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# Labview based testing system for the aim of construction of energy efficient magnetic cores

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**Abstract.** There is increasing demand for more and more energy efficient magnetic cores to be used in modern electrical devices like inverters or smart grid instrumentation (high and medium voltage instrument transformers). The most important magnetic parameters are as high as possible magnetization characteristics ($B_m = f(H_m)$ curve) associated with lowest specific total core losses. As magnetic properties of magnetic cores become worse during production processes it is extremely important to test them in order to improve the production process. In the case of large magnetic cores they cannot be tested in generally used computer systems. Therefore, there is a need for quality testing system for cores of large mass, in the order of several hundred kilogramms.

The paper presents an example of an application for testing the system based on Labview platform for quality checking of large magnetic cores in the order of 1000 kg. Example of testing data for one and three phase core are presented.

## 1 Introduction

There is increasing demand for more and more energy efficient magnetic cores to be used in modern electrical devices like inverters or smart grid instrumentation (high and medium voltage instrument transformers). The most important magnetic properties of magnetic cores, when assessing their quality - should include characteristics of magnetization ($B_m = f(H_m)$), relative permeability ($\mu_r = f(H_m)$) and specific total loss ($P_S = f(B_m)$).

There are many methods for quality checking of magnetic materials like electrical steel sheets, amorphous or nanocrystalline tapes as for example and they are toroidal sample [1], Epstein frame [2], SST [3]. However, technical challenge is to check properties of readymade magnetic cores. Large mass of cores in the order of dozen of kilograms or several hundred kilograms make impossible to test such cores in generally used universal computerized systems for testing of magnetic materials as for example [4-9]. The systems posses limitation of range of flux density measurements at which measurements are performed with specified accuracy at exactly specified waveform of magnetic flux distortion. In a case of relatively large masses in the order of dozens and more kilograms commercially available computer test systems are not usually used. This is due to the need to provide high-power necessary to magnetization if the core which has big amount of a ferromagnetic material. The

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measurement range depends on the size of the core, electrical steel tape grade, as well as the power of amplifier of the measuring system. For example, for 2000 W power amplifier and the core weight approx. 25 kg achieved flux density is equal to 1.6 T for core made of HiB tape, or only 1.1 T in a case of core made of non-oriented tape.

Production of cores from electrical steel tapes requires the use of such technological processes as, for example: cutting, packaging of, squeezing, twisting or welding. These processes, as well as undesirable air gaps cause further deterioration in the properties of the final product. Additionally, magnetic properties of cores become more deteriorated as they are made of high quality ferromagnetics as for example from laser scribed electrical steel. Hence, the correct determination of the magnetic properties of cores gives the ability to maintain the high quality of the final product. Therefore it is necessary to test such large magnetic cores in other testing systems. In the case of magnetic cores producers there is an increasing need for quality testing system working in full or half automatic mode. Labview [10] platform gives possibility to complete this setup it in relatively short time and is open for modernizations.

In this paper the example of an application for testing system is presented to quality checking of one or three phases cores with weights up to 1000 kg. The testing system under consideration is made as portable system and enables test at power frequency 50 Hz/60 Hz. The system allows for precise and first of all repeatable determination of magnetic properties of tested magnetic cores.

**a)**

**b)**

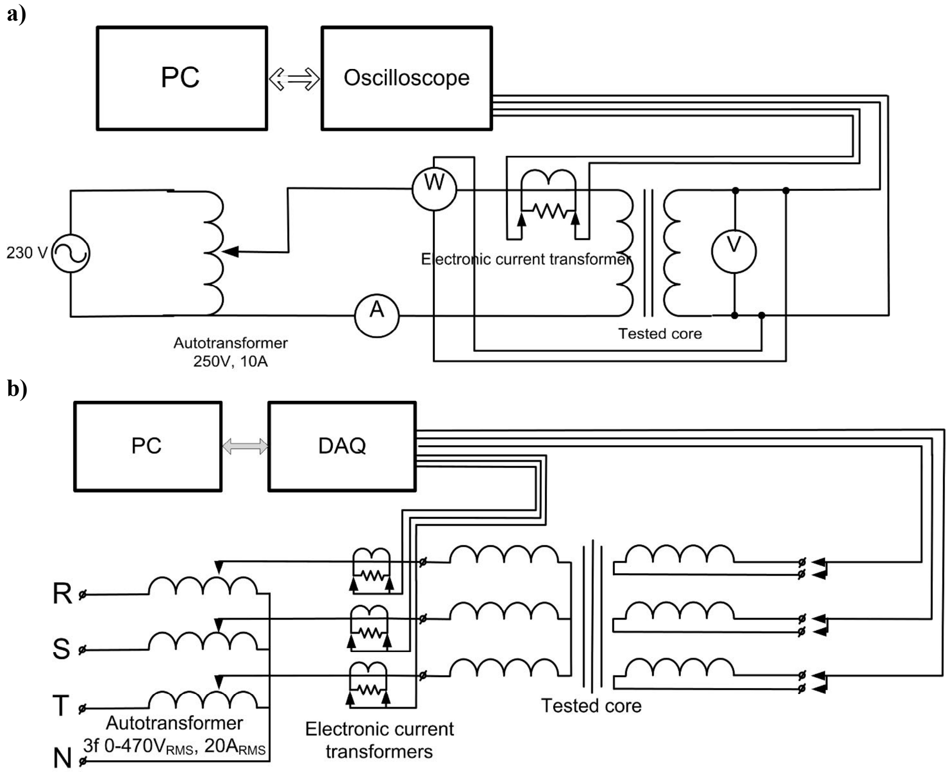


**Fig. 1.** Schematic diagrams of testing systems using wattmeter method for quality checking of: a) one phase magnetic cores with oscilloscope, b) three phase cores with DAQ card and Labview

## 2 Measurement system

Study the properties of soft magnetic materials is to determine, among other such parameters as specific total loss $P_S$ [W/kg] measured at different flux density $B_m$ levels and corresponding, effective flux density $B_{eff}$ [T], maximum field strength $H_m$ [A/m], effective field strength $H_{eff}$ [A/m], remanence $B_r$ [T], coercive field strength $H_c$ [A/m], relative permeability ($\mu_r$) or specific apparent loss $S_S$ [VA/kg] and ac hysteresis loops as well. All the parameters are calculated on a base of measured waveforms: primary current *i(t)* and secondary voltage $u_2(t)$ whose corresponds to flux density waveform *b(t)* and magnetic field strength *h(t)* calculated form (1) and (2).

For determination of magnetic properties of large cores most often wattmeter method is used (Fig. 1a) [11, 12]. This method was considered until recently as more labor intensive and less accurate. The paper presents the application of this method, by using Labview. Also some examples of test results for single and three-phase core are presented later in the paper. The schematic diagram of this system is shown in Fig. 1b).

The measuring system shown in Fig. 1a) is composed of wattmeter, ammeter A, voltmeter V, electronic current transformer and oscilloscope used to control the waveform of magnetic flux density. In that measurement process is also useful to use a computer for data acquisition, which reduces the time of acquisition data and processing results. Power supply of system from Fig. 1a) directly from the network preserve the waveform factor to be within ± 1% as required by standards [1-3] and only at high magnetic field strength it goes to higher values. However, as shown in [12] discrepancies due to waveform factor are not high and can be omitted when core are tested for industrial quality checking purpose.

The system presented in Fig. 1 b) is very similar to the one presented above in Fig. 1a). The main difference is the use of DAQ card instead of many devices such as three wattmeters, ammeters and voltmeters plus minimum three inputs oscilloscope. In presented testing system there was used NI USB-6251 BNC M-series [13]. The DAQ card posses eight differential BNC analogue inputs each of 16 bits resolution at sampling rate of 166 kS/s when used six channels. This card has also twenty four digital I/O channels and some of them are planned to use for measurement automation purposes as for example to change shunt resistors or voltage divider.

The measurement system is equipped with a device that prevents engagement of the connection to the test core when the autotransformer is not in the zero position. It enables to supply one phase or three phase test core.

An ac sinusoidal current inject into the excitation winding which induces a magnetic field H in the sample. The value of current is obtained from electronic current transformer. The value of applied magnetic field *H* is directly proportional to the current according to line integral form of Ampere's law.

$$h(t) = \frac{u_H(t) z_{ct}\, z_1}{R_b l_{av}} \tag{1}$$

where: $l_{av}$ is the effective magnetic path length of the test core, $u_H$ is the voltage on $R_b$ resistance, $R_b$ is the burn resistance of an electronic current transformer, $z_1$ is the total number of turns in the excitation winding, $z_{ct}$ is the number of turns of an electronic current transformer.

As autotransformer does not provide isolation from electrical network the use of an electronic current transformer allows electric separation from electrical network. To obtain the induced flux density B the induced voltage is integrated over time. This results from induction law and is described by (2):

$$b(t) = \frac{1}{s_{Fe} z_2} \int u_B(t)dt \qquad (2)$$

where: $s_{Fe}$ is the cross sectional area of the test specimen on which is wound a secondary winding (test winding), $u_B$ is the induced voltage in measurement winding (secondary site), $z_2$ is the total number of turns in the measurement winding.

Set out by measurement way instantaneous values of magnetic field intensity (1) and of magnetic flux density (2) allow for determination of a number of parameters characterizing the magnetic properties of the tested core. These two waveforms contain all the information about the magnetic properties of interest. If they are plotted in an X-Y plane a hysteresis loop is obtained (Fig. 2a). The area of the loop is directly proportional to the active power loss dissipated in the material and the specific total loss can be calculated from (3).

$$P = \frac{1}{\gamma s_{Fe} z_2 T} \int_0^T h(t) u_B(t)dt \qquad (3)$$

where: $t$ is the time, $T$ is the cycle of measured waveform, $\gamma$ is the mass density of material the tested core is made of.

The apparent power loss also is calculated directly from current and voltage waveforms but taking into account the turn ratio. The apparent power loss is a measure of total power, which needs to be delivered to the core in order to magnetise it to a required level.

Using the system as in Fig. 1b) can be determined such dependences as the dynamic magnetization $B_m = f(H_m)$ or the relative permeability characteristics $\mu_r = f(H_m)$ calculated from the peak values of $b(t)$ and $h(t)$ waveforms. Examples of hysteresis loops for stacked and welded core, weighing approx. 23 kg, made of grainoriented tape shown in Fig. 2.

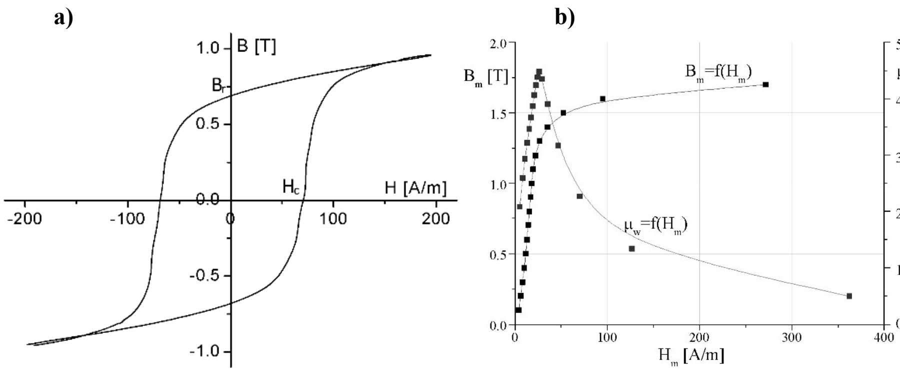


**Fig. 2.** Specific experimental examples of the characteristics measured at frequency of 50 Hz: a) the hysteresis loop for the of magnetic flux density approx. 1.0 T determined experimentally for the core stacked welded with a mass of approx. 23 kg, made of grainoriented tape grade M130-27S and b) the characteristics of $B_m = f(H_m)$ and $\mu_r = f(H_m)$ grainoriented tape grade M130-27S tested in SST (own measurements)

As it is shown later wattmeter method based on Labview and with use of DAQ card, allows easier and more accurate measurement of magnetic properties of the cores of relatively large masses.

## 3 Labview implementation of the measuring system

Labview is a programming environment based on a graphical user interface [10, 14] and is a set of programs created by National Instruments, serves as a development environment, containing an extensive set of routines optimized for fast processing of collecting and analyzing data. What distinguishes the programming of Labview in other programming environments is a way to write code. Labview use graphical interface, wherein the program code is created similarly to build electronic circuits as in Pspice [15] by combining elements in such a way as to implement a predetermined function. There is also the possibility of inserting routines written in other programming languages such as Assembler, however, the concern is usually very specialized calculations. The program is executed in accordance with the concept of Data Flow, wherein the lead wires to the function data, and then receive results that have to carry out the following functions [10]. This approach to programming is very intuitive for electronics engineers and thanks to a well-developed system of aid does not need to remember the names of functions and the order and types of their arguments. National Instruments also provides a dedicated measuring devices connected to the computer (controller) allow for automated data acquisition (usually measurements of electrical signals) and outputting output signals.

The application created in Labview consists of two main components. The first is the front panel constituting the interface input and output. While the second element is a window Block Diagram, in which is stored the source code (in graphical form) program. The user interface (front panel) for the measurement, analysis and storage of electromagnetic is shown in Fig. 3.

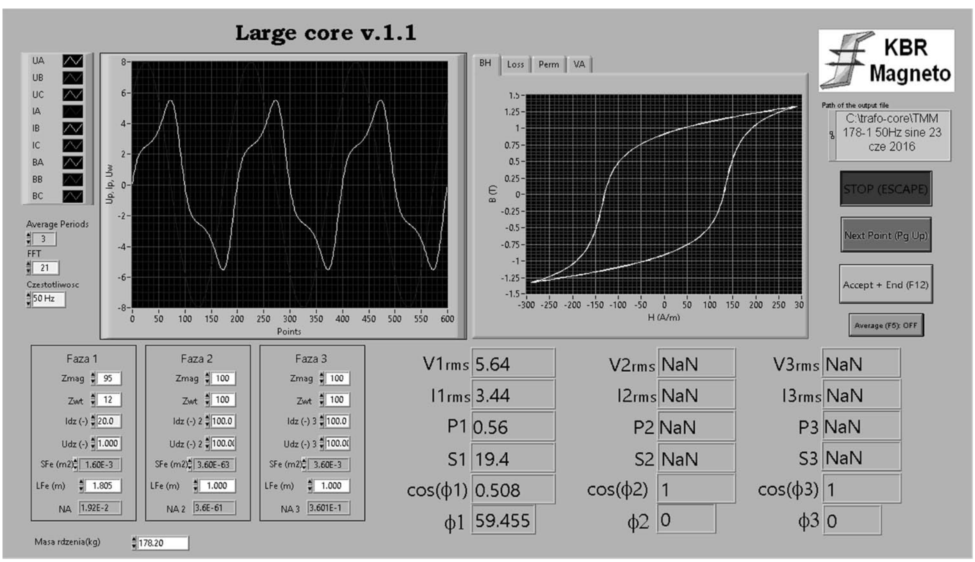


**Fig. 3.** Front panel of the application

The block diagram and example of code is presented in Fig. 4.

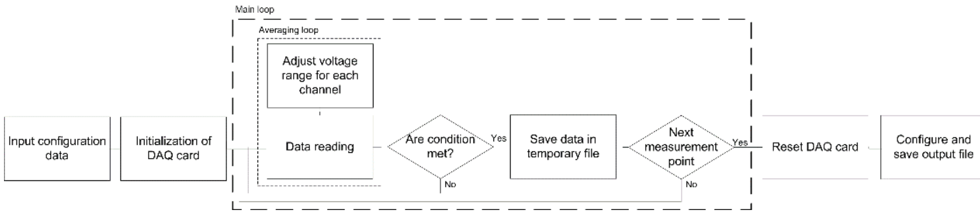


**Fig. 4.** Block diagram of presented system

Source code of developed in this environment measurement application is organized usually in following sections of program. They are configuration section of communication with a used device, section of data acquisition and on-line calculation and last section of data saving. The configuration part consists of creation of metrics of measurements and DAQ card initialization. The file of metrics of measurements consists of date and time of measurement, user ID and path the file saved at the first time. Also at part of the code is loaded data of a magnetic core to be tested including such basic data as core mass, average magnetic flux length, numbers of turns of magnetizing and secondary coils, core cross section on which the secondary coil was wounded and frequency. In core configuration file also are included scaling data of current transformers and voltage dividers. The initialization of a DAQ card consists of choosing a proper card, channels definition and timing setup. In the next section there are two loops which one consists of data reading and adjusting voltage range for each channel which is also used for averaging purposes. The second consists of mentioned averaging loop and calculation and presentation of chosen quantities. In this main loop also temporary data saving is included. The last section resets DAQ card and configure and in the long run save output file.

For precise measurement can be used data acquisition card (DAC) with simultaneous sampling of measured signals. Such DAQ cards are rather very expensive if taken into account accuracy, sampling rate or number of voltage input ranges (increasing significantly accuracy of measurement). In cheaper cards commonly one analogue-to-digital converter is used. As an effect the signals seen by the computer are artificially delayed. This delay can be significant for accuracy in loss calculation. The necessity of precise measurement results from a definition of active power loss P and inductive load that shows magnetic core when tested. The active power loss is equal to:

$$P = UI\cos(\varphi) \tag{4}$$

where: $U$ is the RMS value of voltage induced in secondary winding (proportional to the rate of change of flux density), $I$ is the RMS value of magnetising current supplied to the primary winding (proportional to the magnetic field) and $\varphi$ is the phase shift between $I$ and $U$.

The angle $\varphi$ takes higher values as grows magnetizing current (magnetic field strength) and at the same time increases error in active power loss calculation (due to the trigonometric function cosine). Taking into account that when the system is used to test a magnetic core for three phase transformer there is a need to use minimum 6 channels for measurement and the error in measurement can be significant. For this reason software trigerring was used. The software decides by comparison to one channel at which point each channel should be triggered. The software trigerring applied in this system was succesfully used in [16]. The precize trigerring is particullarly important as averaging of input signal and the aim of the use is to improve accuracy of the measurements [17].

RMS and average voltages are calculated in the conventional manner, the Fourier transform is used for harmonic analysis and THD calculation and values for coercivity and remanence are calculated by linear interpolation of the *BH* loop appropriate neighbouring points. Data processing can only be carried out once and complete cycle of the magnetizing waveform is acquired. Therefore, the time of each iteration and thus the convergence time depend on the the fact whether are measured 3-phases or 1-phase magnetic core. The resulting file consists of metricsof the file, configuration data, calculated results such as maximum, average and RMS values of flux density and magnetic field strength, relative permeability, coercive field, remanence, specific total loss and apparent loss. Also collected waveforms of magnetizing currents, secondary voltages, flux densities and magnetic field strengths for each phase are stored in the resulting files. Name of the resulting file consists of core name, operators name and measurements time. Such name allow easy finding of the files in the future.

## 4 Results

Three cores for test were chosen: two stacked one phase, welded and bolted cores made of non-oriented electrical steel tape of grade M400-50A one of 28 kg in mass (Fig. 5 a) and one of 220 kg (Fig. 5 b). It is important to mention that the core is designed for choke and it has an air-gap of 2 mm. The third core was made as three phase core of 165 kg in mass and was made as cut core and of grain-oriented electrical steel tape of grade M130-30S (Fig. 5 c).

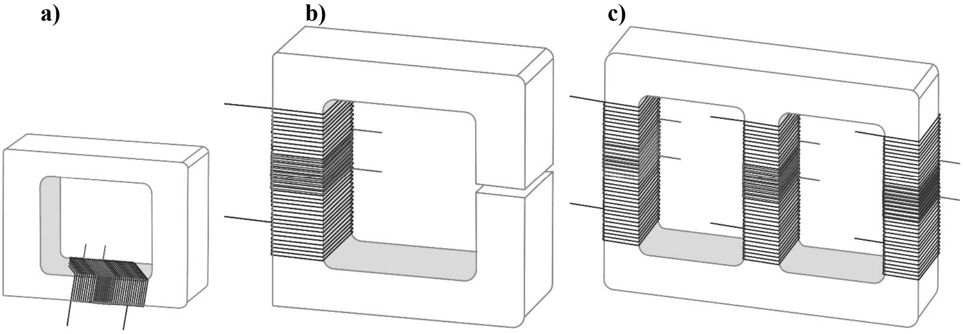


**Fig. 5.** Schematic drawing of tested cores: a) special transformer core(28 kg), b) choke core with air-gap (220 kg), c) three phase core (165 kg)

As presented in the paper [12] the computer system with power amplifier of 2000 W was able to measure properties of a stacked core with distributed air gap of 15 kg (similar to the one presented in Fig. 5a) only up to flux density of 1.6 T. By using wattmeter method was possible to determine the magnetic properties of 28 kg core (Fig. 5a) up to flux density of 1.9 T and the larger flux density was not measured due to weak control on very fast increase of magnetizing current. Thus was improved by the system described in the in the paper (Fig. 6 and 7).

Non-linear characteristics of the magnetization of the ferromagnetic core introduces a significant distortion of the magnetizing current and of the induced voltage on the secondary side even for sinusoidal voltage source. It has been found that with the increase of magnetic flux density from 1.0 T to 1.5 T, there is more than 3-fold increase in THD factor of the secondary voltage [12]. The accuracy of the measurement of the power loss is strongly dependent on the shape of the magnetic flux, in turn, proportional to the secondary voltage [1-3, 5, 11].

It is worth to mention that in general measurements using wattmeter method can be exposed to considerable error. This is mainly due to measure of the maximum magnetic field strength by ammeter and then multiply it simply by $\sqrt{2}$ . The error of determining maximum magnetic field strength by ammeter can be as high as 50% in relation to measured waveform of the magnetic field strength. The error will be different for different construction and different material of magnetic core. It was also shown that the method of using the measurement of waveform *h(t)* allows more precise measurement of the magnetic properties of cores through more precise definition of $H_m$.

It should be noted that during the magnetization deforms not only the magnetizing current (as discussed above), but also the induced magnetic flux and induced the secondary voltage. Changes waveform factor FF corresponds to the nature of changes in harmonic distortion THD of tested cores and the increase in THD is translating into an increase in loss of higher harmonics in the total loss [5, 12]. In the existing standards [1-3], it is assumed that the aspect ratio of the magnetic flux not to deviate from 1.1107 (i.e. for a sinusoid) more than ± 1%. As presented [12] it is possible for stacked core of about 30 kg to take measurements to the value of 1.2 T within the standard requirement.

Fig. 6 shows the characteristics of magnetization $B_m = f(H_m)$, and relative permeability $\mu_r = f(H_m)$ determined by computer system [9] for sample core (Fig. 5b) V made of electrical steel tape grade M400-50A and by the presented wattmeter method with DAQ card (Fig. 1 b) of made choke core (Fig. 5 b).

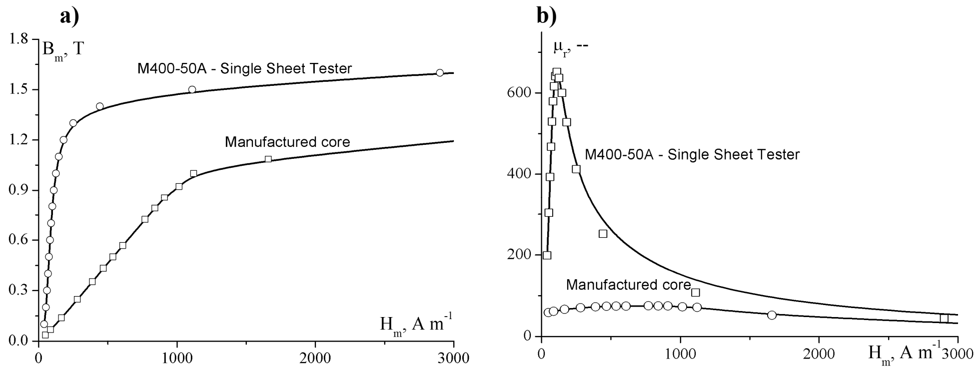


**Fig. 6.** Research results of sample core of 220 kg made of electrical steel tape grade M400-50A determined by computer system and wattmeter method with DAQ card: a) magnetisation characteristic $B_m = f(H_m)$, b) relative permeability $\mu_r = f(H_m)$

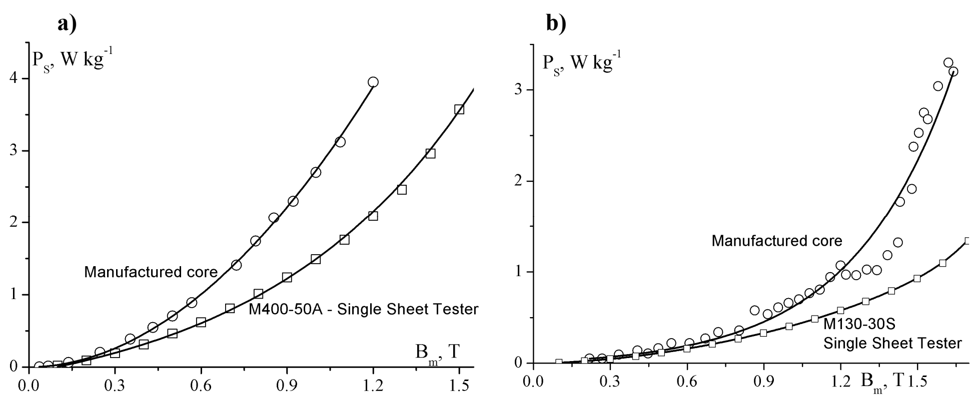


**Fig. 7.** Comparison of specific total loss $P_S = f(B_m)$ measured using computer system with SST [3] and wattmeter method with DAQ card for: a) one phase choke core of 220 kg made of electrical steel tape grade M400-50A and b) special construction of three phase transformer core of 165 kg made of electrical steel tape grade M130-30S

The presented in Fig. 6 difference between characteristics of electrical steel core sample results from airgap of choke core (Fig. 5b). Hence, first part of magnetisation characteristic of choke core is straight line and relative permeability is very low. The test of 220 kg choke core was performed up to magnetic field strength of 3000 A/m and relatively low flux density is considered as satisfactory. Using this advantage Fig. 7 shows the results of measurements of the core loss of one and three phase cores (Fig. 5 b), to a value above 1.5 T.

The data presented in Fig. 7 confirms usefulness of wattmeter method with DAQ card for measuring relatively large magnetic cores. Determination of loss is possible for such core at flux density values 1.4 or 1.6 T (respectively core screw or welded) and up to 1.9 T for smaller cores (like in Fig. 5 a).

Wattmeter method with DAQ card is relatively simple, but is deprived of advantage of forming shape of magnetic flux. The computer system is equipped with an adaptive feedback loop that allows the formation of magnetic flux in the core ensuring that it is sinusoidal in nature - in accordance with the requirements of the standard [1-3]. Wattmeter method with DAQ card is simpler, but not possessing this advantage. In this method, the magnetizing current flows directly from the network via an autotransformer - thus has no possibility to influence the induced magnetic flux in the core. Therefore, it should be count the possibility that for higher values of the flux density B its shape will differ from the standard. However, presented results confirm the high compatibility of the two measurement methods and hence the usefulness of the wattmeter method based on Labview, to assess the quality of cores with very large masses of the order of 1000 kg.

## 5 Conclusion

There is increasing demand for low cost and efficient transformers. At the same time the magnetic cores of transformers are subjected to ever more demanding magnetisation conditions. The intermediate testing allows to gather knowledge about the production process and hence to improve the quality of magnetic cores and finally to increase the efficiency of end product that is transformers.

Development in recent years of environments to support measurement allows relatively easy to create new applications of testing systems. In this work is presented one of such testing systems based on Labview. Selecting the Labview environment was mainly due to an extensive database routines and drivers dedicated acquisition and analysis of measurement data as well as considerations of programming easy for improvement and modernization. Thus it provides a relatively easy adjustment of the measuring system for current needs.

There are presented also test result of some chosen magnetic cores made of electrical steel tapes of masses in the order of 30 kg to 250 kg. It is believed that the system is capable to test magnetic cores and it is estimated that the mass could be so large as 1000 kg. The cores differ not only by mass but also by different construction as stacked and welded and stacked and bolted design for use in one and three phase systems and also made of non- and grain-oriented electrical steel tapes. There were measured basic magnetic properties and every test point is recorded and the control criteria are calculated. It allows real time recording of $b(t)$ and $h(t)$ waveforms which allow to calculate all parameters. The measurement is low cost and can be performed in semiautomatic mode of a series of complex measurements. Presented results of magnetic characteristics of magnetizing $B_m = f(H_m)$, relative permeability $\mu_r = f(H_m)$ and specific total loss $P_S = f(B_m)$ indicate the usefulness of the proposed method for industrial testing of large magnetic cores.

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