Johannes SIEVERT, Heiko AHLERS

Former affiliation: Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

Epstein to SST relationship - statistical rather than deterministic

***Abstract**. The relationship between the measurement results of Epstein frame and Single Sheet Tester (SST) method are of increasing interest since, for technical and economical reasons, manufacturers and users of electrical sheet steel use more and more the SST for grading and quality control of this material. Besides the systematic deviations between these two methods, there is a considerable statistical component in that relationship. This paper is to demonstrate this phenomenon on the basis of the statistical characteristics of former international round robin tests and dispersion characteristics of material production estimated from the internal dispersions within 55 groups of Epstein samples from 9 manufacturers, each group being constituted of 4 or 5 samples of one grade from one manufacturer. The resulting total dispersion is slightly higher than that of a previous corresponding study accomplished in one laboratory.*

***Streszczenie.** Zależność między wynikami badań aparatem Epsteina a testerem próbek arkuszowych SST może mieć duże znaczenie praktyczne ponieważ coraz więcej ośrodków stosuje wymiennie tylko jedną z tych metod. Obok różnic fundamentalnych (zasady fizycznej) ważne sa też badania statystyczne różnic między tymi metodami. W artykule zaprezentowano międzynarodowe porównania różnych urządzę pomiarowych – badania wykonywano na różnych rodzajach próbek. Wyniki wskazują że różnice są większe niż w przypadku wcześniej demonstrowanych różnic między badaniami w jednym laboratorium. (**Zależność między wynikami aparatu Epsteina i testera próbek arkuszowych SST**)*

Keywords: Magnetic Loss Epstein SST
Słowa kluczowe: straty magnetyczne, aparat epsteina, SST.

Introduction

The Epstein method [1] and the Single Sheet Tester (SST) method [2] are the two standardized methods in force for the measurement of the magnetic properties of electrical sheet steel. We confine this consideration to the independent SST92 (IEC standard published in 1992 [2]) and to the measurement of the specific total loss P_s only. The older version SST82 (IEC standard 404-3 published in 1982, overruled through [2]) which must be calibrated tracing to the Epstein method, turned out to be usable as in-house standard only and to be improper for market purposes because of high dispersion when calibrated using differrent reference samples in different laboratories (see e.g. [3]).

The different systematic error characteristics of the Epstein and the SST92 method cause differences of up to 10% between the specific total power loss values, P_s, obtained by the two methods. This high value can occur with grain-oriented material at high flux densities, whereby the Epstein method may contribute up to –8 % and the SST92 up to +2 %, roughly. This has an impact on the values of core loss building factors of transformers [3] referenced to Epstein and SST92 measurements, respectively.

Although the Epstein values are the reference values to which the specification standards refer, the interest in the usage of the SST92 is increasing in particular for grain-oriented material because of simplicity (no annealing of the cut strip sample) and applicability also to highest grade materials (domain refined grades). For these reasons, the supplementation of the specification standards by SST92 reference values has been discussed in IEC. An inquiry for collation of typical values of Epstein to SST relation factors as utilized in industry was circulated recently [4].

Besides the deviations between these two methods due to their systematic errors, a considerable statistical component has to be expected in that relationship suggested from a number of round robin tests among international laboratories the results of which have been published earlier in various papers [3,5-7]. However, it has been observed that the statistical aspect has not been fully appreciated by the community of experts responsible for electrical steel quality control. In particular, it seems that the significance of a single pair of Epstein/SST measurement results is overvalued. One more statistical component is necessary to be included in the statistical issue, i.e. the dispersion introduced by the variation of the production process at the various manufacturers. This statistical component was estimated from the relative standard deviations within 55 groups of Epstein samples (each group consisted of 4 or 5 samples of one grade from one of the 9 participating manufacturers).

The purpose of this paper is to show, quantify and to try to explain the statistical character of this relationship. We confine the consideration to grain-oriented material at flux density values between 1.3 T and 1.8 T and at technical frequencies.

Comparisons and evaluations

We refer to various international comparisons of specific total loss (power loss, P_s) measurements conducted by European as well as worldwide laboratories over the time period between 1985 and 2001. From these data we can estimate the typical dispersion (reproducibility) of Epstein measurements and of SST measurements carried out in accordance with IEC standards 60404-2 [1] and 60404-3 [2], respectively. For this purpose we have the results of two Epstein and three SST round robin tests at our disposal.

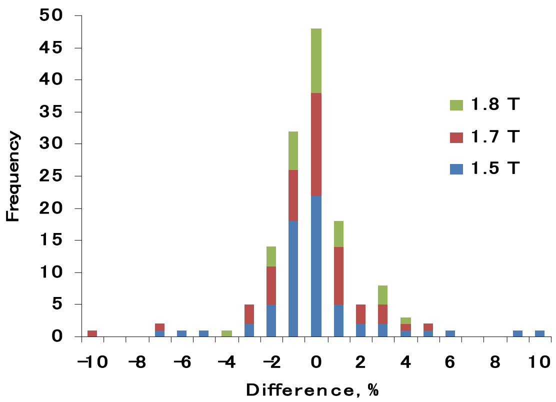

Fig 1 European comparison of Epstein measurements on four grades of n.-o. and g.-o.steel, summarized for 1.5 T, 1.7 T and 1.8 T and 25 Hz, 50 Hz and 75 Hz [5]. Histogram of differences δP_{EPS} related to the average over the 5 participating laboratories.

Fig. 1 shows the results of a comparison of Epstein measurements accomplished in 1985 by 5 European laboratories (IENGF Torino; INPG Grenoble, LCIE Paris, NPL Teddington and PTB Braunschweig) [5]. The δP_{EPS} histogram refers to the relative loss differences according to

(1) $$\delta P_{EPS} = 100 \cdot \frac{P_s - P_r}{X_r}$$

with: P_s individual specific total loss value, X_r average of the P_s values of all labs at one parameter set.

In this case ("Ep1"), the 5 labs measured the loss of two n.-o. and two g.-o. Epstein test specimens at 1.5 T, 1.7 T and 1.8 T (only g.-o- samples) and frequencies of 25 Hz, 50 Hz and 75 Hz. Since the curves showed almost normal distributions for all flux density and frequency values, they were combined to one histogram, and the over-all relative standard deviation was determined to:

$$s_{Ep1} = \pm 1{,}50\ \%\ .$$

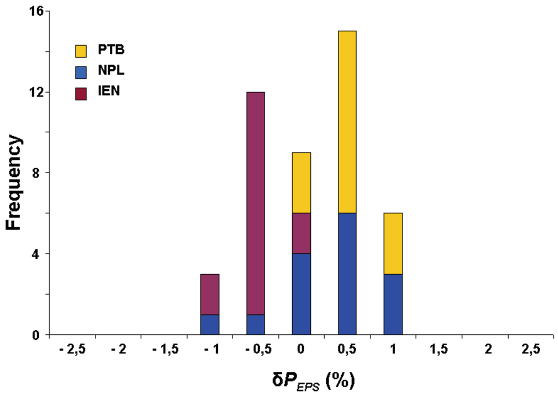

Fig.2: Comparison of measurements on 15 Epstein samples of various grain-oriented grades made at 3 standard laboratories (IEN, NPL and PTB) at 1.7 T [6]. Histogram of the differences δP_{EPS} related to the average over the 3 laboratories

Fig. 2 shows the $\boldsymbol{\delta P_{EPS}}$ results histographically, corresponding to those of Fig.1, measured in 1998 by 3 standard laboratories (INPG, NPL and PTB) on 15 grain-oriented Epstein samples of various grades at 1.7 T and 50 Hz [6] (case "Ep2"). Due to the excellent calibration facilities of these reference labs a low relative standard deviation was achieved:

$$s_{Ep2} = \pm 0{,}88\ \%.$$

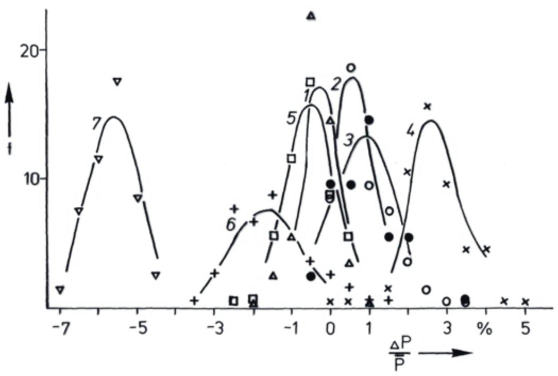

Fig. 3: Comparison of measurements using the independent SST92 (not related to Epstein values) with 6 participating European laboratories (1989, [7]); 20 sheet samples ranging from semi-processed n.o. to High B materials; flux densities were 1.0 T, 1.3 T and 1.5 T for the thirteen n.o. samples and 1.5 T and 1.7 T for the seven g.-o. samples. Histograms of the differences δP_{SST} related to the average over all participants, separately for each lab (2 SSTs used by PTB). The left most curve was excluded from evaluation.

Fig. 3 shows the results of the first international comparison of SST92 measurements carried out in 1989 by 6 European laboratories (British Steel, Cockerill, IENGF Torino, NPL Teddington, PTB Braunschweig and Stahlwerke Bochum) [7] (case "SST1"). The loss measurements were conducted at 50 Hz on 20 sheet samples, the grades ranging from semi-processed n.o. material to High B grades. Flux densities were 1.0 T, 1.3 T and 1.5 T for the thirteen n.o. samples and 1.5 T and 1.7 T for the seven g.-o. samples. The $\boldsymbol{\delta P_{SST}}$ histograms, drawn separately for the various labs, refer to the relative loss differences according to

$$(2)\qquad \delta P_{SST} = 100 \cdot \frac{P_s - X_r}{X_r}$$

with: P_s individual specific total loss value, X_r average of the P_s values of all labs together at one flux density each. The values represented by the left most curve of Fig. 3 were excluded from the evaluation because of missing overlapping probably due to erroneous calibration. The histograms yield an over-all relative standard deviation of

$$s_{SST1} = \pm 1{,}7\ \%.$$

Fig. 4 (case "SST2") shows the $\boldsymbol{\delta P_{SST}}$ results of a comparison based on the same parameters, i.e. participants, materials, flux densities and frequency as in case Ep2, except for the kind of samples, i.e. 50 cm sheet samples were used instead of Epstein samples [6]. The histogram of Fig. 4 for the 45 cases (15 samples, 3 labs) yielded a relative standard deviation of

$$s_{SST2} = \pm 1{,}06\ \%$$

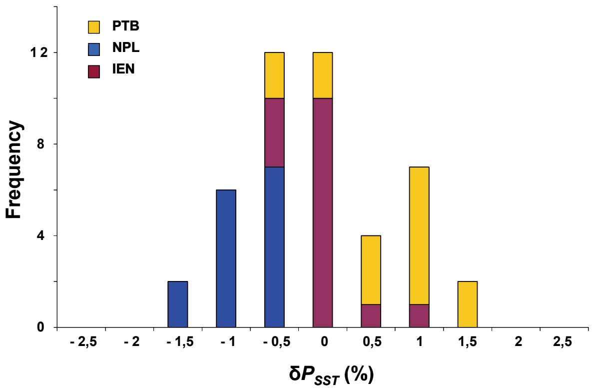

Fig.4: Comparison of measurements on 15 SST samples of various grain-oriented grades conducted at 3 standard laboratories (IEN, NPL and PTB) at 1.7 T [6]. Histogram of the differences related to the average over the 3 laboratories

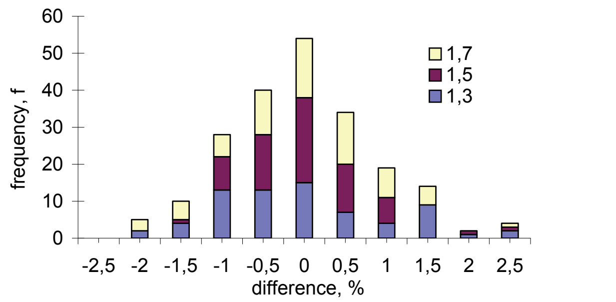

Fig.5:. Comparison of SST power loss measurements; international comparison with 8 participating labs [3]. Histogram of distribution of the relative differences δP_{SST} related to the average over all labs.

Fig. 5 (case "SST3") shows the results of a comparison arranged by ABB in 1997 including RGO, HiB and laser scribed g.o. material [3]. The samples, their thicknesses ranging from 0.23 to 0.35 mm, were measured at 50 Hz and 60 Hz and at flux densities 1.3 T, 1.5 T and 1.7 T. The three flux densities showed very similar, almost normal distributions so that they could be combined to one distribution curve for which we obtained the relative standard deviation value:

s_{SST3} = ± 0,81 %.

This excellent value achieved for 8 heterogeneous laboratories might be also indicate the progress achieved in the measurement precision through the digital measurement procedures that meanwhile have been widely spread.

In addition, we have to consider and include the typical dispersions of the production of material of the various manufacturers. We estimated this number from power loss measurements according to the Epstein method made on 240 Epstein test samples. These samples were supplied by nine principal manufacturers of electrical steel worldwide within a project for the determination of the Epstein to SST relationship in one laboratory [8,9] (for more details of that project see last section below). This sample multiplicity comprised 8 different grades, one grade of one manufacturer formed a group whilst each of the 55 groups contained 4 or 5 Epstein samples. The dispersions δP_{EPS} within the 55 groups involved constitute the histogram of Fig 6 from which a representative relative standard deviation of g.o. steel production can be estimated valued to:

S_{prod} = 1,4 %.

The uncertainty of this figure may be influenced by possible differences in the procedure of sample selection applied by the manufacturers (it had been asked for selection from different coils).

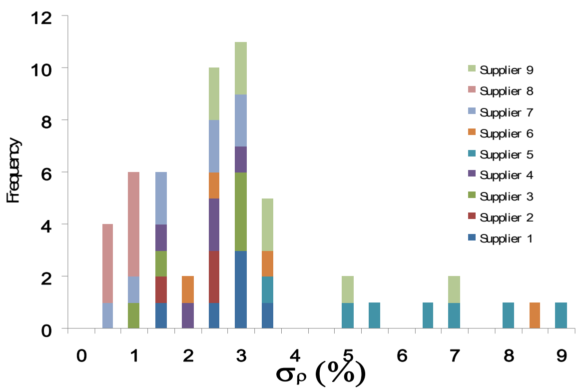

Fig. 6: Histogram of the dispersions σ_P of the relative δP_{EPS} values of the g.-o.- sheet steel production of 9 international manufacturers. The dispersions were calculated for 55 group cases based on the loss measurements on 240 Epstein samples of 8 different g.-o. grades at 1.7 T. Each of the sample groups was constituted by the assembly of 4 or 5 Epstein samples of one grade supplied by one manufacturer. (There was no significant correlation of grades to the position of groups in this histogram)

Discussion and conclusions

The combined relative standard deviation s_1 is proposed as a representation of the 68%-probability-dispersion to be expected when comparing Epstein with correlated SST test specimen results. In the present case it can be calculated using the formula for this combination given by the “GUM” [10] **and applying it** to the means in the categories Eps and SST and to the estimated “prod” number:

$$(3)\ s_1 = \sqrt{\left[\frac{1}{2}\left(s_{Ep1} + s_{Ep2}\right)\right]^2 + \left[\frac{1}{3}\left(s_{SST1} + s_{SST2} + s_{SST3}\right)\right]^2 + s_{prod}^2}$$

Its value resulting from the constituent contributions estimated above, amounts to s_1 = 2.2 %, see also table 1.

Table 1: Constituents and combined relative standard deviation s_1

	s_{Eps1}	s_{Eps2}	s_{SST1}	s_{SST2}	s_{SST3}	s_{prod}	s_1
±	1.5	0.88	1.7	1.06	.0.81	1.4	2.2

The assessment and physical background of these values should take account of the complexity of the physical parameters taking influence: At first there are the crystallographic characteristics such as grain size and texture of the material. An extraordinary role plays also the situation of the internal stress of the individual samples. Whilst the Epstein samples, after cutting and stress release annealing, represent a more intrinsic value characteristic for the material in an idealized state (and insofar show lower dispersion), the sheet samples introduce a more individual property of the respective sample. However, this is not a drawback because the sheet samples present the material properties more realistically, a fact which makes the SST method more and more attractive to users of electrical steel because the SST constitutes a more reliable instrument for the entrance inspection.

The statistic picture obtained here can be compared with the results of a former study aiming at the systematic difference between Epstein and SST measurements on c.g.o. materials but showing also its statistical characteristic. In that study, 240 Epstein-SST-test specimen triplets (2 sheets and 1 Epstein specimen each cut adjacently from the same coil) of 8 grades from 9 international manufacturers were employed [8,9]. The relative standard deviation of the Epstein to SST loss ratio of this multiplicity of samples, the measurements being carried out in one lab using one electrical part of set-up, turned out to be $S_{Epst/SST}$ = 2.0 %. The similarity of this number with the number 2.2 % obtained in this paper may support the significance of the latter although an inequality of parameter values (e.g. different flux density values) exists.

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***Authors**: Dr. Ing. Dipl.-Phys. Johannes Sievert, Billrothstr. 2, 38116 Braunschweig – Germany, email: Johannes.sievert@t-online.de; Dipl.-Phys. Heiko Ahlers, Mühlenstraße 5, 38112 Braunschweig - Germany*