SELECTION OF TRANSFORMER SHEETS USING AN IMPEDANCE METHOD

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ABSTRACT

Different grades of electric steel may appear side by side at the stage of production and repair of transformers. The magnetic parameters of electric steels are also very sensitive to residual stresses and overheating. A handy method to verify the steel grade and the direction of anisotropy is needed. The article presents the impedance method, applied to control magnetic parameters of transformer sheets. The described methods are a complement to the standardized control methods (i.e. EN 60404-2, IEC 60404-3, IEC-60404-10) of transformer sheets applied by the producers and laboratory methods. The theoretical basis of the NDT method is presented. Then, the results of impedance tests carried out on 5 different samples are presented. The obtained results have been verified by single sheet tester (SST) and magneto-optical Kerr effect (MOKE) methods. It has been presented that the impedance measurements of the material might be used in non-destructive tests to quickly and cheaply evaluate the microstructure quality (e.g. selection of transformer sheets), the influence of mechanical and thermal stresses and the processes of fatigue degradation.

KEYWORDS: NDT, Electric steel, Magnetic properties, Measurement, Impedance

1. INTRODUCTION

Electrical steel is a special steel tailored to produce specific magnetic properties: small hysteresis area resulting in low power loss per cycle, low core loss, and high permeability. Electrical steel made without special processing to control crystal orientation, non-oriented steel (NGO), usually has a silicon level of 2 to 3.5% and has similar magnetic properties in all directions, i.e., it is isotropic. Grain-oriented (GO) electrical steel usually has a silicon level of 3%. It is processed in such a way that the optimal properties are developed in the rolling direction, due to a tight control of the crystal orientation relative to the sheet. The magnetic flux density is increased by 30% in the coil rolling direction (GO steel is anisotropic), although its magnetic saturation is decreased by 5%. To reduce electrical losses of GO steel, some manufacturers use laser scribing technology - applying small scraps on the surface of the sheet. Electrical steel is usually electrical insulation coated to increase electrical resistance between laminations, reducing eddy currents, to provide resistance to corrosion, and to act as a lubricant during die cutting. There are various coatings, organic and inorganic, and the coating used depends on the application of the steel. The type of coating selected depends on the heat treatment of the laminations, whether the finished lamination will be immersed in oil, and the working temperature of the finished apparatus. The magnetic parameters of electric steels are very sensitive to residual stresses and overheating. At the stage of production and repair of transformers, different grades of electric steel may appear side by side. A handy method to verify the steel grade and the direction of the sheet anisotropy is needed. The impedance method applied to control magnetic parameters of transformer sheets is presented in the article. The described methods are a complement to the standardized control methods (i.e. EN 60404-2, IEC 60404-3, IEC-60404-10) of transformer sheets applied by the producers and laboratory methods.

2. BASIC KNOWLEDGE

Electrical steel (an iron alloy which may have 0 to 6.5% silicon) is a special steel tailored to produce specific magnetic properties:

- small hysteresis area resulting in low power loss per cycle,
There are two groups of electrical steels that have a different chemical composition, structure, physical properties (electrical and magnetic) and are used in other applications - Fig. 1.

![Fig. 1. Electrical steels [1, inspiration http://www.thyssenkrupp.com](image)](image)

Today, the materials used in power transformers are grain-oriented, which means that the magnetic properties are much better in the rolling direction than in other directions. The important stages of core material development are: oriented, hot-rolled grain-oriented (HRGO), cold-rolled grain-oriented (CRGO), high permeability cold-rolled grain-oriented (Hi-B) and laser scribed [2].

Grain-oriented electrical steel (GOES) contains huge grains of Fe 3wt.% Si. They are oriented within a few degrees deviation of the easy direction from the preferred axis of the material. This kind of texture is known as Goss texture [3-6]. The basic domain structure of well-oriented Goss grains consists of wide domains magnetized parallel and antiparallel to the easy direction. It can be seen as in Fig. 2a), grain A. If the easy direction is slightly misoriented out of plane, it is shown in Fig. 2a), grain B, C, the basic domains are supplemented to reduce the stray field energy, namely shallow surface domains, lancets collect the perpendicular flux, which would otherwise appear from the surface due to the misorientation, and feed it into internal transverse easy-axis domains where it is transported to the other surface of opposite charge polarity or to the neighboring basic domain to be distributed again. The scheme of this process can be seen in Fig. 2c). In another case, the lancets join into combs, it is shown in Fig. 2a), grain C, by using an overall internal transverse domain that is properly oriented to avoid magnetostrictive energy [3, 7].

Transformers with GOES core work in an alternating magnetic field. The magnetization process along the favorable axis occurs by motion of the basic 180° walls. Moreover, during a magnetization cycle, the system of additional domains is destroyed and rebuilt. The energy bound in the supplementary domains is lost in every cycle, thus composing a substantial part of hysteresis loss in transformer laminations. Since several nonplanar easy axes are always engaged in supplementary domain patterns, their beginning and destruction is also connected with magnetostrictive, acoustic noise. It is good to know that the magnetostrictive elongation would not change by the motion of a 180° wall. Two possibilities are to avoid the unfavorable supplementary domains. They can be largely suppressed by mechanical tensile stress along the preferred axis. It is shown in Fig. 2b). It magnetostrictively prefers the basic domains and destroys the transversely magnetized domains. In this case, the basic domain spacing decreases, because otherwise the common stray field energy would increase in the lack of the supplementary domains. The decreased domain width also reduces the eddy current losses, which become important if the basic domain width is larger than the sheet thickness. Further advantage that the planar stress exerted by the stress-effective insulating coating is for the Goss texture equivalent to a uniaxial stress along the preferred axis and will suppress supplementary domains in this way. But, that for magnetostatic reasons, the lancet structure reappears when the basic domains are wiped out during the magnetization cycle as is presented in the sequence in Fig. 2d) and Fig. 2e). It results in extra losses. It is also possible to avoid supplementary domains completely if a misorientation of better than one degree is achieved. However, such a quasi-single-crystalline material would tend to develop very wide basic domains with correspondingly large eddy current losses. It can be seen in Fig. 2f). The domain width can be artificially reduced by scratching or by laser scribing. It is shown in Fig. 2g). The stress engaged locally in this way separates the basic domains, acting like an artificial grain boundary [3, 7].
The GOES has main and supplementary domain structure (the closure domain structures which retain the flux inside the material by forming a closed loop). Power loss of GOES and transformers with GOES core depends upon these structures. The domain structure changes on the application of stress which can change the magnetic behaviour of the material [8]. Anderson [9] has summarised the effect of stress on different magnetic properties of GOES in the rolling direction. From Fig. 3 it can be seen that tensile stress can be beneficial in reducing loss and magnetostriction whereas compressive stress increases the loss and magnetostriction. In case of permeability the optimum value is slightly in the compressive stress region [10].

\[ \mathcal{W}_h = \eta f B^\alpha \]  

where \( \eta \) is the material coefficient, \( f \) is the magnetising frequency, \( B \) is the flux density and \( \alpha \) is the exponent of flux density.

**Fig. 3** A graph representing effect of stress on various magnetic properties of GOES [9]
The Steinmetz model has some limitations concerning frequency $f$ and flux density $B$. Additionally, the model was developed for electrical steel sheets with maximum relative permeability $\mu_r$ lower than 5000. The magnetic permeability of presently produced GOES sheets is higher in the whole range of flux density except near saturation. The experimental work of Steinmetz passes well in limited range of flux density $B_s$ from 0.2 T to 1.5 T. The magnetisation frequency should also be limited to the range between 30 Hz to 100 Hz (500 Hz) [12]. The original Steinmetz equation was modified. The hysteresis and eddy current component were explained by Jordan [13].

$$W = W_h + W_e = \frac{C_0 f B^2}{\text{hysteresis loss}} + \frac{C_1 f^2 B^2}{\text{eddy current loss}}$$  \hfill (2)

Next, the anomalous loss $W_a$ (difference between measurement data and two component model) was introduced in a statistical loss model by Bertotti [14]. The total loss $W$ of ferromagnetic core is described by equation (3). The hysteresis loss coefficient $k_h$ and anomalous loss coefficient $k_a$ are only dependent upon magnetic flux. The eddy current $k_e$ is mainly devoted to domain structure.

$$W = W_h + W_e + W_a = k_h f f(B)B^2 + k_e(B) f^2 B^2 + k_a f 1.5 B 1.5$$  \hfill (3)

The model used for loss separation was proposed by Ionel et al. [15]. The loss per cycle is given by

$$\frac{W}{f} = \frac{k_h f B^2}{\text{hysteresis loss}} + \frac{k_e f B^2}{\text{eddy current loss}} + \frac{k_a f 0.5 B 1.5}{\text{anomalous loss}}$$  \hfill (4)

The equation (2) can approximate frequency behaviour of magnetic loss of non-oriented electrical steel where dependence $P_t/f$ = $f(f)$ forms straight line. This was also a case of electrical steel sheets produced years ago for which the formula was proposed that is hot rolled steel and without Si addition. The dependency of energy loss $P_t/f$ = $f(f)$ is very non-linear in GOES sheets. The non-linearity is particularly visible in low frequency as shown in Fig. 4 for M140-30S electrical steel. This shows that the use of eq. (1) and (2) is more justified for non-oriented than for grain oriented electrical steel sheets [12].

Transformer cores are made of thin laminated sheets. New rolled steel is supplied as coils, slit strip and sheets with electrical insulation coating of two types [10, 16 - 18] – Table 1:

- Coating Conventional (CC) – prime layer based on magnesium and silicon oxides, over which the layer of phosphates is applied (equivalent to <<ЭТ» coating under GOST 21427.1, as well as coating C2 + C5 under ASTM A976M);
Coating Magnetoactive (CM) – prime layer based on magnesium and silicon oxides, over which the layer of phosphates and silicon oxides is applied (equivalent to S2 type coating, as well as coating C2 + C5 under ASTM A976M).

<table>
<thead>
<tr>
<th>Type/class of coating (standard)</th>
<th>Base</th>
<th>Color</th>
<th>Thickness [μm]</th>
<th>Resistance factor [Ohm-cm²]</th>
<th>Thermal resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC (STO 05757650008-2007)</td>
<td>Magnesium and aluminium phosphates</td>
<td>Gray, glossy</td>
<td>1.5-5.0</td>
<td>≥ 20 (1.5-2.0 μm)</td>
<td>830°C, 10h in protective atmosphere (90% N₂ + 10% H₂)</td>
</tr>
<tr>
<td>ЭТ (GOST 21427.1) C2 + C5 (ASTM 976)</td>
<td>Combined (dehydrophosphates of magnesium, aluminum, silicates, chromates)</td>
<td>Gray or grash brown, glossy</td>
<td>1.0-3.0</td>
<td>≥ 30 (1.0-1.5 μm)</td>
<td></td>
</tr>
<tr>
<td>EC-5-G (EN 10342)</td>
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Table 1. Technical characteristics of the electrical isolation coatings on GOES [18]

Dielectric coating the GOES sheets helps in reducing both the losses and the magnetostriiction. Coating minimises the eddy current loss by providing insulation resistance and reduces the hysteresis and anomalous loss by improving the surface roughness and beneficial tensile stress to the substrate. Power losses could be reduced by 30-40% on improving the surface roughness. The magnetostriiction coefficient of the transformer core lamination is a significant parameter in determining the acoustic noise output of the transformer. The coating is beneficial in controlling the magnetostriiction of the material by creating a tension in the steel [10, 19 - 24]. The desirable properties in a coating are insulation resistance, heat resistance, chemical resistance, punctuality, weldability, corrosion resistance, burn out characteristics, resistance to compression, coating thickness, surface roughness and scratch resistance.

GOES quality is verified during production using of among others:

- measurement of total loss for 50 or 60 Hz according to standard EN 60404-2 [25]: min. 24 strips for 25 cm Epstein frame (length 280 – 310 mm ± 0.5 mm, width 30 mm ± 0.2 mm). All strips shall be cut parallel to the direction of rolling;
- measurement of total loss for 50/60 Hz according to standard IEC 60404-3 [26]: A single sheet tester (fully automated double yoke measuring coil system, 300 mm x 300 mm or 500mm x500 mm, 1D or 2D);
- measurement of a. c. magnetic properties in the frequency range 400 – 10000 Hz according to standard IEC 60404-10 [27]: Epstein frame is used;
- Inline measuring coil EBA (eddy currents): a double yoke system for strip in widths up to 1300 mm that is installed directly in the production line [28];
- measurement of insulator resistance according to ASTM A717 [29]: Franklin tester – a unique method of testing single strips of flat rolled electrical steel for surface insulation resistance under pre-dominated DC voltage, temperature and pressure conditions, measuring the insulation via all 10 electrodes or a single resistance per electrode;
- measurement of insulator thickness using a deltascope with magnetic inductive probe or dualscope with magnetic and eddy current probe [30].

3. RESEARCH PROBLEM

The physical parameters of GOES sheets (among others magnetic permeability, electrical conductivity, thermal conductivity of core and insulating layers) and technical parameters of transformers depend on:
- chemical composition of the laminated sheet and type of insulating layer;
- production quality (manufacturers and replacers);
- GOES transport conditions from the manufacturer to the recipient;
- methods and parameters of for cutting the transformer core from GOES sheet;
- transformer assembly quality;
- transformer operation parameters, including overloads, overheating and vibrations.

The same grade of GOES sheet from different manufacturers will have different physical parameters. During production and repair of transformers, it is recommended to control the quality of the GOES sheets and the direction of anisotropy using non-destructive methods.

The Franklin tester is the only standardized device that is used for the determination of the dielectric properties of electric-insulation coatings of GOES. It is used to measure the DC current value on ten electrodes with equal surface
areas that contact the surface of a material; the current is then recalculated into the electric-resistance coefficient of the polarizing coating, which acts as the main characteristic of dielectric properties. It is shown that the values that are measured by a Franklin tester do not characterize the particular dielectric properties of the coating, but only indicate the presence of areas (defects) on which the coating is absent [31].

4. EXPERIMENTAL RESEARCH

4.1 DEVICE UNDER TESTING

The devices under testing (DUT) were samples taken from GOES sheets manufactured by various world producers with a thickness of 0.23 – 0.30 mm. All DUTs met the delivery criteria and were also controlled by standardized method used by manufacturers. Lack of detailed catalog data and details of production technology meant that the DUTs were black box type objects.

4.2. TEST METHODS

The identification of DUTs parameters was performed by laboratory and NDT methods, e.g.:

- Optical tests of the DUT surface were made using Keyence and Olympus microscopes [32, 33]. The feature of the surface layer, including chemical composition (by spectroscopy) and profile, were analyzed.
- The display of magnetic domains through the insulation layer was carried out using the MagEye magnetic microscope with optical Kerr/Faraday effects [34] – Fig. 5a).
- The measurement of physical properties of the DUT were made using the low-frequency electric and electromagnetic impedance methods [35 - 47]. The measurement were made using precision impedance analyzer 4294A [34] – Fig. 5b), and a hand-held tester based on the LDC1000 converter [36, 48] – Fig. 5c).

For the dielectric evaluation an electric field was used between the capacitor covers. The magnetic field produced by coils of various shape (solenoid, circular PCB, rectangular PCB, stretched PCB). The impedance measurement has been performed for some frequencies. Under the influence of capacitive or inductive coupling, the electrical impedance of the probe is changing which describes the equation (5)

\[
Z_m = R_{z0} + \Delta R_z + j(X + \Delta X) = f\left( \sigma, \varepsilon, \mu, \frac{\tau}{d}, L, R_z, Q, SRF, \omega, k_m \right)
\]

where:

- \(Z_m\) is the impedance of probe (capacitor or coil) with influence of DUT; \(Z_0\) is the impedance of probe without influence of DUT; \(k_m\) is coupling coefficient of the probe with the DUT; \(R\) is the resistance (real part of the impedance); \(X\) is the reactance (imaginary part of the impedance); \(\varepsilon = \varepsilon' - j\varepsilon''\) is electrical permittivity (the ratio of the electric displacement field \(D\) to the electric field \(E\)); \(\sigma = \sigma' + j\sigma''\) is electrical conductivity (the ratio of the density of the current \(I\) to the electric field \(E\)); \(\mu = \mu' - j\mu''\) is magnetic permeability (the ratio of the magnetic induction \(B\) to the magnetic field \(H\)); \(\omega\) is angular frequency.

The reference data were the results of the SST method from the DUT tests carried out at the transformer manufacturer.

![Fig. 5 Showing: a) a mobile magnetic microscope MagEye (measurement area: 7x7 mm, optical resolution: approx. 10 \(\mu\)m); b) precision impedance analyzer 4294A (frequency range: 40 Hz to 110 MHz, accuracy: 0.08%); c) a hand-held tester based on the LDC1000 converter (resolution of: impedance Rp: 16-bits, inductance L: 24-bits, LC frequency range: 5 kHz – 5 MHz)]
4.3 RESULTS

On the basis of visual tests of DUTs performed on optical microscopes, quantitative differences were found in the top layer of the tested samples - Fig. 6, including scratch and scribing laser (depth of scratches and distances between scratches). One sample did not have technological features.

![Fig. 6 Visual inspection of DUTs with 50x, 200x and 500x magnification: a) sample #5; b) sample #6; c) sample #9](image)

The chemical composition of ferromagnetic cores and insulating layers was determined based on the spectral analysis of the DUT. It has been claimed that the insulating layers contain chromium, i.e. they are CM insulation layers (Coating Magnetoactive) according to Table 1. Their electrical and electromagnetic impedance is mapped by the real capacitor substitute circuit - a serial circuit containing a capacitor, resistance and inductance. The type and quality of the insulation layer effects the magnetic and electrical properties of the ferromagnetic core DUT. Its equivalent circuit in impedance measurements is the actual resistor - a parallel circuit containing three branches: inductance with resistance, capacitance with resistance and ideal resistance [37-39, 46, 47].

On the basis of measurements by the MagEye microscope, the surface distribution of magnetic domains in DUTs (through the insulating layer) - Fig. 7 was illustrated and the metrological capabilities of this handheld magnetic microscope were verified. The advantages of MagEye are: high optical resolution and reproduction of measurement results in the form of images. The weak point of the microscope is: high sensitivity of the magnetooptic layer to mechanical and medium damage (approx. 100 A/m) magnetic field measurement resolution, which limits the use of MagEye for GOES testing in laboratory conditions. Passive measurements without artificial magnetization reveal the GOES domain structure, but the image has low contrast and requires additional numerical processing.

On the basis of measurements of loss of GOES sheets, the results of laboratory tests with SST measurements were verified - Fig. 8a). The level of disorientation of the magnetization direction with the rolling directions of DUTs was also determined - Fig. 8b).

During impedance measurements among others typical frequency characteristics of DUTs and diagnostic symptoms occurring in the resonance range of the probe - Fig. 9a), which were used for quick verification and selection of DUTs on different resonance frequencies of the probe - Fig. 9b). In order to highlight the diagnostic symptoms, new estimators were developed and tested, including:

\[
k_L = \frac{L_{s,u=\text{const}}}{L_{s,i=\text{const}}} \tag{6}
\]
where \( L_{s,v=\text{const}} \) is the inductance determined at constant probe feed voltage; \( L_{s,i=\text{const}} \) is the inductance determined at the constant probe feed current.

At this stage of the research it was also shown that the DUTs impedance measurement using the hand-held LDC1000 tester enables quick verification of the physical properties of the DUTs material with the standard and evaluation of the direction of anisotropy - a significant parameter during the manufacture and assembly of transformers.

\[
\text{\( L_{s,v=\text{const}} \) is the inductance determined at constant probe feed voltage; \( L_{s,i=\text{const}} \) is the inductance determined at the constant probe feed current.}
\]

**Fig. 7.** Sample depiction of the GOES domain structure with the MagEye magnetic microscope: a) the center of the sample #4, \( H_{\perp} = 40 \text{ A/m} \); b) sample #4, 20% of the sample length, \( H_{\perp} = 40 \text{ A/m} \); c) the center of the sample with laser scribing, \( H_{\perp} = 40 \text{ A/m} \); d) sample #5, \( H_{\parallel} \approx 400 \text{ A/m} \)

**Fig. 8** Illustrated: a) comparison of power losses of two GOES samples (f = 50 Hz, H = 100 A/m) determined at the SST stand and analyser 4294; b) confusion of the direction of magnetization with the direction of GOES rolling

**Fig. 9** Illustrated: a) the characteristics of the frequency \( L_{s,v} \) \( R_{s} \) impedance of the induction probe during the tested M130 - 30S sheet metal by the resonant method (\( f_{\text{rez}} \approx 2.22 \text{ MHz} \)); b) identification of differences in electromagnetic properties of DUTs based on the estimator \( k_{L} \) (\( U_{\text{const}} = 5 \text{ mV}, I_{\text{const}} = 1 \text{ mA} \)) [1]
5. CONCLUSIONS

Based on the experimental tests carried out, preceded by the analysis of the research problem, the effectiveness of the impedance method to quickly verify the quality of grain-oriented electrical steels and selection of transformer sheets has been demonstrated. The impedance measurements of the material might be used in non-destructive tests to quickly and cheaply evaluate the microstructure quality (e.g. selection of transformer sheets), the influence of mechanical and thermal stresses and the processes of fatigue degradation.

ACKNOWLEDGEMENTS

Assistance in laboratory research was provided by Kornelia Zdolska from the Military University of Technology in Warsaw and employees of Schneider Electric Transformers Poland Sp. z o.o. in Mikołów.

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