MEASUREMENT SYSTEM FOR 2D MAGNETIC PROPERTIES OF ELECTRICAL STEEL SHEETS: DESIGN AND PERFORMANCE

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Abstract
A European intercomparison [1] of measurement systems for two-dimensional magnetic properties of electrical steel sheets has shown substantial differences between the results obtained by various laboratories. A detailed analysis of the design and performance of such measurement systems proves necessary. Such an analysis is presented here for the particular case of a Rotational Single Sheet Tester (RSST) with 8 cm x 8 cm square samples and horizontal yokes, designed and built at the laboratory. Special attention is paid to the accuracy of the magnetic field measurement in the setup. The proposed design includes shielding of the tested sample from stray fluxes using shielding laminations placed above and underneath the sample. Two field search coils per phase yield excellent accuracy of the field strength measurement. An estimate of the deviation between results from the RSST and the standard measurement procedure according to norm IEC 404-3 (Single Sheet Tester) is given. Most of the conclusions are generally applicable to other types of RSST's. The circuit model of the complete system is derived as well. A waveform control algorithm is presented, which is based on system identification techniques and the circuit model. The algorithm is generally applicable and allows fully automated measurements.

1. INTRODUCTION
The investigation of the magnetic properties of laminated electrical steels used for transformers and rotating electrical machines is essential for the improvement of the efficiency of these devices. This can be achieved both through improvement of the magnetic material properties and through improvement of the design of the machine. For the latter task, powerful computer aided design (CAD) systems are used which can take into account very sophisticated material models. For the development of these numerical models and for the improvement of the production processes, data on the material behaviour for magnetic excitations similar to the ones that occur in real electrical machines is required. A complete characterization of the material requires measurements under unidirectional (alternating) excitation along arbitrary angles with respect to the rolling direction of the sheet, and also under two-dimensional (rotational) excitation. Considering the modern frequency control of rotating machines and the use of pulse-width modulation (PWM), both types of measurements should be performed for various induction waveforms in a sufficient frequency range (e.g. 1 to 200 Hz). The material properties of greatest interest are the time-dependent relation between the magnetic field strength $H$ and the magnetic induction $B$ (including non-linearity, anisotropy, hysteresis and eddy currents), the permeability $\mu$ and the power loss $P$.

Three types of measurement setups are most widely used for material characterization. For unidirectional sinusoidal magnetization, the Epstein-frame according to the norm IEC 404-2 and the Single Sheet Tester according to IEC 404-3 are used. Both measurement setups yield losses that can deviate up to 10 % from the real physical power loss. The issues of measurements with these two setups are largely covered in the literature [2] and will not be discussed here. For rotational measurements, different types of Rotational Single Sheet Testers (RSST) are used. This type of setup is not standardized and many papers have been published on the issues of design and accuracy of RSST's [2]. However, a European
intercomparison [1] of such measurement systems has shown substantial differences between the results obtained by various laboratories. Further research on RSST's is thus necessary.

This paper describes design and performance issues of the Rotational Single Sheet Tester built at the laboratory. Special attention is paid to the accuracy of the magnetic field strength measurement. The following aspects are addressed in the study:

- **Magnetic field distribution in and around the sample** determined by finite element calculations. The measurement accuracy is assessed, including a comparative measurement between RSST and SST.
- **Circuit model of the complete system** in order to determine the relation between the magnetization of the sample and the excitation voltage.
- **Waveform control algorithm**, based on the circuit model and allowing automated measurements.

2. THE MAGNETIC CIRCUIT: MAGNETIC FIELD DISTRIBUTION AND ACCURACY OF THE MAGNETIC SENSORS

The measurement setup designed and built at the laboratory is presented in Fig. 1 and is based on a widely used RSST configuration, proposed initially by Brix [3]. The square sample of the tested material (8 cm x 8 cm) is magnetized two-dimensionally by the horizontal yoke with perpendicular excitation coils. A sufficiently large area of the sample (order cm²) should be magnetized homogeneously in the plane of the sample material in order to obtain results representative for the macroscopic properties of the laminations. To be able to magnetize the sample up to saturation, the yoke should be constructed much thicker than the sample itself.

The material properties are determined from the measurement of the vector components \( B_x(t), B_y(t), H_x(t), H_y(t) \) in function of the time \( t \), in the central area of the sample, as described below. The power loss for periodic excitations can be determined from:

\[
P = \frac{1}{\rho T} \left[ \int \left( H_x(t) \cdot \frac{dB_y(t)}{dt} + H_y(t) \cdot \frac{dB_x(t)}{dt} \right) dt \right] \left( \frac{W}{kg} \right),
\]

where \( T \) is the signal period (in s) and \( \rho \) the material density (in kg/m³). The field strength components \( H_x(t) \) and \( H_y(t) \) should be measured at the sample surface, while the induction components \( B_x(t) \) and \( B_y(t) \) are the mean induction values over the cross section of the sample [4].

Finite element analysis can be used to determine the magnetic field distribution in and around the tested sample. The results yield estimates of the field homogeneity in the central area of the sample and of the accuracy of the magnetic field sensors used.

(a) Magnetic field distribution in and around the sample; field homogeneity

A complete modeling of the RSST requires three-dimensional (3D) finite elements software. However, a 3D model is difficult to set up and the calculations are very time consuming, so that mostly 2D software is used. Several authors [5,6] have studied the field distribution by a two-dimensional model in the plane of the sheet (further called the \( xy \)-model). A first question concerning the RSST design is what shape of the sample provides the best field homogeneity. In [5,6], square and circular samples are compared to conclude that a square sample yields better field homogeneity than a circular one. Furthermore, the field homogeneity improves with an increase of the air gap. However, a larger air gap increases the excitation power demand.
The xy-model implies the simplification that the setup is infinite along the z-axis and that the finite size along the z-axis does not significantly affect the obtained result [6]. However, as the yoke is much thicker than the sample, a study of the field distribution in a vertical plane proves necessary. Such a zy-model is shown in Fig. 2a and 2b [7]. Due to symmetry, only one-forth of the setup is modelled. Two possible configurations, with and without shielding laminations paced above and underneath the actual sample, are presented in Fig. 2a and 2b, respectively. In a first approximation, a high permeability linear nonhysteretic material is used. All calculations are quasi-static. The zy-model without shielding (Fig. 2a) shows the substantial influence that stray flux lines and fringing have on the field distribution in the sample, even in its central area, where the measurement is performed. The xy-model is thus not sufficient for the analysis of the field distribution, and should be combined with the zy-model in Fig. 2 [7]. Furthermore, even a material with high permeability will be magnetized inhomogeneously due to fringing. In order to magnetize the sample homogeneously, shielding laminations that shield the sample from the stray flux lines should be mounted above and underneath the sample, Fig. 2b, as reported in [8]. Indeed, without shielding, the deviation between the local magnetic induction in each point in the central measuring area (4 cm x 4 cm) and the mean induction in this region varies between -7 % to +3.5 %, while moving from the edge of the measuring area to its centre. With shielding, the numbers are reduced substantially: -0.04 % to +0.09 %. The shielding laminations should be made from the same material as the sample, and mounted with their rolling direction parallel to that of the sample. The use of shielding laminations is essential for sufficient homogeneity, although it raises the necessary excitation power.

The xy- and zy-models can be combined in the calculations by using an equivalent air gap $\delta_{eq}$ instead of the actual air gap $\delta$ in the xy-model [7]. The equivalent air gap $\delta_{eq}$ is defined as the air gap in a 2D xy-model (infinite along the z-axis) which will have the same reluctance as the air gap in the actual setup, taking fringing into account. The zy-model can be used to calculate $\delta_{eq}$ [7]. The relation between the two air gaps is called the z-axis factor $f_z = \delta/\delta_{eq}$. The z-axis factor $f_z$ depends on the geometry of the magnetic circuit [7]. For a physical air gap $\delta = 5$ mm, without shielding laminations, $f_z$ is about 20. With shielding, $f_z \approx 5$. The thickness of the sample and shielding laminations, the distance in between, the shape of the poles of the yoke and the saturation level of the sample also have a slight influence on $\delta_{eq}$. It is this equivalent air gap $\delta_{eq}$, rather than the actual air gap $\delta$, which should be used when estimating the field homogeneity in the sample with the xy-model. The equivalent air gap $\delta_{eq}$ is important in developing the circuit model of the system as well, as described in the next section.
(b) Estimation of the magnetic sensor accuracy

The magnetic induction components \( B_x(t) \) and \( B_y(t) \) are measured using either search coils wound through holes in the central area of the sample, or needles [2]. An overview of the issues of magnetic induction sensors is given by Moses [9].

For the measurement of the field strength components \( H_x(t) \) and \( H_y(t) \), flat search coils \( \{H\text{-coils}\} \) wound on a nonmagnetic carrier are used (Fig. 3a), mounted above and underneath the actual sample. They measure the field strength in the air above and underneath the sample, which approximately equals the field strength at the surface of the sample. Thus the accuracy of the measurement of the field strength \( H \) depends strongly on the field distribution above and underneath the sample. The relation between the calculated mean field strength \( H \) at the surface of the sample, taken over the \( H \)-coil area, and the field strength \( H_m \) that would be measured with the \( H \)-coil is investigated with the \( xz \)-model, Fig. 2. The \( H \)-coil is modelled as two conductors, carrying no current (Fig. 3b) [8]. The field strength \( H_m \) follows from the flux linked with the coil, as calculated with the finite element software. Table 1 presents the relative deviation \( \delta_H \) between \( H_m \) and \( H \) for various configurations. The influence of yoke shape, shielding laminations and number of \( H \)-coils per phase is studied. The magnetic material is considered linear and nonhysteretic in the model. In Table 1, the \( H \)-coil is 4 cm long. One or two \( H \)-coils per phase are used, with a total thickness of 5 mm.
Table 1. Accuracy of field strength measurement for various configurations

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$\sigma_f$ (%)</th>
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<tbody>
<tr>
<td>(a) 1 H-coil, chamfered yoke (Fig. 2c), no shielding</td>
<td>+130</td>
</tr>
<tr>
<td>(b) 2 H-coils, flat yoke (Fig. 2d), no shielding</td>
<td>+1.2</td>
</tr>
<tr>
<td>(c) 2 H-coils, chamfered yoke, no shielding</td>
<td>+1.0</td>
</tr>
<tr>
<td>(d) 1 H-coil, flat yoke, shielding</td>
<td>+2.9</td>
</tr>
<tr>
<td>(e) 1 H-coil, chamfered yoke, shielding</td>
<td>-2.2</td>
</tr>
<tr>
<td>(f) 2 H-coils, chamfered yoke, shielding</td>
<td>+0.02</td>
</tr>
</tbody>
</table>

The accuracy of the field strength measurement is very good when using shielding laminations as described above: $\varepsilon M = \pm 2.9\%$ or $-2.2\%$ depending on the yoke shape, cases (d) and (e). An improved accuracy can be obtained by using two H-coils per phase (between the sample and the shielding) and by extrapolating the resulting values to the sample surface [10]. Even without shielding, such a configuration yields very accurate results: $\varepsilon M \approx \pm 1\%$, cases (b) and (c). Using two H-coils per phase in combination with shielding laminations provides excellent accuracy: $\varepsilon M = +0.02\%$, case (f). The yoke shape does not have a substantial influence on the accuracy, compare cases (b) with (c) or (d) with (e).

The configurations (e) and (f) are further used to discuss other parameters that influence the accuracy of the field measurement. Increasing the length of the H-coil (and thus the size of the measurement area) reduces the measurement accuracy: $\varepsilon f = -0.9\%$ for a coil of 1 cm length and $\varepsilon f = -2.8\%$ for a coil of 5 cm length. A slight difference between the permeabilities of the sample and the shielding laminations influences the field pattern in the H-coil(s) as well. This difference can be caused by a slightly different orientation of the rolling direction or by a slight difference between the magnetization of the sample and the shielding. The two H-coils configuration yields excellent accuracy even if the difference in the permeability reaches 25%: $|\sigma| = 0.25\%$. The one H-coil configuration, with $|\sigma| = 10\%$, is much more sensitive to differences in permeability. Calculations with a typical anhysteretic curve of a nonlinear material instead of linear magnetic material allow the investigation of the influence of magnetic saturation on the measurement accuracy. In such a case, $|\sigma|$ can reach 6.5% at an induction of 1.5 T for the one H-coil configuration, while $|\sigma|$ is limited to 1.5% for the two H-coils configuration.

Concluding, one H-coil per phase in combination with shielding laminations provides good field strength measurement accuracy. Using two H-coils per phase instead of one yields excellent measurement accuracy. These estimates do not take into account systematic errors due to the electronic conditioning of the H-coils signals. These errors are slightly larger for the two H-coils system due to the larger number of components.

(c) Comparison between results from RSST and SST

As the Rotational Single Sheet Tester (RSST) can be used both for unidirectional and two-dimensional measurements, it is advisory to compare its results with the results from the Single Sheet Tester (SST) in the case of unidirectional measurements. An important reason for the deviation between the two systems is the use of different methods for the measurement of the field strength. Indeed, while the RSST uses H-coils, the SST derives the field strength from the measurement of the magnetizing current, using the equivalent magnetic path length $l_m$. According to the IEC 404-3 SST standard, $l_m$ equals the distance between the inner slices of the magnetizing yoke [2].
3. CIRCUIT MODEL OF THE COMPLETE SYSTEM

In order to determine the relation between the magnetization of the sample and the excitation voltage of the setup, a circuit model of the complete system is derived. This circuit model is essential for the development of an automatic waveform control algorithm, as described in the next section. The following assumptions are made:

- The magnetic flux density in and the magnetic resistance of the yoke are negligibly low. As the yoke is much thicker than the sample (also including shielding laminations), this assumption will be valid even for high flux densities in the sample. In a xy-model the assumption corresponds with a yoke material which is linear, with infinite permeability.

- The excitation coils of the two phases are perfectly perpendicular to each other. Should the sample be linear and isotropic, there would be no coupling between the two phases and each of them could be considered independently. For electrical steel samples, there is however coupling between the phases due to the saturation and anisotropy of the sample. The coupling will be taken into account as described below.

With these assumptions, each of the axes of the setup, e.g., the x-axis, can be modelled by a serial circuit of a magnetizing e.m.f., a stray inductance \( L_{xy} \), and a resistance \( R_x \), see also [11]. The magnetizing e.m.f. is the time derivative of the flux \( \psi_{m,x}(t) \) which passes through the sample and the shielding laminations and is coupled with the magnetizing coil along the x-axis. This results in:

\[
\frac{v_x(t)}{L_{xy}} = R_x i_x(t) + L_{xy} \frac{di_x(t)}{dt} + \frac{d\psi_{m,x}(t)}{dt},
\]

where \( i_x(t) \) is the magnetizing current. The magnetizing flux can be determined as:

\[
\psi_{m,x} = 2H_x w SB_x(t),
\]

where \( S \) is the total cross-sectional area of the sample and the shielding laminations and \( w \) the number of windings on one magnetizing coil. The factor \( f_w \) equals unity for the ideal case of field homogeneity over the whole area of the sample and the shielding laminations. Mainly in saturation of the sample material, \( f_w \) will differ slightly from unity, according to the field distribution as a function of \( B_x \). The relation between the field \( H_x \) in the sample and the magnetizing current \( i_x(t) \) can be established from Ampere's law:
\[ \oint H \cdot dl = 2 \frac{B_s}{\mu_0} \delta_{eq}(B_s) + f_{ir}(H_s)H_s l_s = 2w_i, \]

thereby neglecting the m.m.f. drop in the yoke according to the first assumption. Here \( l_s \) is the length of the side of the square sample. Note that the equivalent air gap \( \delta_{eq} \) should be used in (3), rather than the actual air gap \( \delta \). As mentioned already, \( \delta_{eq} \) varies slightly with the saturation level of the sample, hence can be expressed as a function of \( B_s \). Similar to \( f_{ir} \), the factor \( f_{ir} \) equals unity for the ideal case of field homogeneity over the sample and varies slightly as a function of \( H_s \). Note that in practice \( B_s \) and \( H_s \) are the induction and field values measured by the field sensors in the central area of the sample. Combination of Eqs. (2), (3), and (4) leads to:

\[ v_x(t) = a_x B_x(t) + b_x \frac{dB_x(t)}{dt} + c_x H_x(t) + d_x \frac{dH_x(t)}{dt}, \]

where

\[ a_x = \frac{R_x \delta_{eq}(B_x) w}{\mu_0}, \quad b_x = \frac{L_x \delta_{eq}(B_x) w}{\mu_0} + 2f_{ir}(B_s) w S, \]

\[ c_x = \frac{R_x f_{ir}(H_s) y_s}{2w}, \quad d_x = \frac{L_x f_{ir}(H_s) y_s}{2w}. \]

The parameters \( a_x, b_x, c_x, \) and \( d_x \) can be calculated when the x-axis field and induction components \( H_s \) and \( B_s \) are known.

Up to now, the vectors \( \mathbf{B} \) and \( \mathbf{H} \) were considered as independent of each other. Actually they are related to each other through the constitutive law of the sample material. This is also the reason the two phases are coupled. The coupling can be expressed as:

\[ B_s(t) = f_y(H_y(t), H_s(t)), \quad B_y(t) = f_x(H_x(t), H_s(t)). \]

Eq. (7) takes hysteresis, nonlinearity, anisotropy and eddy currents into account.

Eq. (5), can be regarded as an input-output model for one phase of the RSST, with the excitation voltage \( v_x(t) \) as the input and the measured \( B_x(t) \) and \( H_x(t) \) as the outputs of the system. Analogous equations hold for the y-axis.

4. AUTOMATIC WAVEFORM CONTROL

Due to the nonlinearity, anisotropy and hysteresis of the sample, the necessary excitation voltage waveform for a preset (e.g. circular) induction waveform should be determined using a control algorithm. For periodic signals, an iterative waveform control algorithm is widely used [12]. In such an algorithm, in each iteration the induction waveform is measured for a certain known excitation voltage waveform. The excitation voltage waveform is then updated based on the remaining deviation between the measured and the preset induction waveform. The process is repeated until the measured induction waveform converges to the preset one. The construction of the excitation voltage waveforms \( v_x(t) \) and \( v_y(t) \) is based on the system equation (5). However, as the parameters \( a_x, b_x, c_x, \) and \( d_x \) used in (5), vary with the induction and field values (see Eq. (6)), it is convenient to use system identification techniques based on the (recursive) least squares method to identify the parameters from measurements of the input and output signals. A detailed description of the algorithm is given in [11,13]. Fig. 4a presents the initial and final (after 10 iterations) induction and field loci for circular magnetization of a grain-oriented material with an amplitude of 1.3 T. Fig. 4b shows the corresponding excitation voltage waveforms. Note that, although the sample is very anisotropic, the algorithm efficiently takes the coupling between the phases into account and yields a circular induction locus. The algorithm is fast, robust and generally applicable for arbitrary magnetization patterns and both for nonoriented and grain-oriented materials. Fully automated measurements are possible as well.
5. CONCLUSIONS

An analysis of the design and performance of a Rotational Single Sheet Tester (RSST) with 8 cm x 8 cm square samples and horizontal yokes is presented. Special attention is paid to the accuracy of the magnetic field measurement in the setup. A feature of the proposed design is the shielding of the tested sample from stray fluxes using shielding laminations placed above and underneath the sample. The shielding improves the field homogeneity in the sample and the accuracy of the field strength measurement. One field search coil (H-coil) per phase, placed between the sample and the shielding, provides good accuracy for the measurement of the field strength. When using two H-coils per phase, the accuracy is excellent. As the Single Sheet Tester (SST) according to norm IEC 404-3 has a systematic error itself, a deviation of at least 5 % between the power losses measured by RSST and SST can be attributed entirely to the different field sensing methods used in the two devices. The measured deviation between RSST and SST is between 5 % and 10 %. Most of the conclusions are generally applicable to other types of RSST's. The circuit model of the complete system is derived as well. A waveform control algorithm is presented, based on system identification techniques and the circuit model. The performance of the algorithm is illustrated by applying it to a circular induction locus in a grain-oriented material. The algorithm is generally applicable and allows fully automated measurements.

6. REFERENCES

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