Accuracy of Power Losses Measurement at AC Magnetization

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Abstract. *The paper deals with problems of industrial AC measurement of magnetic properties of steel sheets and strips. The single sheet testers and on-line testers accuracy is influenced first by exciting magnetic field homogeneity, magnitude, shape and frequency of waveform, second by the accuracy of conversion of magnetic to electric quantities and third by the electric quantities processing. Classical measurements have been done for the closed specimens but the modern AC measurement should be realized for open steel sheets and strips. The original Mikulec's compensation method allows measurement of the magnetic properties of single sheets and strips in the same way as the closed specimen properties. The problems of conversion of magnetic to electric quantities can be improved by optimization of the mmf compensation circuit; the third problem improvement gives the digital signal processing of measured variables. The basic ideas in all mentioned areas are discussed in the paper.*

Keywords: soft magnetic materials, power losses measurement, MMF compensation method, digital power measurement accuracy, asymmetrical magnetization

1. Introduction

The industrial measurement of soft magnetic material properties should be done on open specimen, i.e. on sheets or strips of magnetic steels using the single sheet testers (SST´s) or on-line testers (OLT's). There are three basic SST types in use. The first one is the SST with the high quality yoke, where the magnetic field strength may be approximately obtained from the magnetizing current, the second one makes the magnetic field strength to voltage conversion by the H-coil at the vicinity of the measured specimen surface and the third one is based on the feedback magnetic voltage (MMF) compensation (see [1]).

The accuracy of these methods are influenced mainly by accuracy of the exciting field, accuracy of the field quantities to electrical quantities conversion and accuracy of electrical signal processing (see [2]).

2. The compensated SST

The basic arrangement of the compensated SST is shown in Fig.1.

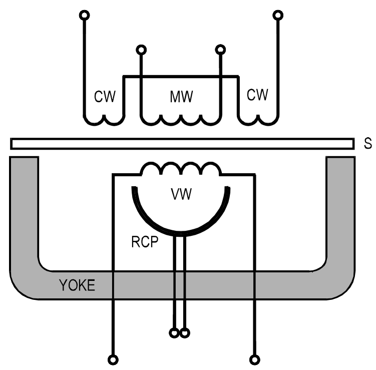

Fig. 1. Compensated Single Sheet Tester

The measured specimen is placed inside the voltage winding VW and magnetizing winding MW. The signal from Rogowski-Chattock potentiometer RCP drives the current in compensation winding to set the RCP induced voltage to zero thus the first Maxwell equation gives

$$\oint \mathbf{H}d\mathbf{s} = \int_A^B \mathbf{H}d\mathbf{s} + \int_B^A \mathbf{H}d\mathbf{s} = U_{m\mathrm{AB}} + U_{m\mathrm{BA}} = N_1 i_1 \quad (1)$$

where AB is the path of the length l along the specimen surface and BA is the path along the RCP axis. N_1 is the number of turns of the middle part of the magnetising winding surrounded by RCP, i_1 is its magnetizing current.

The gain of the compensation loop is limited due to the necessity to fulfil the condition of stability, thus the MMF along the RCP axis is different from zero. This imperfection causes the difference ΔH_{av} between magnetic field strength H_{av} found from (1) supposing $U_{m\mathrm{BA}}$ =0 and its actual value H_{av}^*

$$H_{av}^* = H_{av} - \Delta H_{av} = \frac{N_1 i_1}{l} - \frac{U_{m\mathrm{BA}}}{l} \ . \quad (2)$$

Supposing that the magnetic flux waveform is sinusoidal we can evaluate this error from the first harmonic components of H_{av} and ΔH_{av} according to the formula

$$\delta_p = \frac{p_{err}}{p} = \frac{\Delta H_1 \cos\varphi_{\Delta H_1}}{H_1 \cos\varphi_{H_1}} 100\% \quad (3)$$

where H_1 (ΔH_1) is the first harmonic component of $H_{av}(\Delta H_{av})$ and φ_{H_1} ($\varphi_{\Delta H_1}$) is its phase shift.

The limitation of accuracy given by the limited gain of the compensation loop can be improved by digital signal processing of controlling signals with the robust algorithm taking into account strongly non-linear properties of the soft magnetic materials (see [3], [4]).

3. The influence of asymmetrical magnetization

The magnetic field lines of the specimen should be closed by a yoke. When a SST with a single yoke corresponding to Fig. 1 is used for the AC magnetic measurement of specimen the length of which is greater than the distance between yoke edges, the additional eddy currents occurs in the tested specimen on the side of yoke. Due to these currents the total eddy current density on the lower surface J_1 is increased and the density on the upper surface J_2 is decreased compared with the average surface density J_{av} which will correspond to magnetization in the symmetrical double yoke (see [5]).

Supposing specimen width b is much greater than its thickness d and the specimen length l >> d, too, we can calculate the power losses by integration of the squared eddy current density. Supposing the specimen thickness d is relatively small with the penetration depth δ we can find the specific power losses at the symmetrical case p_s and asymmetrical case p_a as

$$p_s = \frac{J_s^2}{3\rho\sigma} \ ; \ p_a = p_s \frac{4\left(r^2 - r + 1\right)}{(r+1)^2} \ , \quad (4)$$

where ρ is the density and σ the conductivity of specimen and r $=J_1/J_2$ is the ratio of current densities on the lower and upper specimen surface. Similarly for the relatively thick specimen (i.e. d>> δ) we obtain

$$p_s = \frac{J_s^2 \delta}{2a\rho\sigma} \ ; \ p_a = p_s \frac{2\left(r^2 + 1\right)}{(r+1)^2} \ . \quad (5)$$

The ratio r is dependent on the overhang and the specimen thickness and may be in practice up to 3. The actual value of the eddy current component of power losses in a single yoke increases up to 30% in comparison with a double yoke measurement.

When H-coil or compensation method are used the measured value of power losses depends on the position of the H-sensor. When H-sensor is placed on the side of yoke the influence of asymmetry is greater because the measured value is greater than the actual one. In the opposite case the measured value is less than the actual one.

The theoretical solution of the asymmetry influence on measured values when *H*-sensor is used can be made by Poynting's vector integration according to formula

$$p = \frac{1}{\rho V} \,\mathrm{Re} \oiint \left(\mathbf{E} \times \mathbf{H}^*\right) \cdot \mathrm{d}\mathbf{S} \qquad (6)$$

The measured values corresponding to lower sensor position p_{a1} and upper sensor position p_{a2} in these cases are

$$p_{a1} = p_s \frac{2r}{(r+1)} \; ; \; p_{a2} = p_s \frac{2}{(r+1)} \, . \qquad (7)$$

The measurement error may reach 20 to 40% in the case the sensor is on the side of yoke. In the opposite case the increasing of actual losses is partially compensated by decreasing of measured value and the errors can be $\pm$ 15 %.

4. Digital measurement of the specific power losses

The specific power losses of the closed specimens at AC magnetization can be evaluated from the magnetizing current and the secondary induced voltage according to formula

$$\begin{aligned} p &= \frac{P}{m} = \frac{P}{\rho V} = \frac{f}{\rho} \oint H \, \mathrm{d}B \\ &= \frac{1}{\rho V} \frac{N_1}{N_2} \frac{1}{T} \int_0^T u_2 i_1 \, \mathrm{d}t = \frac{N_1}{N_2} \frac{P_m}{m} \end{aligned} \qquad (8)$$

where N_1, i_1 (N_2, u_2) are parameters of the primary (secondary) winding, P_m is the active power determined from the magnetizing current and induced voltage and *m* is the mass of the tested specimen. Using the compensation method we can extend this method for open specimen, too (taking into account the mass *m* of the measured part of specimen only).

The accurate measurement of the active power is very difficult in this case due to a small power factor $\lambda = P/S$ and the great crest factor of the magnetizing current. The analogue power measurement errors are usually greater than 1 % at high magnetic flux densities, thus there is possible to improve these errors only using the digital methods of signal processing.

Supposing the magnetic flux waveform is the sinusoidal one we can express the induced voltage and the magnetizing current as

$$\begin{aligned} u(t) &= U_a \sin(\omega t), \\ i(t) &= \sum_{k=1}^{\infty} I_{ak} \sin(k\omega t + \varphi_k) \end{aligned} \qquad (9)$$

and the active power is given by the first harmonic components only.

The digital method of the active power evaluation is based on the sampling of both voltage and current signals and summarization of the synchronous samples product. Using this process two different uncertainties will occur, errors due to finite sampling and errors due to finite quantisation. Supposing the equidistant sampling with *N* samples per period we can write

$$\begin{aligned} P_s &= \frac{1}{N} \sum_{m=0}^{N-1} u_m \, i_m = \frac{1}{N} \sum_{m=0}^{N-1} U_a \cdot \\ &\cdot \sum_{k=1}^{\infty} I_{ak} \sin \frac{2\pi m}{N} \sin\left(\frac{2\pi k m}{N} + \varphi_k \right) \end{aligned} \qquad (10)$$

The last formula can be simplified as

$$\begin{aligned} P_s &= \frac{1}{2} U_a I_{a1} \cos\varphi_1 + \\ &+ \frac{1}{2} U_a \sum \left(I_{ap} \cos\varphi_p - I_{aq} \cos\varphi_q \right) \end{aligned} , \qquad (11)$$

where $p = kN - 1$, $q = kN + 1$.

The worse case of the error due to finite sampling can occur when the phase shift cosines will reach ± 1. Supposing the $\cos\varphi_1 \geq 0.1$ we can evaluate the maximum possible error due to sampling

$$\delta_s \leq 10 \sum_{k=1}^{\infty} \left(\frac{I_{ap}}{I_{a1}} + \frac{I_{aq}}{I_{a1}} \right) \, . \qquad (12)$$

The theoretical maximum errors evaluated from (12) were compared with the measured ones for the different number of samples per period. The both theoretical and experimental results show that for N = 32 the errors due to sampling can exceed slightly 1%, if $N \geq 64$ the errors are less than 0.25%.

The errors due to quantization were evaluated in [6] theoretically according the formula

$$\delta_q = \frac{\sigma_q}{P_{av}} = \frac{\sqrt{\frac{1}{3N}\left[(I_r U_{av})^2 + (U_r I_{av})^2\right]}}{2\left(2^{b-1} - 1\right)(UI)_{av}}, \qquad (13)$$

where U_r, I_r represent the corresponding full scale range, b is the number of bits used for quantization

The last formula and the experimental results show that the sufficient accuracy of standard power losses measurements need 12-bits A/D converter and minimum number of samples 64 per period.

5. Results

All theoretical conclusions were experimentally verified by measurement of specific power losses of non oriented and grain oriented steel sheets in the compensated ferrometer KF8 designed in the Dept. of Circuit Theory in Czech Technical University in Prague. This device give possibility to measure steel sheets up to the width 500 mm for magnetic flux densities 2 T and magnetic field strength 10 kA/m.

The theoretical solution and the experimental results show that using of an asymmetrical yoke is acceptable only for narrow strips testing and approximate measurement of sheets with the length equal to the distance of yoke edges. For precise measurement of wide sheets, measurement of longer specimen and on-line measurements it is necessary to use every time symmetrical double yoke.

The digitization of MMF compensation loop can decrease the uncertainty of magnetic field strength conversion twice or three times and to reach the total uncertainty less than 1%.

Digital processing of measured voltages and currents is helpful if the number of samples per period is greater then 64 and as minimum 12-bit converter with matching of full scale range is used. The sampling of both measured variables should be synchronous because due to the small power factor phase shift errors can not exceed 0.01 rad, i.e. the time delay cannot exceed 0.002 of the period length.

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