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A simple compensation method for the accurate measurement of magnetic losses with a single strip tester

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We present a new method for the accurate characterization of soft magnetic sheets using a permeameter based on the precise compensation of the magnetomotive force (MMF) drop in the flux-closing yoke. It has been developed in order to overcome the systematic uncertainty affecting the value of the magnetic field strength in single sheet testers when obtained, according to the standards, through the measurement of the magnetizing current. This phenomenon is more critical for high permeability materials, because of the reduced MMF drop across the sample. While additional sensors and auxiliary windings have been proposed in the literature, a novel approach is demonstrated here, based on the use of the permeameter upper half yoke as the MMF drop sensor and of an auxiliary winding on the lower half yoke, implementing compensation. This solution, dispensing one from dealing with the usually small signal levels of the conventional MMF drop sensors (e.g. Chattock coils), provides best results with the introduction of wedge-shaped magnetic poles, in order to accurately define the magnetic path length. The method is validated by measurements of power loss, apparent power, and hysteresis cycles on non-oriented and grain-oriented Fe-Si steel sheets, which are compared with local measurements performed on the same samples using *H*-coil and *B*-coil across a uniformly magnetized region.

Index Terms—Magnetic loss, hysteresis cycle, compensated permeameter, apparent power.

I. INTRODUCTION

THE PROPER design of electrical machines and electromagnetic devices requires an accurate prediction of iron loss. Indeed, in modern embedded applications such as hybrid or electric vehicles [1][2], the best compromise must be found between the machine efficiency [3][4] and torque density [5]. But any predictive model starts from a proper material characterization [6][7]. The standard testing technique of soft magnetic steel sheets is based on the use of the Epstein test frame [8]. It shows good reproducibility, demonstrated by inter-laboratory comparisons of power loss and apparent power measurements [9]. However, this method besides requiring tedious preparation of the samples, is inevitably affected by appreciable systematic deviations (up to about 10 % at high inductions) from the true values of the measured quantities, as obtained, for example, by accurate measurements using *H*-coils [9][10][11]. But the *H*-coil method requires the integration of low-level signals and is hardly acceptable in the industrial practice. Increasing interest is therefore attached, at present time, to the Single Sheet Testing (SST) method, applied according to the pertaining IEC Standard [12][13], because of the convenient use of wide lamination samples. The SST method does not require stress relief of samples upon cutting, can be directly applied to the domain-refined high-grade grain-oriented materials, and shows good reproducibility of measurements [9] [14]. Consequently, there is demand by industry for including SST reference values in the material specification standards. With the SST arrangement, where the sheet sample is inserted in a double-C laminated yoke, the magnetic field strength is calculated using the measured magnetizing current and defined magnetic path length ($l_m = 0.45$ m) is adopted. A main problem here is that the magnetomotive force (MMF) drop in the flux-closing yokes may not be negligible with respect to

the one across the sample, especially with high-permeability materials. This can lead to overestimated magnetic field values. At the same time, the yoke itself can provide a certain contribution to the measured loss, depending on its manufacture and the possible existence of interlaminar eddy currents at the pole faces [15].

One way to overcome this difficulty is, as discussed in [16], one of compensating the drop of the MMF in the yokes of the permeameter by an auxiliary magnetizing winding. This is driven by a Chattock coil, placed over the measuring sample region of length l_m and a very high-gain amplifier, implementing a feedback control on the auxiliary current, such as to compensate the MMF drop outside the length l_m [16]. Like all the *H*-coil measurements, this method has a weak point in the necessity of handling small signal levels.

In this paper, we consider a single strip double-C yoke permeameter, applied to annealed Epstein samples, where a new compensation method, simpler and more effective than previous literature solutions [16], is implemented. Epstein strip samples are used in the present experiments for practical convenience, but the method could be easily adapted to standard SST permeameters. The idea is one of using the upper half of the yoke as a zero MMF indicator and the lower half for accommodating the compensation circuit. It is a simple measuring arrangement, where the signal to be controlled is relatively large and much easier to handle than the weak and noise-prone signal generated by a Chattock coil. As a further advantage, there is no geometrical discontinuity in the magnetizing winding, as required instead, with ensuing inhomogeneity of the applied field, by the insertion of the Chattock coil [16]. The method is validated by comparison with accurate measurements performed upon a relatively restricted median region of the strip sample by the *H*-coil method. Non-oriented (NO) and high-permeability grain-oriented (GO) Fe-Si samples have been tested, with very good

70 agreement between the results obtained with the magnetizing
 71 current and those obtained by localized H and B coils.

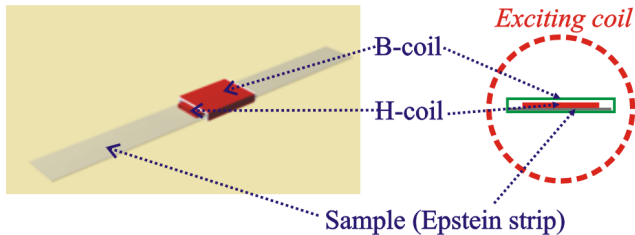
72 II. THE COMPENSATED PERMEAMETER

73 In this section we describe the geometry of the system and
 74 the circuit for the compensation of the MMF drop.

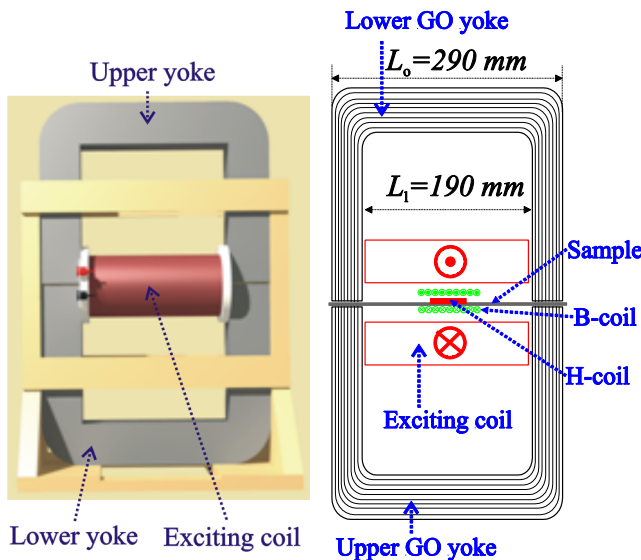
75 A. System geometry and magnetic path length

76 The sample is a conventional annealed Epstein strip. The
 77 induction derivative is measured by means of a 500-turn
 78 mm long pickup coil placed at the center of the strip. Inside
 79 the B -coil, a many-turn calibrated flat H -coil (1 mm thick
 80 turn-area $2.25 \cdot 10^{-2} \text{ m}^2$) of same length is placed upon the
 81 sample surface (see

82 Fig. 1). The H -coil provides, after integration of the
 83 measured voltage, the tangential field upon the measuring
 84 area. Since in the measuring region the applied field and the
 85 induction are verified to be highly uniform, tangential field
 86 and internal field are bound to coincide. The measured local
 87 loss is thus identified with the true loss figure of the material,
 88 that is, the reference quantity for the results obtained with the
 89 compensated permeameter.



92 Fig. 1 - Sample (Epstein strip), with enwrapping B -coil and tangential H -coil
 93 (3D view and front view).



94 Fig. 2 - a) 3D view of the permeameter. b) 2D view of magnetizer, exciting
 95 circuit, and measuring coils.

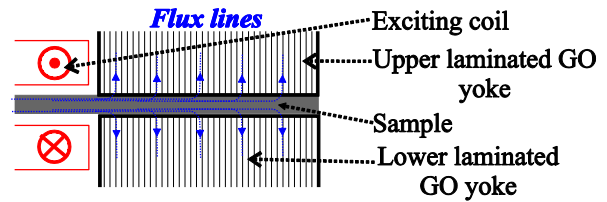
94 The developed permeameter, shown in Fig. 2, consists of
 95 double-C laminated yoke of $50 \text{ mm} \times 50 \text{ mm}$ cross-section
 96 area, made of 0.30 mm thick high-permeability GO strips.
 97 uniformly wound magnetizing solenoid covers the distance
 98 $= 190 \text{ mm}$ between the pole faces of the yoke. It is endowed
 99 with series connected additional narrow windings at its ends

100 by which maximum uniformity of the applied field across the
 101 whole distance L_i is obtained ([11], p. 109).

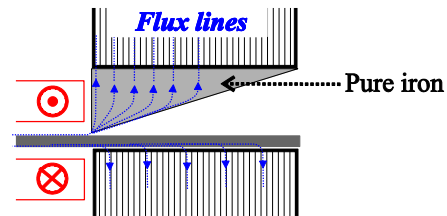
102 According to Ampère's law, the magnetomotive force NI
 103 generated by a current I flowing into the N -turn solenoid is
 104 related to the magnetic field H along a closed path L by the
 105 equation

$$N \cdot I = \oint_L H \cdot dl. \quad (1)$$

If a method is found by which the drop of the MMF in the
 flux-closing yoke is made either negligible or fully
 compensated, (1) simply becomes $N \cdot I = H \cdot L_s$, where L_s is the
 length of the mean magnetic flux path in the sample. L_s has
 value intermediate between L_i , the distance between the pole
 faces, and L_o , the width of the permeameter (Fig. 2b), as the
 obvious result of flux channeling from the sample into the
 yokes (see Fig. 3a). It is actually not well defined and it
 depends on the magnetization level in the sheet sample. It will
 appreciably change on approaching the material saturation.



(a) Standard configuration.



(b) Modified configuration.

Fig. 3 - Defining the magnetic flux path length in the sample.

116 We wish to impose a flux path such that the length L_s
 117 coincides with the distance between the pole faces L_i . To this
 118 end, the following modification of the upper yoke is proposed.
 119 Two identical wedge-shaped pure iron poles are placed
 120 beneath the two limbs of the upper yoke, as shown in Fig. 3b
 121 and Fig. 5, with the contact lines between the sheet surface
 122 and the poles placed exactly at the distance L_i . As discussed in
 123 the following Section, this is expected to force, under the
 124 action of a feedback system employing auxiliary windings on
 125 the yokes, the flux path length in the sample to be equal to L_i .
 126 Under these conditions, the magnetic field H in the sample
 127 will be obtained according to the relation

$$N \cdot I = H \cdot L_i. \quad (2)$$

independent of the way the flux lines enter the lower yoke.

B. The principle of MMF compensation.

The idea here developed follows to some extent from the
 method using a Chattock coil sensor to cancel the MMF on a
 known length, as described in [16]. Here we take the yoke
 itself as a zero MMF indicator. A few-turn secondary coil
 wound around the upper yoke provides the derivative of the
 magnetic flux Φ flowing in it. According to the simplified
 reluctance description of the system shown in Fig. 4, where

137 the reluctance of the sample is R_s , the reluctance of the upper
 138 and lower yokes is R_y , and that of the wedge-shaped pole
 139 R_p , the MMF drop E pertaining to the magnetic circuit outside
 140 the sample is proportional to the flux Φ . Since there is
 141 MMF source in the upper yoke, E will be reduced to zero
 142 canceling the flux Φ , that is, bringing to zero the voltage
 143 correspondingly induced in the secondary coil. This can be
 144 accomplished by adding a compensation winding on the lower
 145 yoke and controlling it in such a way that the correspondingly
 146 generated MMF $N_c I_c$ leads to the condition $E = 0$. The control
 147 loop is schematically shown in Fig. 5. An analog control card
 148 (PID controller) keeps the voltage $v_1 \propto d\Phi/dt$ equal to zero,
 149 properly supplying, via a high-gain linear amplifier, the
 150 compensation winding on the lower yoke. Consequently,
 151 the flux Φ in the sample is made to entirely flow in the lower
 152 yoke.

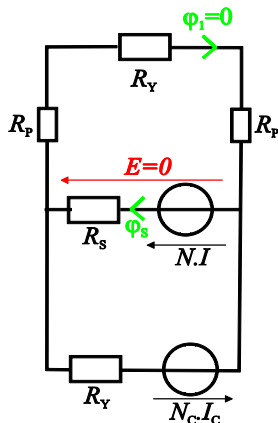


Fig. 4. Reluctance network of the compensated permeameter.

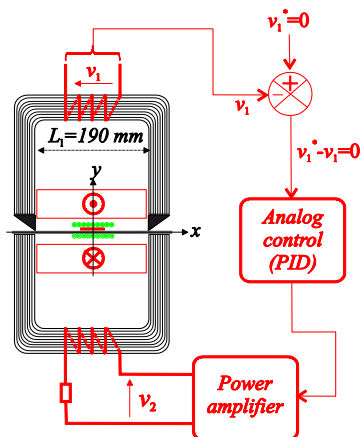


Fig. 5. Compensated permeameter and control circuit.

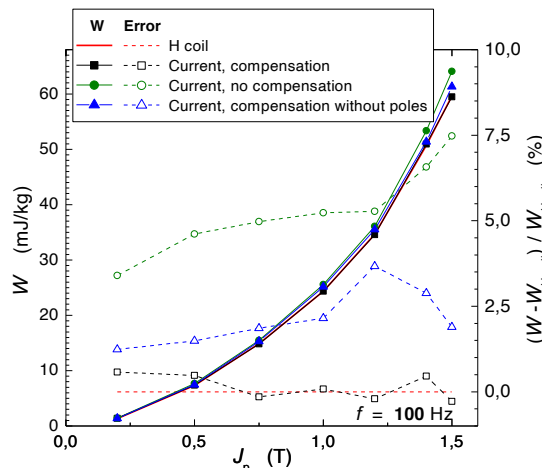
153 This compensation method is simple and sensitive, since
 154 does not require any specific MMF sensor and a high signal
 155 to-noise ratio is ensured by the high permeability of the GO
 156 laminations employed in the yokes. The voltage v_1 is, for
 157 example, always much larger than the one achievable by
 158 Chattock coil, and its control around the zero value
 159 correspondingly easier and more precise. To be remarked that
 160 imperfect contact between the wedge shaped poles and the
 161 sample, which can be lumped in the pole reluctance R_p , has
 162 little detrimental effect on the permeameter performance,
 163 because the flux in the upper yoke is made to vanish.

III. EXPERIMENTAL RESULTS

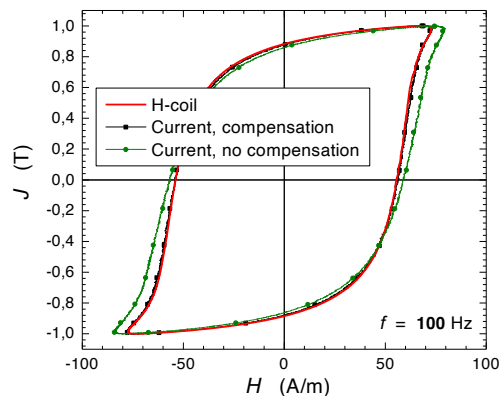
The novel compensated permeameter has been tested on nonoriented Fe-(3 wt%)Si sheets (thickness 0.35 mm) and high-permeability (HiB) grain-oriented sheets (thickness 0.28 mm). Energy loss, apparent power, and hysteresis loops were measured under sinusoidal induction waveform at $f = 100$ Hz and peak polarization values $0.2 \text{ T} \leq J_p \leq 1.5 \text{ T}$. The value of the magnetic field H was obtained both by measuring the magnetizing current and by integrating the signal induced in the H -coil placed at the center of the Epstein strip.

A. Non-oriented Fe-Si sheets

Fig. 6 shows the measured energy loss vs. peak polarization obtained through the H -coil and current methods.



177 Fig. 6. NO Fe-Si sheets. Comparison of the energy loss measured by the H -
 178 coil method and the current measurement method. The permeameter can be
 179 compensated as described above, non-compensated (the compensation circuit
 180 is not switched on), or compensated without the iron poles. The dashed lines
 181 provide the deviations of the loss figures measured with the current method
 182 with respect to the H -coil method.
 183



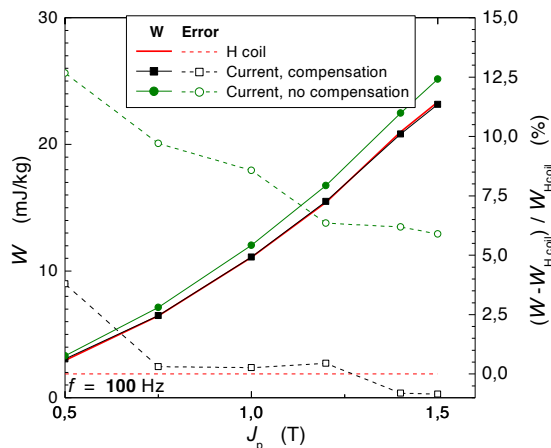
184 Fig. 7. NO Fe-Si sheets. $J_p = 1 \text{ T}$. Comparison of the hysteresis loops
 185 measured by the H -coil method and by the current measurement method, with
 186 and without compensation.

187 It appears that the results by the H -coil method and the current
 188 method with compensation and wedge-shaped iron poles on
 189 the upper yoke show remarkable agreement. On the other
 190 hand, because of the additional loss contribution by the yokes,
 191 overestimated figures are obtained by use of the
 192 uncompensated permeameter, the higher J_p the higher the loss
 193 deviation (up to about 7 %). If the compensation procedure is
 194 applied to the standard permeameter configuration without
 195 wedge-shaped poles, the loss value is still overestimated (from
 196 2% to 4%), because the magnetic path cannot be fully
 197

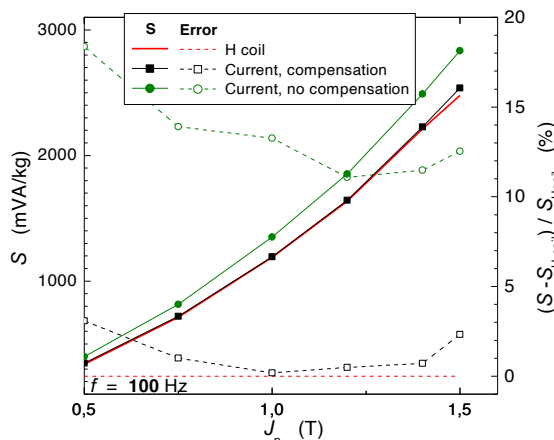
198 constrained to the sample length L_i and is slightly longer. 230
 199 The good agreement between the H -coil and the compensated 231
 200 current methods is confirmed by the corresponding 232
 201 measured hysteresis loops shown in Fig. 7. 233

202 *B. HiB grain-oriented sheets* 234

203 Measurements of high permeability GO materials are 235
 204 demanding, because the MMF drop in the yokes may be 236
 205 from negligible with respect to the one in the sample. At 237
 206 the same time, the localized measurements using the H -coil are 238
 207 difficult, especially at low frequencies, because the signal can 239
 208 be very small. This adds to the interest for the here proposed 240
 209 solution, which includes also the measurement of the apparent 241
 210 power. Fig. 8 compares the energy loss values obtained with 242
 211 the H -coil method and the magnetizing current method, with 243
 212 and without compensation, in the GO sheet. It is apparent that 244
 213 the compensated permeameter and the H -coil measurements 245
 214 provide close results. Under uncompensated conditions, one 246
 215 finds instead that the current method overestimates the 247
 216 magnetic loss by a substantial extent, especially at low 248
 217 inductions (about 10% for $J_p = 0.5$ T, 6% for $J_p = 1.5$ T). This 249
 218 is expected, because the loss in the yoke depends only on 250
 219 not on the type of material under test, and its ratio to the 251
 220 sample loss increases with better materials 252
 221



222 Fig. 8. High-permeability GO sheets. Comparison of the energy loss 223
 224 measured by the H -coil method and the current measurement method, with 225
 226 and without compensation. 227



227 Fig. 9. High-permeability GO sheets. As in Fig. 8 for the apparent power. 228
 229

Fig. 9 shows the behavior of the measured apparent power. Again, we find good agreement between the results provided by the two methods: H -coil and compensated permeameter. It is noted that part of the small discrepancies occurring between the H -coil and compensated current measurements could be attributed to the difficulties intrinsic to the H -coil method (small signal, integration problems...). This further stresses the merits of the here proposed approach.

IV. CONCLUSIONS

A permeameter has been developed, which applies a simple and effective magnetomotive force compensation method for the accurate characterization of soft magnetic steel sheets. It does not require specific sensors, except wedge shaped pole faces for the precise definition of the magnetic path length. It works on the principle of using the flux-closing yoke itself for both sensing and compensation.

The performances of this permeameter have been validated by measurements on non-oriented and grain-oriented Fe-Si sheets, whose results excellently compare with the results provided by measurements performed using the tangential H -coil method.

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