Experimental and Simulation Tests of Magnetic Characteristics of Electrical Sheet Steel

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Abstract: The article is devoted to the method of evaluation of magnetic characteristics of electrical sheet steel and information and measurement system intended for its implementation. This method is based on combination of application of special primary differential transducer of magnetic flow with implementation of further 'recovery' of real magnetic characteristic of the item's material. The authors propose an information and measurement system based on the realization of such method which provides for evaluation of magnetic characteristics of electrical steel of arbitrary thickness in alternating magnetic field. The authors have developed an algorithm and program package, which allow to set mechanism of re-magnetizing, register dependency of magnetic flow on the current in magnetizing system in the form of flux-current characteristic of an item, to define the magnetization curve (B-H characteristic) of the material. Distinctive feature of this device is possibility to make measurements on the samples of arbitrary form and size. Information and measurement system is realized on the platform of the company *National Instruments* and can be used both in laboratory tests and at a factory.

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1. Introduction

Modern development of technologies and increase in production of electric energy extends the area of application of soft magnetic materials and demands development of methods and instruments for control over the parameters of electrical items and their components. One of the key components of any electrical item is magnetic conductor formed by a package of pre-formed plates made from electrical steel. The characteristics of steel determine the features of ready item, such as its electro- and energy effectiveness, power-to-size ratio (P). For example, interrelationship of power-to-size ratio of a transformer P, frequency of magnetizing current f, coefficient of filling of magnetic conductor k_c, aperture occupation ratio k_o, current density in the coils j, maximum B_m and residual B_r magnetic induction, cross section area of magnetic conductor S_c, cross section area of air aperture of magnetic conductor of an item S_c [1]:

$$P = \frac{1}{2q} f k_c k_o j (B_m - B_r) S_c S_o$$

shows that basic method of minimizing of dimensions (reduction of cross-section area of magnetic conductor S_c) without changes in power leads to use of steel with better magnetic characteristics (B_m of materials must be higher). Here it is necessary to take into consideration that the process of formation of unworked pieces for plates influences resulting characteristics of the item greatly [2-4]. Definition of magnetic characteristics after mechanical and thermal processing is an important stage because of appearance on the unworked piece of the area of cold-work strengthening with worsened magnetic characteristics. Measuring of magnetic characteristics of magnetic conductor in miniature items in which cold-work strengthening area is rather large in comparison with the total area of the item is of utter importance because it influences integral characteristics of the whole item to a greater extent. Knowing magnetic characteristics of an unworked piece in the condition of flow process allows to adjust parameters of flow process [5], for example, to set temperature and length of burning in the oven.

Most of existing devices for testing electrical steel either do not provide high speed of tests and tests of unworked pieces of any form or do not provide all the functions for evaluation of both magnetic characteristics and the most important magnetic parameters. [6].

Earlier a sensor (mounted on top without fixing) and a device based on it were designed which allow to control magnetic characteristics of samples [7]. Disadvantage of this device is dependency of measurement's results on the form of an item and degree of magnetic saturation of magnetic conductor of primary transducer while testing miniature unworked pieces. It is not possible to evaluate magnetic characteristic of material of a sample exactly. Proposed by us method of experimental and simulation tests can solve this problem [8]. The key idea is to measure magnetic, for example, flux-current characteristic, of a system 'item -magnetic conductor of primary transducer of magnetic flow'. Then magnetic characteristic is calculated (magnetization curve) of the item's material as a first approximation. In order to do that it is assumed that magnetic conductor of primary transducer of magnetic flow does not influence the result of flux-current characteristic measurement. Calculated magnetization curve is then substituted into special mathematical model of the system and calculations are made. As a result so called 'calculated' flux-current characteristic of a magnetic system is obtained which is different from experimental one. At the next stages sequential change of magnetic characteristic of the item's material are made until flux-current characteristic of a system obtained by simulation will not coincide with flux-current characteristics of magnetic system, obtained experimentally. The result of it is the conclusion that magnetization curve substituted in stimulation is the true characteristic of tested material.

2. Methods.

While preparing materials for this article we used the elements of magnetic field theory, methods of experiment planning, measurement theory, mathematical stimulation methods with use of applied programs *LabVIEW, GMSH, Femm.*

Development of the structure of information and measurement system.

Main magnetic characteristic of the material used for designing of electrical items is dynamical normal magnetization curve. This characteristic is built by the coordinates of tips of hysteresis loops defined through injection tested sample with alternating magnetic field with increasing amplitude. (Figure 1).

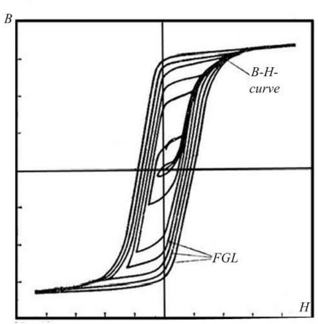

Figure 1 - Defining of magnetization curve: B-H-curve - magnetization curve, FGL – family of hysteresis loops

We have developed the information and measurement system for measurement of magnetic characteristics of electrical steel (IMS MMCES) which allows to define magnetization curve in accordance with Figure 1. Structural diagram of (IMS MMCES) is shown in the Figure 2. (IMS MMCES) includes: magnetizing device (MD) - differential transducer of magnetic flow [9], providing for avoidance of influence of the form of an item on the result of measurement, to three lower ends of which tested item is attached (TI); amplifier of AC (aAC); current sensor; sensing coils (SC1, SC2); interface board NI 6321 [10] connected to personal computer (PC).

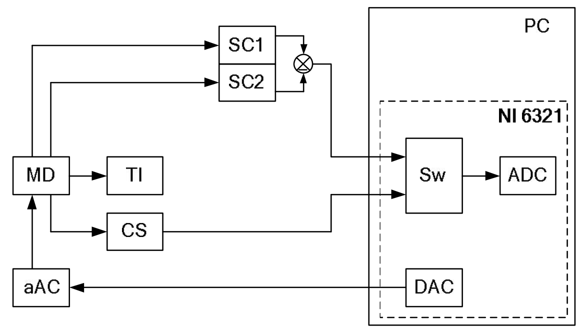

Figure 2 - Structural diagram of information and measurement system for identification of magnetization curve of sheet electrical steel.

In order to control the process of measurement, registration of information from sensors and changing of this information into the dependency form B(H) (magnetization curve) the program was implemented in *LabVIEW 2012* environment.

Information and measurement system operates in the following way. In accordance with algorithm on which control program is based the following actions take place in series: demagnetization of the item, then magnetization of it by means of increasing magnetic field with parallel registering of measurement information about EMF in the sensing coil *e(t)* and current in the magnetizing coils *i(t)*. Magnetic flow in tested area of TI is identified ([PHI]$_{ta}$(t),) which is connected with EMF inducted in the output of sensing coil, *e(t)* by formula [11]:

$$\Phi_{ta}(t) = \frac{\int e(t)dt}{2 \cdot w_{ta}}$$

By obtained dependencies [PHI]$_{ta}$(t), and *i(t)* a characteristic is build [PHI]$_{ta\_max}$(i_{max}) and then the material magnetization curve B(H) is "recovered" and displaying of these values on the PC screen.

Development of mathematical model of magnetic system.

In order to ‘recover’ characteristics method of experimental and simulation tests is used [8]. In order to use this method 3D and 2D models of magnetic system were designed (Figure 3, 4)

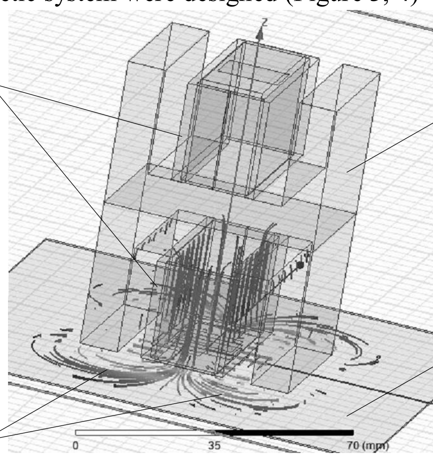

Figure 3 - 3D model of magnetic system.
1 - magnetic conductor, magnetizing coils, 3 - tested item, 4 - lines of magnetic flow.

We investigated 3D model which is implemented in GMSH-system and compared its indications with indications of of 2D-model implemented in Femm 4.2 system. During investigation parameter 'depth' of the model was set in accordance with width of tested sample. The results of calculations have shown that difference in models’ indications is not great (up to 3%) and in order to increase the speed of ‘recovering’ process of magnetic characteristic of the material it is better to use 2D-model. The resulting model is shown in the Figure 4.

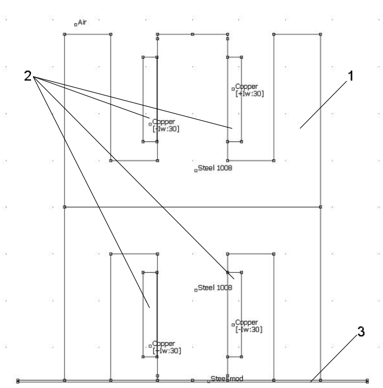

Figure 4 – 2D-model of magnetic system:
1 - magnetic conductor, magnetizing coils, 3 - tested item.

Development of algorithm of method of experimental and simulation tests.

In order to provide automation of the process of identification of magnetic characteristic we developed sub-program in the language lua4.2 providing automatic search for the magnetization curve which fits the result of physical experiment. Algorithm of this program is shown in the figure 5.

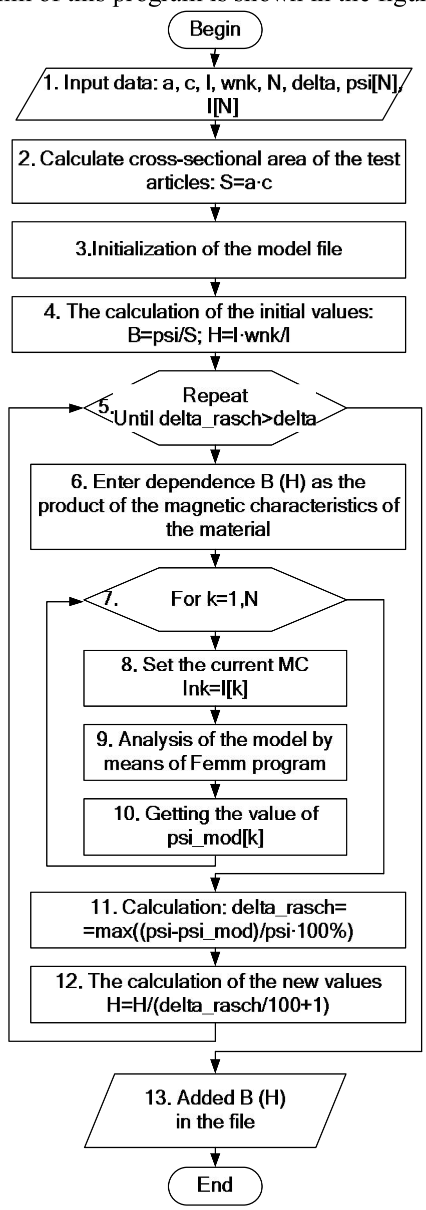

Figure 5 - Algorithm of recovering of magnetic characteristic of the item’s material in accordance with method of experimental and simulation method.

In algorithm (Figure 5) the following identifications are used: a -the width of tested area of an item; c - the thickness of the item; L - difference between the poles of differential transduser of magnetic flow; wnk - windings number of magnetizing coil of differential transducer of magnetic flow; N - a number of measured points of the magnetization curve; delta - maximal mistake of approximation ('recovering') of dependency $[PHI]_{ta\_max}(i_{max})$ obtained by simulation to analogous dependency, obtained by experiment; psi[N] - array of maximal values of magnetic flow $[PHI]_{ta\_max}$ obtained by experiment; I[N] - array of maximal values of current in the magnetizing coils for every cycle of re-magnitization (Figure 1) imax; S - area of cross-section of tested area of the item; B - array of maximal values of magnetic induction of material characteristic; H - array of maximal values of intensity of magnetic field; delta_rash - current nominal value of error of delta; psi_mod - array of maximal values of magnetic flow $[PHI]_{ta\_max}$ obtained by simulation.

Approbation of this algorithm was done on a sample with thickness of 0,4 mm. At the first stage flux-current characteristic with number of points N=20 was measured. Measured values of magnetic flow and the current in magnetizing coils of magnetic system were written in text files. Then the control was handed over to sub-program implementing algorithm depicted in the Figure 5. At the second stage this sub-program actuated the process of recovering of the material magnetization curve of the sample B(H) - see Figures 6 and 7. The figures show that characteristic of the material (Figure 6, curve 6) which fits given experimental values $[PHI]_{ta\_max}(i_{max})$ (figure 7, curve 1) was drawn through 6 stages of serial approximation. The process took 10 minutes, which is less than time necessary for putting measuring coil on the items of arbitrary complex form.

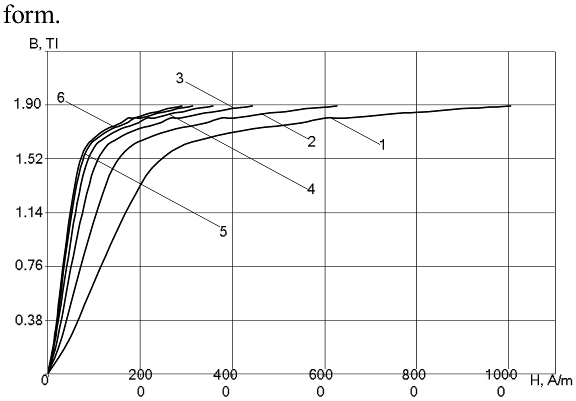

Figure 6. - Changing of magnetization curve of sample's material *B(H)* in order to provide in the model dependency of $[PHI]_{ta\_max}(i_{max})$ corresponding to the experimental $[PHI]_{ta\_max\ ex}(i_{max\ ex})$: 1,2,3,4,5 - curves in the process of approximation, 6- resulting (or 'recovered') characteristic of the material.

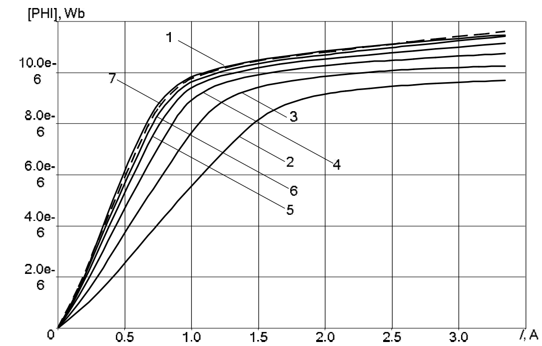

Figure 7. - Stage-by-stage approximation of dependency $[PHI]_{ta\_max}(i_{max})$ (curves 2-7), obtained by means of the simulation (model), to experimental characteristic $[PHI]_{ta\_max\ ex}(i_{max\ ex})$ (curve 1)

Obtained in the result of application of designed information and measurement system and, in particular, proposed algorithm the characteristic (Figure 6, curve 6) was verified by comparison with sample one - taken by means of special sensing coil put on the sample. The result is shown in the figure 8. Maximal relative error in any point of the characteristic does not exceed 5%.

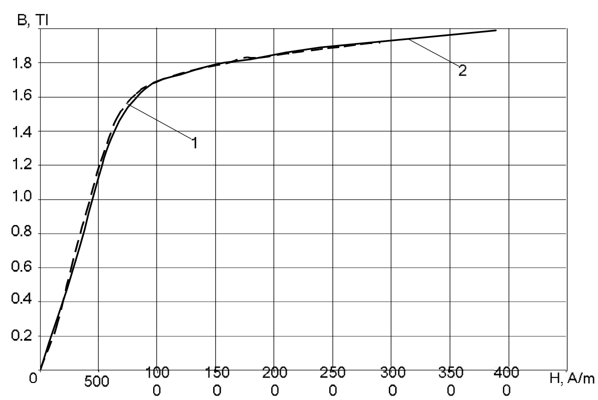

Figure 8 - Measured magnetization curves: 1 - obtained by means of proposed IMS, 2 - of a sample.

Inference

We propose information and measurement system based on developed earlier device for control of magnetic parameters of sheet electrical steel intended for measuring magnetic characteristics of samples of steel of arbitrary form. In order to identify magnetization curve IMS uses method of experimental and simulation tests implemented in the form of a set of programs which allows in automated mode by measured flux-current characteristic to ‘recover’ magnetization curve. In order to reach this set goal the following tasks were solved: development of mathematical model in 3D of magnetic field of magnetic system 'magnetizing device - sample', verification of 2D model; development of algorithm for tests of samples of sheet electrical steel which implements the method of experimental and simulation tests. Approbation of developed soft- and hardware complex was made by comparison of the results of measurement with known characteristic.

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