Measurement of Power Losses at AC Magnetization

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Abstract

Magnetic measurements represent relatively difficult area of the electrical engineering. Classical measurements have been done for the closed specimens but the modern AC measurement should be realized for open steel sheets and strips. For these measurements it is necessary to keep the prescribed conditions. The total error of any magnetic measurement depends on the exciting field error, the error of the magnetic to electric variables conversion and the error of integral electric values measurement. Research team from the Dept. of Circuit Theory of the Czech Technical University has developed original compensation method improving the quality of the open specimens magnetizing. The original method of MMF compensation allows measurement of the magnetic properties of single sheets and strips in the same way as the closed specimen properties. The method accuracy is limited due to the finite gain of the feedback loop fulfilling the condition of its stability. The digitalisation of the compensation loop and the convenient processing of the error signal can improve rapidly the accuracy. The basic ideas of this new approach and the experimental results are described in the paper.

Keywords: single sheet tester, on-line tester, soft magnetic material, compensation method.

1. Introduction

Modern methods of AC magnetic measurement are realised either by single sheet testers (SST's) or on/line testers (OLT's). The magnetic circuit created by the open specimen and the yoke is not a homogeneous one thus it is impossible to find the magnetic field strength from the magnetizing current. The MMF compensation method (see in [1]) allows to compensate the MMF drops along the yoke and the air gaps thus the MMF along the measured part of the specimen is proportional to the magnetising current. This method was successfully tested in Research Steel Institute Dobrá, Rolling Works Frýdek-Místek, and also in the Wolfson Centre for Magnetic Research in UK (see [2]). The accuracy of this method is restricted mainly by the limited gain of feedback loop due to the stability problems. Digitisation of the feedback loop has improved strongly the measurement accuracy.

2. The SST power losses measurements

The standard arrangement of the SST contains a set of two windings (magnetizing winding and voltage winding) surrounding the tested sheet. The compensation method complete this basic set with two compensating windings in vicinity of yoke poles. These windings create the additional MMF for compensation of MMF drops along the yoke and the air gaps. The middle part of the magnetising winding is surrounded by the Rogowski-Chattock potentiometer (RCP) measuring the difference between the MMF of magnetizing winding surrounded part and the actual MMF along the tested specimen surface. The electronic feedback circuit controls the compensating windings current to reach the condition of zero voltage induced in RCP at any time instant (see Fig. 1).

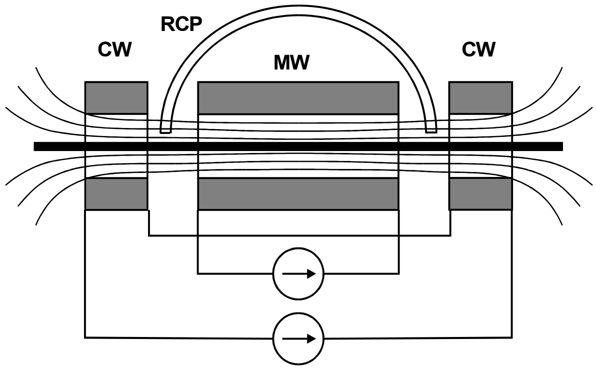

Fig. 1. Arrangement of the SST windings

The first Maxwell equation gives for the closed path created by the RCP axis and the line segment between the RCP edges

$$\oint \mathbf{H}\mathrm{d}\mathbf{s} = \int_{\mathrm{A}}^{\mathrm{B}} \mathbf{H}\mathrm{d}\mathbf{s} + \int_{\mathrm{B}}^{\mathrm{A}} \mathbf{H}\mathrm{d}\mathbf{s} = U_{m\mathrm{AB}} + U_{m\mathrm{BA}} = N_1 i_1 , \tag{1}$$

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, i_1 is its magnetizing current.

Supposing the gain of compensation loop approaches to infinity the MMF along the RCP axis is set to zero, thus the average value of the magnetic field strength along the measured part of the specimen is given by

$$H_{av} = \frac{U_{m\mathrm{AB}}}{l} = \frac{N_1 i_1}{l} . \tag{2}$$

The knowledge of the average values of the magnetic field strength and the magnetic flux density gives possibility to find the specific power losses in the measured part of specimen according to the formula

$$p = \frac{P}{m} = \frac{P}{\rho V} = \frac{f}{\rho}\oint \mathbf{H}\,\mathrm{d}\mathbf{B} = \frac{f}{\rho}\int_0^T H\frac{dB}{\mathrm{d}t}\mathrm{d}t \tag{3}$$

and

$$p = \frac{1}{\rho V}\frac{N_1}{N_2}\frac{1}{T}\int_0^T i_1\, u_i\, \mathrm{d}t = \frac{N_1}{N_2}\frac{P_m}{m} \quad , \tag{4}$$

where N_1, N_2 are number of turns of primary and secondary windings, P_m is the measured active power corresponding to magnetised current i_1 and induce voltage u_i, and m is the mass of the specimen measured part.

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 evaluated from (2) and its actual value H^*_{av}

$$H^*_{av} = H_{av} - \Delta H_{av} = \frac{N_1 i}{l} - \frac{U_{m\mathrm{BA}}}{l} . \tag{5}$$

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

$$\delta_p = \frac{p_{err}}{p} = \frac{\Delta H_1 \cos\varphi_{\Delta H_1}}{H_1 \cos\varphi_{H_1}} 100\% , \tag{6}$$

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

Formula (6) shows that the power losses measurement error can be decreased by minimising the first harmonic component ΔH_1 of the error signal. The actual causal system for signal processing in real time can not solve this task. We can use the pseudo real time signal processing based on cutting the feedback loop into parallel branches (see Fig.2). The first one is the original analogue feedback branch consisting of the RCP, differential preamplifier DA, power amplifier PA and the compensation winding CW. The second branch represents the off line operating DSP unit. This unit operates with two input signals, compensation loop error signal $u_{err}(t)$ and induced voltage waveform. $u_{vw}(t)$. The DSP unit output signal $u_{out}(t)$ is added to the loop error signal on the power amplifier input.

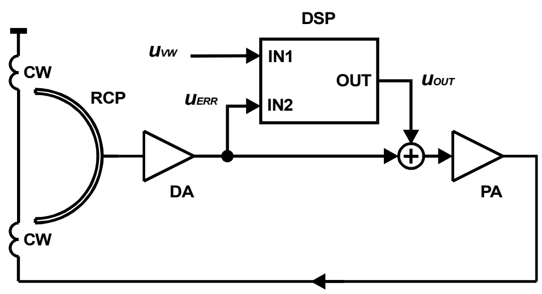

Fig. 2. Digitised compensation feedback loop

The exciting signal of the power amplifier is the summa of the error signal $u_{err}(t)$ and the DSP unit output signal $u_{out}(t)$ (correction signal) . Starting from zero correction the DSP iteration algorithm generates step by step the sinusoidal correction signal synchronous with induced voltage $u_{vw}(t)$. In the next step the correction signal is equal to the summa of the first harmonic component of the new error signal $u_{err}(t)$ and the correction signal from the previous step (the next FFT processing starts after the end of the previous step transient). After an infinite number of steps the first harmonic component of the power amplifier exciting signal from the original analogue branch is completely replaced by the artificial signal from the DSP unit. Then the analogue signal at the output of the differential preamplifier (corresponding to the MMF error signal) does not contain the first harmonic component. This process operates as PI controller in an analogue system.

3. Experimental part

Measurements were made on the compensated SST KF7 with additional equipment. As the DSP unit it has been used the fixed point 16-bit signal processor TMS320C5x with codec and filters. It were measured specimens of the grain oriented material Eo 10 for B_a up to 1,8 T and of the non-oriented material Ei 60 for B_a up to 1,6 T at the frequency 50 Hz. The Accuracy of the original analogue compensation loop and accuracy of the digitised loop have been measured and compared for analogue loop gain values 30, 24 and 18 dB. The experimental results are summarised in Tab.1. G_0 is the open analogue loop gain, A_{H1} the first harmonic component suppression achieved by the digital signal processing, $|\delta_{pA}|_{max}$ is the original analogue loop power losses measurement error, $|\delta_{pD}|_{max}$ is the error of the experimental digital loop.

G_0(dB)	A_{H1}(dB)	$\|\delta_{pA}\|_{max}$	$\|\delta_{pD}\|_{max}$
30	18.5	2,8 %	0,8 %
24	24,2	4,1 %	0,6 %
18	29,2	6,8 %	1,0 %

Tab. 1. Power losses measurement error for Eo10

G_0(dB)	A_{H1}(dB)	$\|\delta_{pA}\|_{max}$	$\|\delta_{pD}\|_{max}$
30	27,4	1,6 %	0,10 %.
24	26,9	3,1 %	0,25 %
18	27,3	6,0 %	0,60 %

Tab. 2. Power losses measurement error for Ei60

Typical waveforms of the important measured quantities are shown in Fig. 3 and Fig. 4. Curve marked H corresponds to the magnetic field strength waveform $H(t)$, curve 10xΔH to the scaled waveform of the magnetic field strength error $\Delta H(t)$ (dashed line) and curve 50xUi to the scaled induced voltage waveform $u_{vw}(t)$. We can observe considerable first harmonic component suppression in the digitised loop error waveform $\Delta H(t)$ (Fig. 3) on the contrary with $\Delta H(t)$ waveform for original analogue loop (Fig. 4).

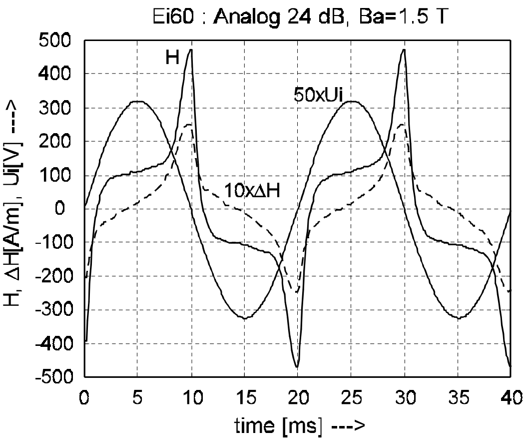

Fig. 3. Typical measured waveforms for original analogue loop and for material Ei60

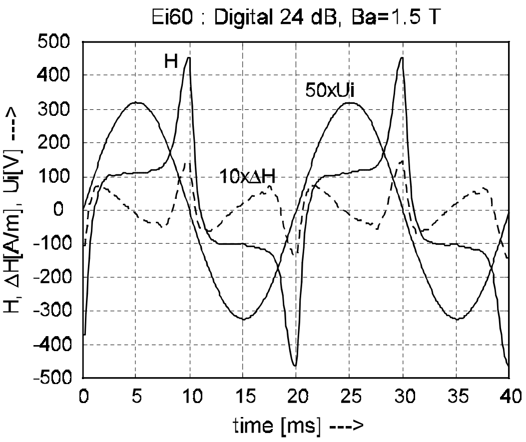

Fig. 4. Typical measured waveforms for digitised loop and for material Ei60

4. Conclusion

The accuracy of the MMF compensated SST's is limited due to the finite gain of the compensation feedback loop. The realised digitisation of the compensation loop and the convenient processing of the error signal gave the possibility of increasing the compensation accuracy. The experimental results show that using DSP circuits the error of the MMF compensation method can be decreased approximately 5 times for measurement of grain oriented materials and more than 10 times for non-oriented materials. It gives the possibility of using the MMF compensation method in all kind of precise measurements including the cases of saturation. Tab. 3 summarises improvement of the power losses measurement accuracy achieved by digitisation of the compensation feedback loop.

material	$\lvert\delta_{pA}\rvert_{max}$	$\lvert\delta_{pD}\rvert_{max}$	$\dfrac{\lvert\delta_{pA}\rvert_{max}}{\lvert\delta_{pD}\rvert_{max}}$
Eo10	6,8 %	1,0 %	6,8
Ei60	6,0 %	0,6 %	10,0

Tab. 3. Power losses measurement error for Eo10

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