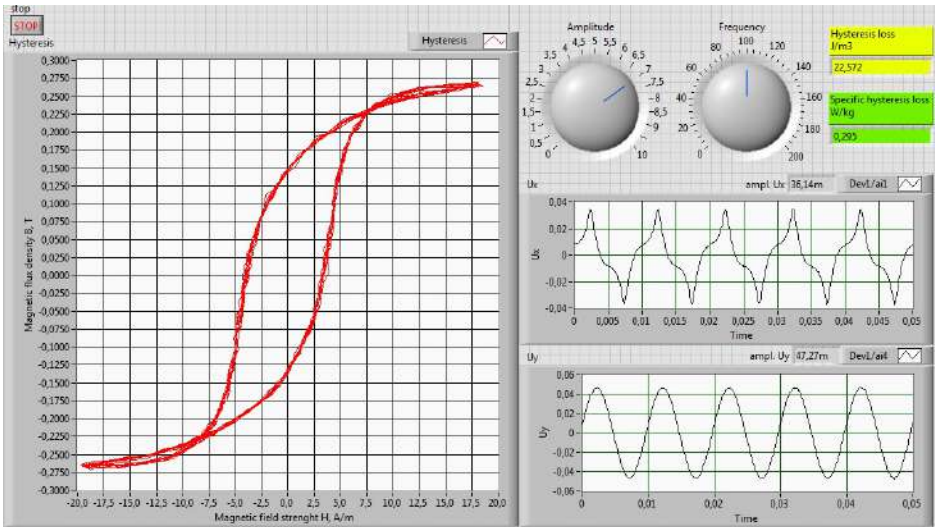

Fig.8. Control panel of the program by output voltage from channel AO 1 - U_{pp} = 7V, f = 100Hz.

On the Fig. 6 to Fig.8 the magnetization of the specimen are represented in the range of 5 V – 7 V for peak to peak value of the output voltage u_{pp} of the DAQ channel AO 1, by constant frequency $f_{const.}$ = 100 Hz. It is shown the corresponding drop of the voltages on the resistor R_1 in the primary circuit – u_x, as well as the inducted voltage in the secondary circuit - u_y.

The obtained graphical and numerical results show gradually increasing stages of the magnetization of the specimen. It is obvious (Fig. 6 to Fig. 8) that for magnetization current of 100 Hz, for this experimental set, is needed to supply voltage u_{pp} = 7 V in order to reach saturation level and border hysteresis curve.

This input voltage, causes a vast distortion level into the primary circuit (u_x), respectively on the magnetization current. The hysteresis closed curve is not clear shaped, due to the dynamical fluctuations during the cyclically magnetization. This causes alternating line borders of the curve during the time period, change its area and therefore the calculated hysteresis loss. In Table 1 data of the magnetization by frequency are represented in the range 60Hz – 140Hz of the magnetization input voltage u_{pp}. Increasing magnetization frequency, makes reaching the saturation level on higher values of the input voltage u_{pp}.

This is an effect of the increasing of the reactance in the primary circuit, which restricts the magnetization current. The trend in frequency domain is shown on the Fig. 9. Specific hysteresis loss P_H, is in dependence on the magnetization current, because of the enlarging the area of the curve S_H during the u_x and magnetization frequency f (eq. (10)). This is represented on the graphics in the Fig. 10.

Table 1

Hysteresis loss obtained by frequency range 60 – 140 Hz of the input magnetization voltage

$f_{const.}$	u_{pp}	u_x, amplitude value	u_y, amplitude value	E_H	P_H
Hz	V	mV	mV	J/m^3	W/kg
60	3	11,94	34,20	8,35	0,066
	4	23,56	44,85	12,91	0,101
	4,25	40,98	47,43	13,27	0,104
70	3	9,68	29,04	7,35	0,067
	4	14,20	38,40	12,02	0,112
	5	45,66	47,92	15,74	0,144
90	4	10,33	30,33	10,45	0,123
	5	13,55	37,59	15,76	0,185
	6,5	71,63	48,89	19,32	0,227
100	5	11,62	34,20	14,82	0,194
	6	16,13	40,82	20	0,261
	7	47,76	48,24	23,20	0,303
140	6	9,84	29,69	16,62	0,304
	8	14,52	39,20	27,43	0,502
	10	51,95	49,21	33,67	0,617

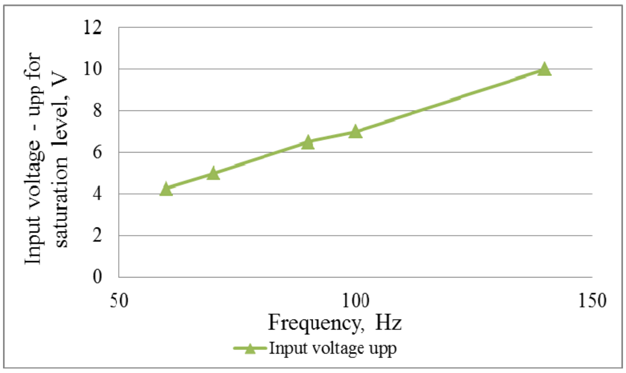

Fig.9. Needed Input voltage for reaching saturation level.

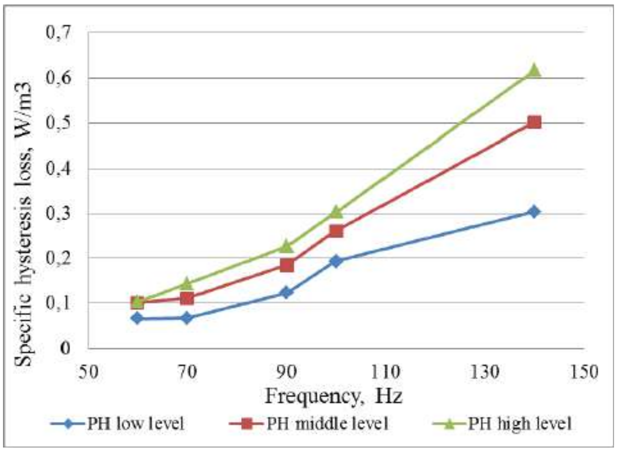

Fig.10. Specific hysteresis loss.

It has to be mentioned, that this manner of calculation of the hysteresis curve area is applicable below of the levels of saturation of the material. Above this level of the magnetization, the dynamic curve loop forms intersections and respectively the areas with the opposite sign in (13) are occurred. This makes the calculations not correct.

Conclusion

The experiment clearly shows one application of the DAQ systems in measurement the main parameters of the magnetic materials. DAQ system capabilities were applied upon the small magnetic specimens, which is one advantage of the experimental set. This could be done also for the specimens with bigger sizes, using appropriate amplifiers and transducers. With this basic experimental set, could be measured in real time a big number of the main parameters of the magnetic materials. This makes possible to be represented immediately the magnetization trends and characteristics such as hysteresis curve, primary magnetization curve, permeability during the magnetization and also to find the coercivity and retentivity. One crucial advantage over the oscilloscope's method, using DAQ in this type of measurements, is obtaining the dynamic hysteresis curve. The width of the curve borders shows the dynamic level of the process. Thus the fluctuations in the loss value can be estimated also. This could be observed during the low levels of magnetization. The involving of the DAQ system in the experiment increases the data accuracy and expands the measurement potential.

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