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System for controllable magnetic measurement with direct field determination

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ABSTRACT

This work describes a specially designed setup for magnetic hysteresis and Barkhausen noise measurements. The setup combines two main elements: an improved fast algorithm to control the waveform of magnetic induction and simultaneous direct determination of the magnetic field. The digital feedback algorithm uses only the previous measurement cycle to correct the magnetization voltage without any additional correlation parameter; it usually converges after several tens of cycles. The magnetic field is measured at the sample surface using a vertically mounted array of sensitive Hall sensors. Linear extrapolation of the tangential field profile to the sample surface determines the true waveform of the magnetic field. This unique combination of physically based control for both parameters of the magnetization process provides stable and reliable results, which are independent of a specified experimental configuration. This is illustrated for the industrially attractive measurements of non-oriented electrical steels with a 50 Hz sinusoidal induction waveform.

1. Introduction

There are two standard methods for the measurement of magnetically open strips/sheets of electrical steel, whose magnetic softness (usually the hysteresis losses at power line frequencies of 50–60 Hz) is their determinative technological parameter [1]. A classical Epstein apparatus has remained the main instrument for the evaluation of electrical steel quality in industry for more than a century. For testing, steel strips $300 \times 30 \times 0.25–0.5\ mm^3$ in size are combined in a square frame with the magnetization and the induction windings [2]. The method is accurate but has serious drawbacks; notably, it is expensive and time consuming. European initiatives to simplify the testing have led to the implementation of the second standard method, a single sheet tester (SST). This technique requires only one steel sheet positioned inside the magnetization-induction windings and pressed from both sides by two big yokes from magnetically soft transformer steel [3].

Cumbersome constructions of both standard instruments are required for high repeatability of the results. These quasi-closed magnetic circuits are needed to keep (i) the induction waveform of the sinusoidal shape in accordance with the standard requirement and the application conditions and (ii) the current field method valid (the sample magnetic field is proportional to the current in the magnetization windings). This also keeps the total measurement error at the usual level of 2–3%. However, extreme attention must be paid to ensure good contact quality between the constituents of the composed magnetic circuit, or the measurement error can increase to 5–10%. Therefore, these standard procedures cannot be adapted for continuous online testing on a production line [1,4].

There is no exact match between the data from the Epstein and the SST techniques, which is due to different "design" sources of field determination error [4]. This factor, together with some commercial and industrial conservatism, has delayed the replacement of the outdated Epstein apparatus with SST in practice. Another interesting fact is that the SST standard includes a more physically based modification with a flat air-core H-coil at the sample surface for the direct field determination [5]. However, the standard gives preference to the initial current field method because of its simplicity and the errors associated with the H-coil measurement [3].

More imperfect magnetic circuits than these two standard techniques cannot ensure the accuracy of the current field method [4]. At the moment, a field compensation technique is accepted to be the best for the measurement in the magnetically open configuration. This method uses a Rogowski–Chattock potentiometer to evaluate a magnitude of the magnetization imperfection. An analog feedback loop supplies a correction current to additional magnetization coils in order to minimize the potentiometer signal. This procedure adjusts the magnetization process to the ideal condition of the closed magnetic circuit, when the current field method can be applied [6,7].

Currently, digital measurement techniques and modern magnetic field sensors afford the opportunity to examine this old problem from a different standpoint. The physical idea is to control the magnetic induction waveform using a digital feedback

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procedure and to measure the magnetic field directly and precisely. This is expected to provide repeatable and reliable results, even for magnetically open circuits [8]. This work describes such a newly designed setup in detail, together with all of the particular measuring and technical problems: the stable and fast digital feedback algorithm, accurate direct field measurement and hysteresis loop symmetrization. The expectations about the setup efficiency for the measurement of magnetically open samples are supported by the experimental data.

2. Setup description

Fig. 1(a) presents the block scheme of the setup. The measurements are PC-controlled through a high-speed multifunction data acquisition board, NI PCI-6251, and a GPIB card. The magnetization signal is generated by the acquisition board, and the voltage is amplified by a low-cost APEX MP39 module that is mounted on an EK59 evaluation kit. The stable voltage amplification is used to avoid auto-oscillations of the current amplification mode. A power film resistor mounted on a heat sink is used for the accurate reading of the magnetization current. The signals from the Hall sensors and the induction coil are amplified using SRS instrumentation modules; the amplification coefficients are software adjusted through the GPIB card. Fig. 1(b) shows a magnetizing-sensing unit used in this work for the result presentation. The setup is designed as a flexible system, that is capable of measuring various ferromagnetic structural materials at different induction waveforms. However, the current activity is focused on the industrial task of electrical steel testing with a 50 Hz sinusoidal induction waveform [9].

The software was realized in a NI LabVIEW graphical programming environment; the algorithm block scheme is shown in Fig. 2. At first, the measurement is performed without the induction waveform control: a given induction amplitude B_{max} is iteratively adjusted with 0.5% accuracy by selecting an appropriate amplitude of the board generated voltage V_{gen}. Because of the accommodation effect, the signals are collected from the fifth measurement cycle. The magnetic induction B is obtained from the numerical integration of the sampled induced voltage U_{ind} according to Faraday's law: $B(t) = (-1/nS)\int U_{ind}\, dt$, where n is number of turns of the induction winding and S is the sample cross-section. The zero threshold is compensated for by levelling the B amplitudes, and the waveform is symmetrized around zero. Before each measurement, the demagnetization procedure is performed. The five signals (magnetization, three Hall sensors, and the induction voltages) are acquired through a board multiplexer at a maximum sampling rate of 200 kHz and on-the-fly averaged over adjacent data points to the final 1000 points for one magnetization cycle. Averaging over the consequent magnetization cycles can be performed for additional signal smoothing [10]. At the condition of 50 Hz magnetization, the output voltage can be generated at the sampling rate of up to 100–200 kHz, which is sufficient for a smooth signal. Data evaluation and saving are also performed by the software; all classical hysteresis parameters (coercive force, hysteresis loss, and remanent induction) are calculated at the current and the direct field representations. The measurement results are visually controlled in the LabVIEW graphic environment.

The second step is conducting repeated measurements with the controlled induction waveform, whose algorithm is comprehensively described in the following subsection. The next two subsections are devoted to the procedures of the direct field measurement and the final loop symmetrization with respect to the field, respectively.

The setup can also be used for complementary Barkhausen noise measurements performed with and without waveform control [10,11]. Two channels (magnetization and Barkhausen noise voltages) are acquired at a maximum sampling rate of 500 kHz and are similarly averaged over adjacent data points and magnetization cycles. The noise voltage is increased thousands of times using the SRS low-noise preamplifier SR560. Then, it is band-pass analog and digitally filtered; the cut-off frequencies of the analog SRS filters are adjusted through GPIB (see Fig. 1(a)). Using the previous hysteresis measurement, the Barkhausen noise data are correlated with the direct field and the induction signals; the Barkhausen voltage profile is also evaluated in the various fields and induction representations. Further consideration of the issue of Barkhausen noise measurement is beyond the scope of this work; for other details, see our previous works and the references cited therein [8,10].

2.1. Digital feedback

The closed inductive circuit automatically maintains the sinusoidal shape of an AC induction waveform of low amplitude. This is the operation condition of the magnetically soft electrical steels, which

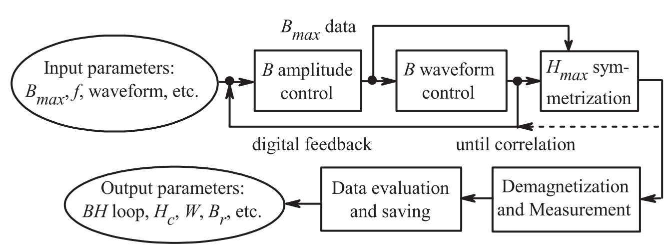

Fig. 2. Block scheme of the measurement algorithm.

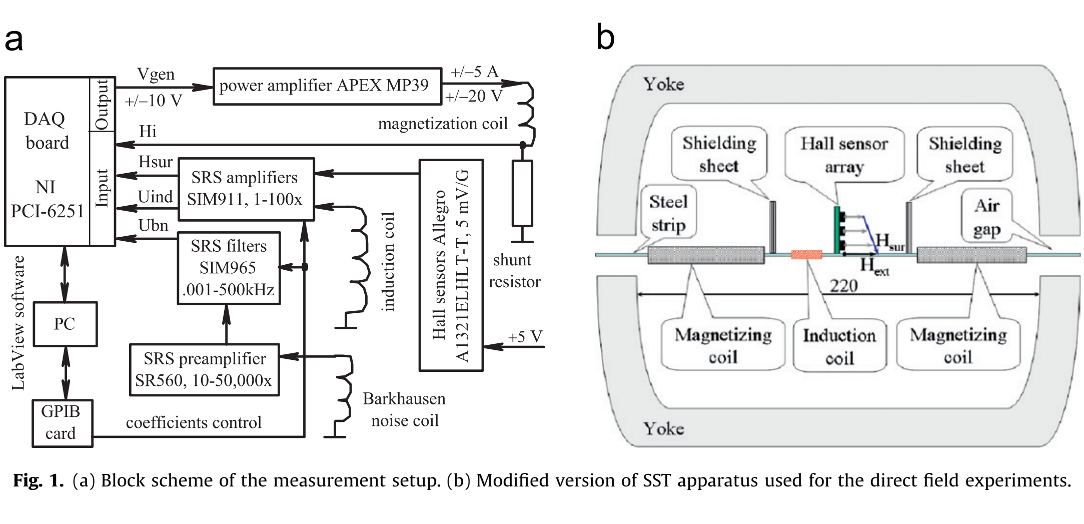

Fig. 1. (a) Block scheme of the measurement setup. (b) Modified version of SST apparatus used for the direct field experiments.