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Determination of magnetic loss under magnetic polarization waveforms including higher harmonic components – Measurement, modelling and calculation methods

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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DETERMINATION OF MAGNETIC LOSS UNDER MAGNETIC POLARIZATION WAVEFORMS INCLUDING HIGHER HARMONIC COMPONENTS – MEASUREMENT, MODELLING AND CALCULATION METHODS

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IEC/TR 62383, which is a technical report, has been prepared by IEC technical committee 68: Magnetic alloys and steels.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
68/309/DTR	68/315/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the maintenance result date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

INTRODUCTION

The specific total loss has to be measured for the design of electrical machines and classification of electrical steel sheets. During the last 20 years, electrical engineers have determined the magnetic induction waveforms of electrical machines [1] to [4][1], and calculated the magnetic power loss under non-sinusoidal waveform of magnetic polarization [5] to [13]. They designed electrical machines using numeric calculation (FEM, BEM) and high speed computers, including non-linear and hysteresis properties of magnetic materials.

Under standard measurement conditions, the specific total loss of electrical steel is to be measured only under the condition of sinusoidal waveform of the magnetic polarization. However, the actual magnetic polarization waveforms of the electric machine are almost always not sinusoidal because of the material behaviour (anisotropy, non-linear B-H performance in high polarization regions such as the stator tooth of electrical machines), because of PWM modulated voltage for variable speed motors and because of the layout of the magnetic circuit and the winding scheme (tooth harmonics).

Specific total loss values obtained by the standard method are not really applicable to an actual electrical machine design because the specific total loss of ferromagnetic material cannot be predicted easily due to non-linear and hysteresis effects, but these higher harmonic polarizations bring about a large increase in magnetic loss.

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[1] The figures in square brackets refer to the Bibliography.

DETERMINATION OF MAGNETIC LOSS UNDER MAGNETIC POLARIZATION WAVEFORMS INCLUDING HIGHER HARMONIC COMPONENTS – MEASUREMENT, MODELLING AND CALCULATION METHODS

1 Scope

Nowadays, by computer aided testing (CAT), a.c. magnetic properties of electrical steel sheets can be measured under various measuring conditions automatically. For example, the magnetic loss in the presence of higher harmonic frequency components of magnetic polarization can be measured using the arbitrary waveform synthesizer, digitiser and computer.

The present standard methods (IEC 60404-2, IEC 60404-3 and IEC 60404-10) for the determination of specific total loss are restricted to the sinusoidal waveform of magnetic polarization, and these standards are still important for the characterization of core materials. However, actual waveforms of magnetic polarization in the electrical machines and transformers always include higher harmonic polarizations, and nowadays electrical machines can be designed using numerical methods including higher harmonics. But for these conditions, there is still no standard testing method.

This technical report reviews methods for measurement of the magnetic loss of soft magnetic materials under the condition of magnetic polarization which includes higher harmonic components.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60404-2, *Magnetic materials − Part 2: Methods of measurement of the magnetic properties of electrical steel sheet and strip by means of an Epstein frame*

IEC 60404-3:1992, *Magnetic materials − Part 3: Methods of measurement of the magnetic properties of magnetic sheet and strip by means of a single sheet tester*

IEC 60404-6, *Magnetic materials − Part 6: Methods of measurement of the magnetic properties of magnetically soft metallic and powder materials at frequencies in the range 20 Hz to 200 kHz by the use of ring specimens*

IEC 60404-10, *Magnetic materials − Part 8: Specifications for individual materials – Section 10: Specification for magnetic materials (iron and steel) for use in relays*

3 Principles of measurement

3.1 General

The described method of measurement with the inclusion of higher harmonics is, in principle, also applicable using the Epstein frame or a ring core as a magnetic circuit. With the Epstein frame, one should be aware of the particular path length characteristics which are also not exactly known in the higher frequency range.

The proposed test apparatus is based on the magnetic circuit of a double U-yoke SST. It can be considered to consist of the following parts.

3.2 Yokes, windings and test specimen

Each yoke is formed in the shape of a U and is made up of an insulated sheet of electrical steel or nickel iron alloy. The construction methods of yokes could follow the instructions of Annex A of IEC 60404-3. The dimensions of the yokes and specimen are not restricted, but if the yoke size becomes smaller, the effective magnetic path length l_{eff} should be equal to the inside width corresponding to the procedure given in IEC 60404-3. It is preferable that the initial permeability of the yoke should be reasonably constant with frequency up to the maximum higher harmonic frequency to be measured. Regarding the windings and the test specimen, it should again be referred to IEC 60404-3 and, in the case of ring specimens, to IEC 60404-6.

Capacitance and dielectric effects become an issue for higher frequency components. The dielectric loss should be minimised by careful management of the winding space and dielectric constants of the formers and wire insulation.

The temperature of the test specimen should be measured at all times. For higher frequency measurements, the temperature rise becomes a major factor and steps should be taken to minimize this.

3.3 Power amplifier

The power amplifier shall have low output impedance, and the frequency bandwidth of the power amplifier should be higher than the highest harmonic frequency to be measured. The output voltage of the power amplifier should be high enough to magnetize the specimen over the full higher harmonic frequency range. For details, reference should be made to IEC 60404-2, IEC 60404-3 and IEC 60404-6.

3.4 Waveform synthesizer

An arbitrary waveform can be synthesized by computer programming. The frequency of the generated wave should be synchronized with the digitiser frequency, and the frequency uncertainty of the waveform synthesizer shall be better than 0,01 %. The waveform synthesizer output should allow arbitrary waveforms generated by synthesized digital wave data. The relative uncertainty of the frequency should be less than 0,01 %.

3.5 Digitiser

For the digitisation of the secondary induced voltage $U_2(t)$ and the voltage $U_s(t)$ across the non-inductive precision resistor R_s which is connected in series with the primary winding to determine the magnetizing current, a 2-channel digitiser is necessary. The 2 channels must be sampled simultaneously and then digitised. Following this, the data are recorded in a memory.

If the length of the period divided by the time interval between the measuring points, i.e. the sampling frequency ratio f_s divided by the magnetizing frequency f_m, is an integer (Nyquist condition), the power integral can be, without mathematical error, be replaced by the corresponding sum. The sum correctly represents the power integral up to the n^{th} harmonic where 2n is the number of samples per fundamental period. Keeping the Nyquist condition is possible only where the sampling frequency f_s and the magnetizing frequency f_m are synchronized to a common fundamental clock and thus have a fixed integer ratio.

In that case, the hysteresis loop must be scanned using a sampling frequency f_s higher than twice the bandwidth of the B- and H-signals,

$$f_s = 2nf_m \tag{1}$$

where n is the highest harmonic to be measured.

However, the commercial hardware components are not usually synchronized in this way and the ratio f_s/f_m is then not an integer. In that case, the sampling frequency must be considerably higher (for instance 1 024 samples per period) in order to keep the deviation of the true period length from the closest multiple of intervals of sampled measurements small.

Keeping the Nyquist condition becomes a deciding advantage in the case of higher frequencies. The use of a low-pass antialiasing filter must be considered in order to avoid contributions from low-frequency apparent harmonics which do not exist in the measurement signal. The antialiasing filter must limit the system bandwidth to $<f_s/2$.

Regarding the amplitude resolution, with a lower than 12-bit resolution, the digitalization error can be considerable, particularly for non-oriented material with high silicon content. Thus, at least a 12-bit amplitude resolution is recommended. Moreover, the two voltage channels should transfer the signals without a significant phase shift. The phase shift should be so small that the total uncertainty is not significantly affected.

When magnetic loss is measured under conditions of magnetic polarization which include higher harmonic components and the higher harmonic amplitude becomes high enough to produce minor loops, the digital sampling condition for the higher harmonics should also satisfy the above described sampling conditions.

3.6 Control of secondary voltage

The waveform of the secondary voltage should be controlled to have the required components. This control can be achieved by feedback techniques using digital or analog means.

The deviation should be below 1 % for each harmonic component.

3.7 Peak reading apparatus

For the measurement of the peak value of the magnetic polarization, a Miller type analog integrator and a peak reader should be used with a frequency bandwidth higher than the highest harmonic frequency f_h to be measured.

The peak reader should be able to repeat peak readings at an appropriate time rate.

The uncertainty of the peak reading apparatus should be better than 0,2 %.

NOTE An average type voltmeter may not be used for measurement of the peak value of the magnetic polarization because the secondary induced voltage may have more than two zero crossing per period.

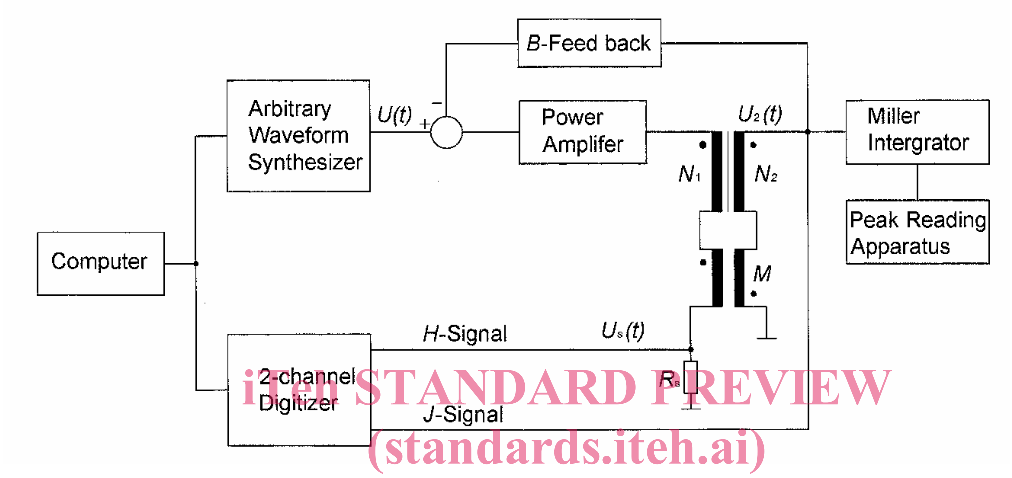
3.8 Air flux compensation

Air flux should be compensated. This can be achieved by a mutual inductor. The primary winding of the mutual inductor is connected in series with the primary winding of the test apparatus, while the secondary winding of the mutual inductor is connected to the secondary winding of the test apparatus in series opposition.

The adjustment of the value of the mutual inductance shall be made so that, when passing an alternating current through the primary windings in the absence of the specimen in the apparatus, the voltage measured between the non-common terminals of the secondary windings shall be no more than 0,1 % of the voltage appearing across the secondary winding of the test apparatus alone.

4 Measuring system

The measuring system can be constructed using the components which are described in Clause 2 . The block diagram of the circuit is shown in Figure 1.



Components

N_1	magnetizing winding
N_2	secondary winding
M	mutual inductor
R_s	non-inductive precision resistor

Figure 1 – Block diagram of the measuring system for the measurement of magnetic loss of electrical steel sheets under magnetic polarization waveforms which include higher harmonic components

5 Measurements

5.1 Generation of the magnetic polarization waveform including higher harmonics

The time dependent magnetic polarization including higher harmonics can be described by

$$J(t)=\sum_{j=0}^{N} J_{(2j+1)}\sin[(2j+1)\omega_1 t+\phi_{(2j+1)}] \qquad (2)$$

where

j	is a non-negative integer;
N	corresponds to the highest harmonic frequency f_h ;
ω_1	is the fundamental angular frequency($\omega_1 = 2\pi f_1$);
$J_{(2j+1)}$	is the amplitude of the $(2j+1)^{th}$ harmonic at the angular frequency $\omega_h = (2j+1)\omega_1$;
$\phi_{(2j+1)}$	is the phase angle.