IEC TR 62981

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TECHNICAL REPORT

colour inside

Studies and comparisons of magnetic measurements on grain-oriented electrical steelsheet determined by the single sheet test method and Epstein test method

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CONTENTS

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STUDIES AND COMPARISONS OF MAGNETIC MEASUREMENTS ON GRAIN-ORIENTED ELECTRICAL STEELSHEET DETERMINED BY THE SINGLE SHEET TEST METHOD AND EPSTEIN TEST METHOD

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IEC TR 62981, 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
68/535/DTR	68/543/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 stability date indicated on the IEC website 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- withdrawn,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
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STUDIES AND COMPARISONS OF MAGNETIC MEASUREMENTS ON GRAIN-ORIENTED ELECTRICAL STEELSHEET DETERMINED BY THE SINGLE SHEET TEST METHOD AND EPSTEIN TEST METHOD

1 Scope

This document, which is a Technical Report, provides the results of international exercises and comparisons focusing on achieving the knowledge of the statistical performance of single sheet tester (SST) measurements made on grain-oriented electrical steel. These experiments aim at specifying obligatory reference values, measured by the single sheet test method, for the grading of high permeability (P grades) grain-oriented (g.-o.) materials, independently from the Epstein classification as it is practiced today. Besides this, Epstein test measurements have been made in order to gain more up-to-date statistical performance for comparison with the SST statistical characteristics. A few experiments were carried out aiming at improved knowledge on the systematic error performance of the SST, i.e. they were to determine the correlation between the quality of insulation separating laminations in the SST yokes and the measured loss.

There are various designations for "non-oriented electrical sheet steel" and for "grain-oriented electrical sheet steel" in use, for example in the IEC 60404 classification and specification standards, and there are also abbreviations like CGOS (for conventional grain-oriented steel) often used in industry. In this report, the following designations and abbreviations are used:

– electrical steel as generic term;
– n.-o- electrical steel and g.-o. electrical steel as generic terms for these two types;
– S-type electrical streel or c. g.-o. electrical steel for "conventional grain-oriented electrical steel";
– P-type g.-o. electrical steel or high-permeability g.-o. electrical steel;
– DR g.-o. electrical steel for "domain refined grain-oriented electrical steel";
– where two terms are used, it can depend on the context;
– "electrical steel" can be replaced with "material", depending on the context.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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 60050-121, *International Electrotechnical Vocabulary – Part 121: Electromagnetism* (available at http://www.electropedia.org)

IEC 60050-221, *International Electrotechnical Vocabulary – Chapter 221: Magnetic materials and components* (available at http://www.electropedia.org)

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-221 and IEC 60050-121 apply.

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- IEC Electropedia: available at http://www.electropedia.org/
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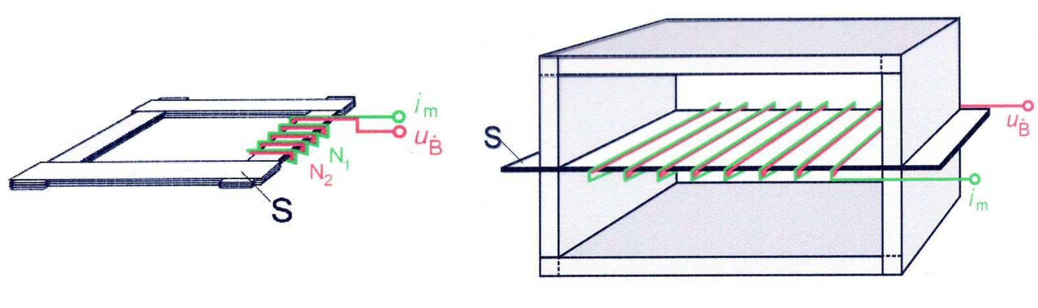
4 Background

4.1 Historical background and former concepts of the SST-Epstein relationship

The magnetic characteristics of electrical steel are significant in two regards. Firstly, they are decisive for the possible applications of the material. Secondly, the magnetic loss performance is essential for the material grading and for the efficiency of the energy transformation, i.e. for the energy costs and the economic and environmental aspects.

The Epstein method [1][1] and the single sheet tester (SST) method [2] are the two standardized methods for measuring the magnetic properties of electrical steel. Whilst the Epstein method, based on the 25-cm-frame, was designed about 60 years ago, the first edition of the single sheet tester standard was published in 1982 after intense discussions at IEC meetings (see Figure 1). This SST(82) standard comprised 500 mm x 500 mm sheet samples forming the closed magnetic circuit together with two symmetrical flux closure yokes made of grain-oriented electrical steel or nickel iron alloy. This first 1982-version was characterized by reference to the Epstein test method, i. e. it had to be calibrated using Epstein strips, 50 cm long and 30 mm wide, measured in the Epstein square and then, inserted side by side, in the SST. This method turned out to be considerably dispersive for reasons which are mentioned in 4.2 and 5.4.

Therefore, 10 years later, IEC published the independent single sheet test method in the IEC SST(92) standard [2] that includes the use of a conventional effective magnetic path length of l_m = 45 cm. However, due to the different designs of their magnetic circuits, SST(92) and Epstein methods show, in particular with high grade GOES materials, significant differences of their results when applied to the same material (for details, see 4.2).



Key

N_1 magnetizing winding

N_2 secondary winding

Figure 1 – Epstein frame and single sheet tester, schematic view, windings partly omitted

The Epstein method has been in use continuously, from its beginning to the present time, defined as the only reference method determining the quality reference in the specification standard. Correspondingly, the grade designations are directly related to the Epstein loss values, for instance the designation M150-35S5 designates a conventional (S-type) grain-oriented steel of 0,35 mm thickness with a maximum specific loss value of 1,50 W/kg measured by the Epstein method at 1,7 T and at 50 Hz. Thus, Epstein loss values have been the reference values for trade and application purposes, laid down in the lists of the

1 Numbers in square brackets refer to the Bibliography.

specification standards, for about 60 years. For this reason, the Epstein to SST relationship was the subject of intense studies during the last two decades [3] [4] [6]. These studies are described in detail in Clause 5.

It is not easy to change this situation although the SST method is superior when applied to grain-oriented electrical steel because of its practical simplicity (no stress-relief annealing of sample needed) and also its suitability to the highest grade materials (e.g. domain refined grades which do not withstand stress relief annealing without deterioration of their properties). Therefore, an increasing part of the industry involved requests that SST reference values be included in the specification standards for these material grades [5].

4.2 Establishing reference values for grain-oriented electrical steels determined by independent SSTs – A new approach to the purpose

Earlier studies always based their considerations of the Epstein to SST relationship on the following formula:

$\delta P_{SE} = (P_{SST} - P_{Ep}) / P_{Ep}$ (or on the equivalent ratio P_{SST} / P_{Ep}).

The different systematic error characteristics of the Epstein and SST methods with grain-oriented materials can result, for instance, in differences of 4 % to 10 % between the specific total loss values, P_S, measured by them at a peak magnetic polarisation of 1,7 T. The systematic errors were found to be caused by the different magnetic circuit designs of the two methods, i.e. the inhomogeneity of the Epstein circuit formed by the double-overlapping joints of the strips (decrease of value), and, on the other hand, by the loss contribution through the SST yokes (increase of value).

Above, the main sources of systematic errors of both, Epstein and SST, are mentioned. Whilst systematic errors might be partly explainable, the statistical errors (dispersion), which are almost of the same magnitude for Epstein and SST, can only partly be assigned to specific phenomena. However, the Epstein to SST ratio, showing pretty good agreement between laboratories when identical samples are circulated, shows significant higher dispersion when the comparison refers to varieties of samples of the same grade (see for example 5.1). The intrinsic properties of those sample individuals are supposed to vary to an extent which is determined by the complexity of the process of sample preparation. Thus, it is probable that there is a significantly larger dispersion with Epstein samples rather than with SST samples (see also Figure 8 and [11]).

Recently, initiated through experts from industry closely involved in practical metrology [5], the awareness has grown that the Epstein to SST relationship, comprising the systematic and statistical error performance of both, Epstein and SST method, is an improper quantity for upgrading the SST to a reference method for high grade g.-o. electrical steel. The main reason is a phenomenon which was ignored with the studies published earlier, including the empirical SST-Epstein relation curve shown in Annex C of [2] which was obtained predominantly for conventional grain-oriented material. This phenomenon is the uncertainty that has to be assigned to the preparation of the Epstein strip samples which necessitates a stress relief annealing operation. This suppresses eventual internal stress due to the production process and, thus, has a misleading impact on the Epstein to SST relationship. This effect is more pronounced with high permeability g.o. material. This uncertainty accounts for a dispersion component of the properties of individual Epstein strip samples caused by the difference in the preparation procedures between laboratories and the randomly arranged strips in the sample stack. Items causing this dispersion component are the following.

Firstly, cutting the plate into strips creates basically a specimen with different properties: the flux is constricted to the strips. High permeability grades partly have grain sizes larger than the Epstein strip width. Flux paths in legs and corners of the strip's stack then undergo drastic changes compared with the entire sheet, and they depend on the random stacking. Internal stress is introduced through the cutting which shall then be removed through suitable annealing. Variations in this procedure create further dispersion:

– the method of cutting and sharpness of the cutting tools;
– the shape of the annealed samples – single strip or stack, with or without weight;
– the annealing procedure – duration, temperature, atmospheres, type of furnace;
– the handling of the samples.

This dispersion is not reflected by comparisons based on circulation of identical Epstein samples to the participating laboratories as it was practiced in the past.

However, this consideration does not include the still more complicated situation with domain refined grades which do not withstand stress relief annealing without deterioration of properties (see below).

In the case of non-domain-refined grades, the cutting to Epstein strips and the process of annealing the strips can, as mentioned above, change the intrinsic properties of the original product; in particular, it can make an inferior quality product which includes severe internal stresses seemingly better by releasing the stresses. This might be tolerated where the building process of the transformer core involves an annealing stage (e.g. wound cores). For manufacturers of stacked transformer cores, this is unacceptable [4].

Whilst companies having stable production processes and applying constant sample preparation may achieve a reasonable in-house-reproducibility of the Epstein method, this is not sufficient for the grading metrology worldwide. Generally, it can be stated that the higher the grade, the stronger is the influence on the dispersion from the Epstein sample preparation.

Finally, with laser domain refined materials, the Epstein test is even not applicable without an expensive wire cutting of the strips to avoid stress. Also, in this case, a certain dispersion caused by the different variations of the process of the Epstein sample preparation may be assumed, however there is no information which allows to quantify this. What remains is the random flux path fluctuation when large-grain material is cut to strips as was mentioned above.

Thus, if single identical Epstein sample stacks are passed through various laboratories, a small dispersion of the measured specific total loss does not tell us the full story. This might also hold for SST samples, however to a smaller extent, because they are prepared in only one step, the cutting. The items listed above suggest that the sample preparation procedure makes the Epstein method results inappropriate as a reference for the conversion into nominal SST values to be listed as specification of grain-oriented material of higher grades. Thus, the independent SST method according to IEC 60404-3 [2] is needed as the more appropriate method for this purpose. This will become more evident by the results shown in Clauses 5 and 6.

5 Preliminary comparisons and experiments

5.1 General

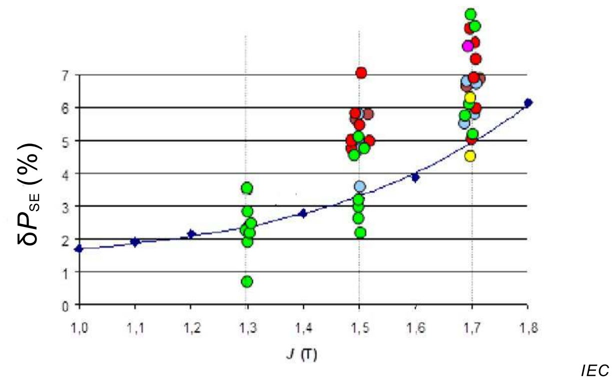
In the first phase of this IEC project, a comparison of the relative difference $\delta P_{\mathrm{SE}} = (P_{\mathrm{SST}} - P_{\mathrm{Eps}})/P_{\mathrm{Eps}}$ measured by steel manufacturers on their own products using their own set-ups was performed. It turned out that the information was not sufficient for specifying reference values for SST sheet samples (see 5.2 and 5.4).

In order to assess the influence of the yokes on the SST measurement results, further preliminary comparisons and experiments were subsequently made in China. Four laboratories and six SST fixtures with yokes having stacked lamination were involved. These experiments were to improve, besides the knowledge about the dispersion, the knowledge of the systematic error performance of the SST which becomes more significant when SST results would be upgraded to independent reference values (see 5.3 and [18]).

5.2 Comparison of the relative difference $\delta P_{SE} = (P_{SST} - P_{eps})/P_{Eps}$ measured by steel manufacturers on their own products using own set-ups

In 2012, seven manufacturers took part in this exercise and made their data measured on related pairs of Epstein and SST samples available for comparison. Two of them contributed data measured on non-oriented materials of grades 270-50A, 400-50A, 470-65A, 600-50A and 700-50A (5 sample pairs each). These δP_{SE} results turned out to be between +14 % and –9 %. They were inconsistent and partly contrary to results published earlier. Therefore, and because the number of two contributors was too low for any statistical evaluation, further consideration of these findings related to non-grain-oriented products was abandoned. However, in the case of grain-oriented material, the simpler sample preparation, wider applicability and a measurement result that is closer to an imagined true value are the impetus for the great interest in the Epstein-SST relationship, or, very recently, in the intention of introducing SST reference values for the grading of grain-oriented materials.

Correspondingly, six manufacturers have contributed δP_{SE} results measured on 5 or more samples for some of the following grades of their grain-oriented products: M90-23P, M100-27P, M103-27P, M105-30P (2x), M130-27P, M110-23S, M120-23S, M120-27S, M130-27S, M130-30S, M140-30S (2x), M150-35S, M155-35S. Figure 2 shows the resulting relative difference $\delta P_{SE} = 100 \cdot (P_{SST} - P_{EP}) / P_{EP}$, averaged for each manufacturer and grade, determined by the 6 contributors, as circles [6]. The different colours of the fillings are assigned to the different contributors. The continuous curve represents the least square fit to the measurement results achieved for 240 of the related grain-oriented Epstein-SST sample pairs (almost all of S-type, a few of P-type material) [3] which is quoted as the informative conversion factor in Annex C (informative) of IEC 60404-3:1992/IEC 60404-3:1992/AMD1:2002 [2].



NOTE The circles are the data from 6 industry laboratories on 13 g.-o. grades (colours assigned to manufacturers). The blue continuous curve is δP representing the least square fit to the older PTB measurements [3] quoted as the informative conversion factor in IEC 60404-3 [2] (the uncertainty of the curve is characterized by a relative standard deviation of about σ_1 = 2 %[3].

Figure 2 – Relative difference $\delta P_{SE} = 100\ (P_{SST} - P_{EP}) / P_{EP}$ versus peak magnetic polarization J measured by six contributors on samples of their own products

The discussion of these findings within IEC TC 68 considered these results as unsatisfactory with regard to the purpose of introducing SST reference values for the grading of grain-oriented material. In the course of this discussion, experts from steel manufacturing industry [5] opened a new view on the Epstein-SST problem by pointing to the deceptive role of the assessment of Epstein results as seemingly absolute reference values, based on arguments given in 4.2. Moreover, whilst in general the dispersion of Epstein and SST loss values are similar, the Epstein method shows a larger dispersion than the SST method when applied to high-permeability material at the key magnetic polarization 1,7 T (see σ-values in Figure 15 a) and b)). As a consequence, the realization of a thorough comparison of measurements on grain-oriented SST sheet samples including high permeability and domain refined material according to IEC 60404-3 and its evaluation independent of Epstein measurements was proposed. Epstein measurements were to be executed in parallel in order to achieve a parallel assessment of the two dispersion characteristics.

5.3 Preliminary comparisons and experiments made by four Chinese laboratories using six SSTs with stacked yokes

Two laboratories in China measured the magnetic loss of one grain-oriented SST sample and found a difference of 7 % between their results determined under equivalent conditions. The search for the reason revealed a considerable difference in the inter-lamination resistance of the yokes of the two SSTs. This encouraged the initiation of a comparison of measurements among 4 laboratories: China Jiliang University Hangzhou, Bao Steel Shanghai, Wuhan Iron and Steel Company (WISCO) and National Institute of Metrology Beijing (NIM) using 6 SST fixtures with stacked lamination yokes. Specific power loss P_S and apparent power S_S at f = 50 Hz were measured at peak magnetic polarisation levels of J = 1,5 T, 1,7 T, 1,8 T on four related SST-Epstein sample pairs, each cut adjacently from the same coil, of the grain-oriented grades: M130-30S, M105-30P (a and b) and M095-23P. Besides, the inter-lamination resistance in the air gaps of the SST yokes was measured over 5-cm-sections.

For the determination of the conductivity factor C_Y of the yokes' lamination, the following Formula (1), derived from the classical power loss definition [9], was used:

$$C_\mathrm{Y} = \sum_{i=1}^{N_\mathrm{S}} \frac{1}{R_\mathrm{Si}} \cdot d_\mathrm{s}^{\,2} \tag{1}$$

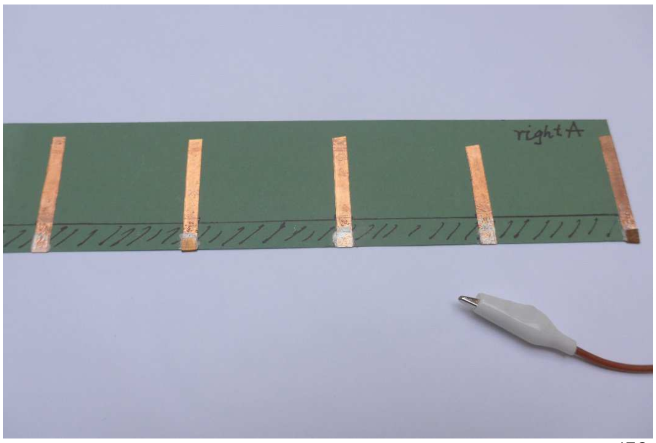
where

N_s is the number of sections;

d_s is the length;

R_si is the resistance of section i.

The contact paperboard strip shown in Figure 3 was turned over for the measurement of upper and lower yokes weighted together in parallel circuitry.



NOTE Paperboard, 0,3 mm thick, copper contacts arranged to 50 mm wide sections; hatched part outside the air gap, with reinforced contacts.

Figure 3 – Contact pattern for the measurement of lamination resistance in the air gap of SST yokes

In almost all cases, only the front side allowed proper access for the measurements so these values were considered as representative for the whole. Since, intentionally, the SSTs were selected for having yokes of widely different quality, the C_Y covered a very wide range extending from 8 Ω^{-1} cm^2 to 8 000 Ω^{-1} cm^2.

Figure 4 shows the ratio of the power loss P_{SST} measured on the 4 sheet samples using the six SSTs, to the power loss value measured by the "best" SST, P_{SSTopt} (showing the lowest conductivity factor), plotted versus the lamination conductivity factor of the SSTs, C_Y. It appears an evident correlation between the yokes' quality, characterized by the inter-lamination conductivity, and the excess loss exceeding the value measured by the best SST. From these results, recommended limits for the yokes' inter-lamination resistance could be derived as 10 Ω per section and 100 Ω over the whole length of the parallel upper and lower yokes' resistance.

The participants of the China studies also measured the air gap widths profile of their SSTs. The profile was averaged over the air gap length (45 cm), and a correlation between the average value and an excess value, corresponding to the resistance procedure, of their apparent power ratio S_{SST}/S_{SSTopt} was searched for – however, a correlation was not found.

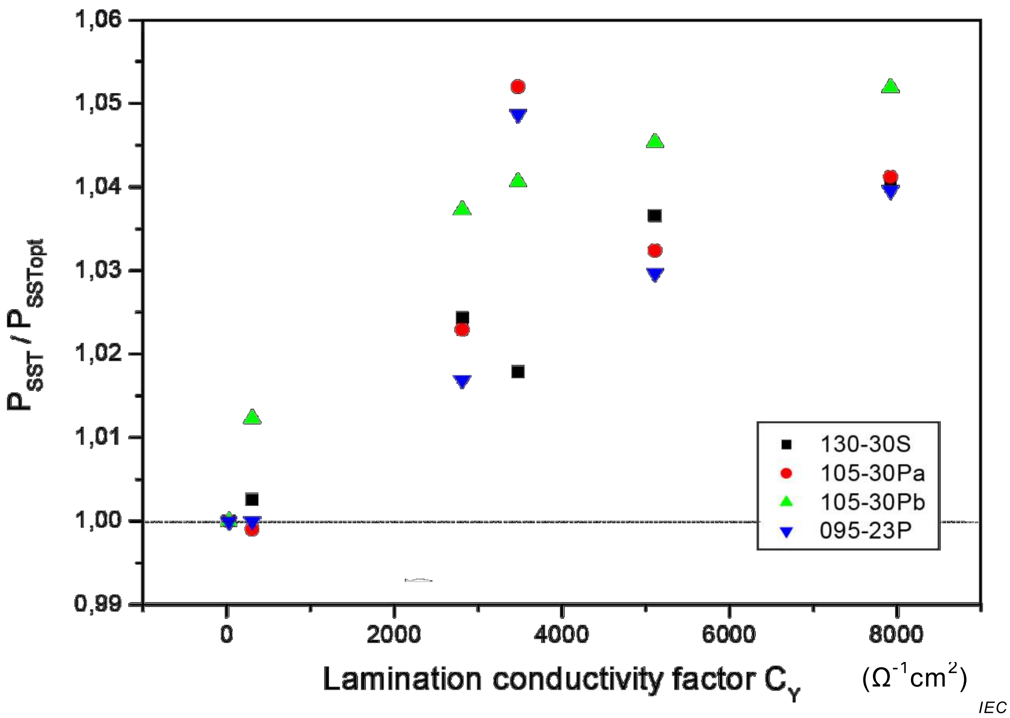
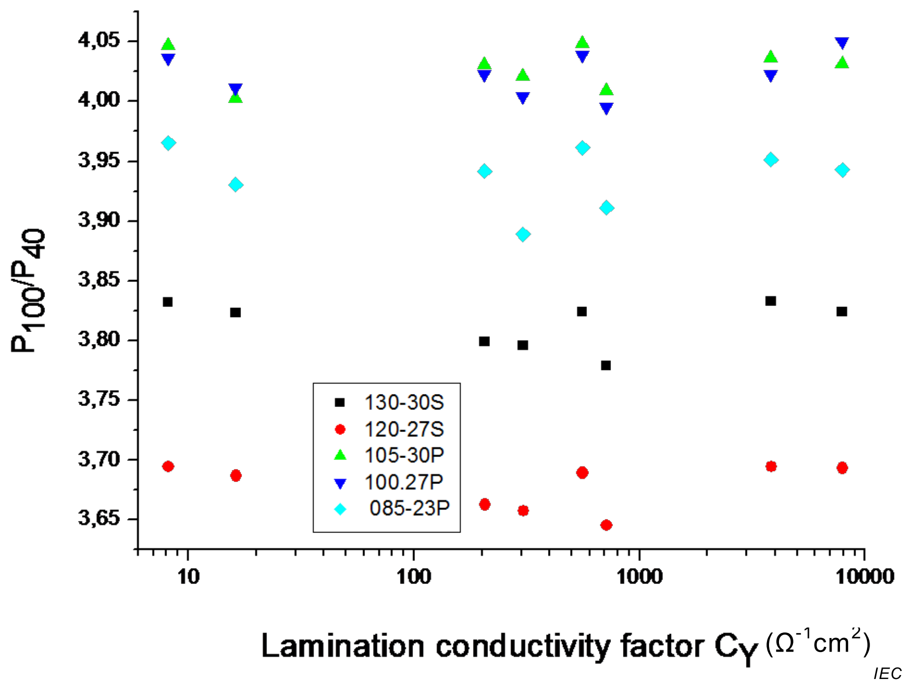


Figure 4 – Ratio of the power loss P_{SST} to that of the SST with the best yokes, P_{SSTopt}, versus lamination conductivity factor C_Y of the yokes

Encouraged by the positive result regarding the correlation of lamination resistance to excess loss, the participants of the IEC RRT (2013-14) (see Clause 6) were asked to carry out the same resistance and air gap widths measurements. The results of the China studies could not be reconfirmed by the IEC RRT results. The diagrams showed stochastic distributions and no trend. F. Fiorillo has proposed a possible explanation of this phenomenon based on the hypothesis that the heterogeneity of the system leads to incorrect results in the resistance measurements. Similar findings on soft magnetic composite material were presented by C. Cyr [20]. However, this does not explain why the effect is found with the China experiment, and with the IEC RRT it does not appear.

On the other hand, this negative result was confirmed by another experiment, i.e. the frequency dependence of the magnetic loss in the light of the lamination conductivity factor C_Y. The participants of the IEC RRT (2013/14, see Clause 6) have measured the magnetic quantities also in the frequency range from 40 Hz to 100 Hz (some started from 20 Hz). Figure 5 shows the ratio of power loss measured at 100 Hz to that at 40 Hz plotted against the yokes' lamination conductivity factor C_Y in logarithmic plotting. It was expected that there would be a significantly increasing trend in the curves with the increase of the measured yokes' lamination conductivity factor C_Y. Apparently, this did not appear, i.e. according to this finding the lower resistance of the lamination of the yokes seems to have no observable influence on the loss measurement result. This contradicts earlier experiences.



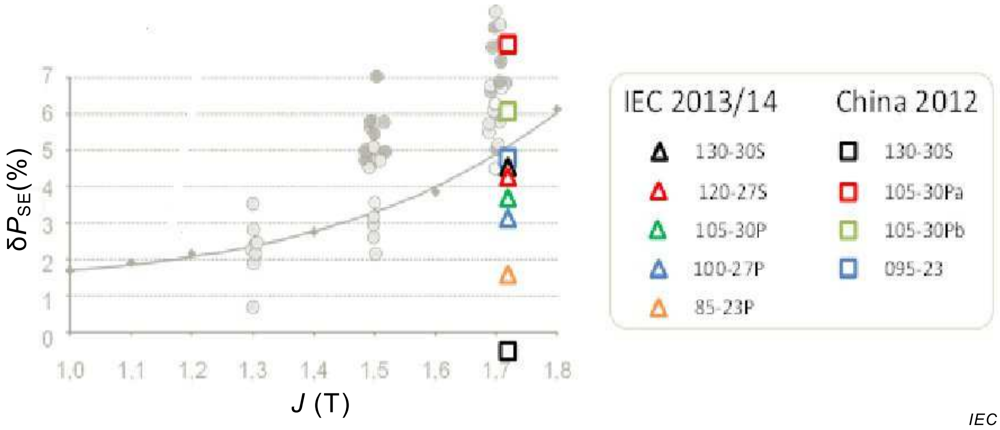
NOTE 085-23P is laser-scribed material.

Figure 5 – Ratio of the power loss at 100 Hz to that at 40 Hz, P_{100}/P_{40}, at 1,7 T, versus lamination conductivity factor C_{Y} of the yokes

5.4 Necessity of comparing independent SST results

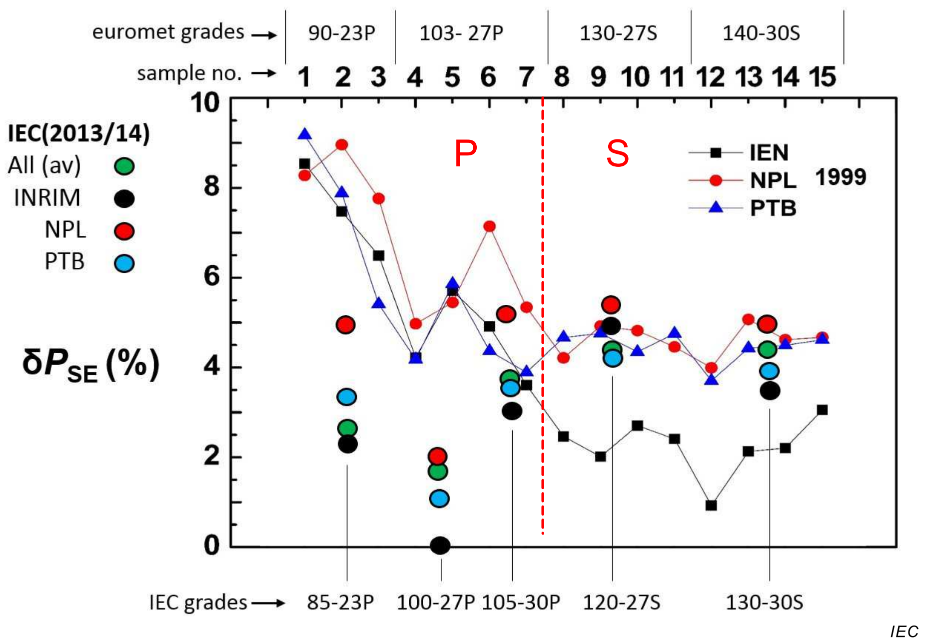
In order to achieve a comparative view of several comparison studies and to assess their value for establishing a list of reference loss values for high grade grain-oriented material, the quantity δP_{SE} = 100 (P_{SST} – P_{eps})/P_{Eps} was plotted versus the applied magnetic polarization, combined in Figure 6, for the conversion curve in IEC 60404-3:1992/IEC 60404-3:1992/AMD1:2002, Annex C, for the comparison of manufacturer results (see 5.2), for the China studies (2012) and for the IEC RRT comparison (2013-14) (anticipated from Clause 6.). The two last studies are presented only by their values at 1,7 T, the most important normative value. At this polarization, the δP_{SE} values spread over a range of about 10 %, clustering partly within the different studies' results. Thus, these results suggest that it is inappropriate to base the establishment of high grade SST reference values on their relation to Epstein results.

Similar conclusions can be drawn from the results shown in Figure 7. The smaller symbols (the connecting lines have no physical meaning) represent the related power loss difference, δP_{SE} , measured, within an euromet comparison project, by the three Standard Laboratories, IEN (Italy), NPL (UK) and PTB (Germany), on 15 related grain-oriented SST and Epstein samples. Their grades are indicated in the line "euromet grades". The S-type samples show, with the exception of the outlying black curve, a relatively good agreement. An explanation could be that the small grains form a statistically averaging situation in the legs and corners of the Epstein frame, compared with the more chaotic situation with large grains, and secondly, the magnetization is closer to technical saturation compared with the P-type samples which is again in the more chaotic Barkhausen stage at this magnetic polarization.



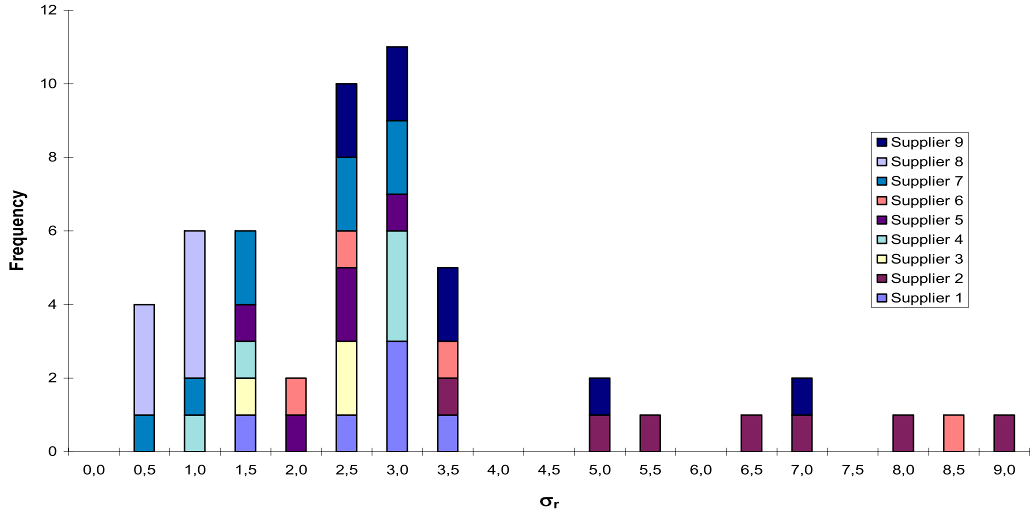
NOTE Light grey: copy of Figure 2. Coloured symbols: squares (China 2012) and triangles (IEC RRT 2013/14): average of participants at 1,7 T. 085-23P is laser-scribed material.

Figure 6 – Relative difference $\delta P_{SE} = 100(P_{SST} - P_{EP}) / P_{EP}$ versus magnetic polarization



NOTE Small symbols: euromet comparisons (1999, [19] eval.in [6]), on 15 related Epstein-SST-sample pairs of 2 different P-grades and 2 different S-grades ("euromet grades"). Large circles: IEC RRT (2013/14) [8], measured on 5 sample pairs ("IEC grades"), for details see Clause 5.

Figure 7 – Relative difference $\delta P_{SE} = 100(P_{SST} - P_{EP}) / P_{EP}$ at 1,7 T determined by three standard laboratories, IEN, NPL and PTB, on S- and P-type g.-o. sample pairs



NOTE Histogram of the relative standard deviations σ_r within the 53 groups of 4 or 5 samples each; one group = one manufacturer, one grade.

Figure 8 – Dispersion of manufacturer's grain-oriented material production in form of Epstein samples (PTB 1999)

Another relevant aspect regarding the scope of 5.4 is the dispersion performance of the Epstein values as it appears with different Epstein samples prepared from different coils but for the same nominal grade. This performance was investigated by PTB in 1998 in connection with the SST-Epstein-relationship experiments leading to the curve of IEC 60404-3: 1992/IEC 60404-3:1992/AMD1:2002, Annex C [2]. The 240 grain-oriented Epstein samples were divided in 53 groups consisting of 4 or 5 Epstein samples of the same grade, each produced by one manufacturer. The relative standard deviations of the 4 or 5 samples of these groups, σ_r, are arranged in the histogram (see Figure 8). The combined dispersion of the scattering of the material production and of the Epstein preparation within one producer is presented and shows a focus at 2,5 % to 3,0 %. The scatter of the Epstein sample preparation assigned to a group of various producers is still not included. A crucial experiment could be thought of to clarify this: a batch of P-type 50 cm-sheet samples, as homogeneous as possible, should be supplied by one manufacturer and circulated to other manufacturers, one sample to each, for preparing an Epstein sample. Those samples should then be measured by a reference laboratory, and their loss values compared. This would answer the question of the dispersion component introduced by Epstein sample preparation.

6 International comparison of SST measurements on grain-oriented electrical steel and accompanying Epstein measurements

6.1 General conditions, samples, participants

In consequence of the findings described above IEC TC 68 decided to undertake an extended and methodically sound comparison between 11 participating laboratories of the power loss and apparent power measurements on grain-oriented electrical steel sheets using the SST method, covering a range of material grades, frequencies, and peak polarization values, in order to better assess the SST reproducibility features and provide solid background for its adoption as a reference method.

Four metrological institutes and seven industrial laboratories took part in the comparison. They are listed in Table 1. Besides the 500 mm × 500 mm sheets, Epstein strips taken from the same batch were circulated and tested at the same time, thereby providing further information on the relative dispersion performance of the two methods and on the consistency of the measuring equipment.

The material was supplied by Thyssenkrupp Electrical Steel, Isbergues in the form of SST plates and Epstein strip samples of respectively the same grades. Four Epstein samples of non-domain refined material were stress relief annealed according to the standard recommendations; the Epstein samples made from domain refined grain oriented material were obtained by careful wire cutting technique in order not to bring stress to the strips. This Epstein sample did not undergo stress relief annealing treatment. The magnetics laboratory of the Istituto Nazionale di Ricerca Metrologica (INRIM) acted as pilot laboratory. In Clause 6, we summarize and discuss the results of this measurement exercise, focusing on the distribution of the SST values obtained by the participating laboratories around the reference values and the dependence of the standard deviation on magnetizing frequency and peak polarization. Comparisons will be made with the dispersion characteristics of accompanying Epstein results.

Table 1 – Participating laboratories

Laboratory, address
INRIM, Istituto Nazionale di Ricerca Metrologica, Torino, Italy (pilot laboratory)
PTB, Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
NPL, National Physical Laboratory, Teddington, UK
NIM, National Institute of Metrology, Beijing, China
TKES, ThyssenKrupp Electrical Steel, Isbergues, France
TKES, ThyssenKrupp Electrical Steel, Gelsenkirchen, Germany
Brockhaus Messtechnik, Lüdenscheid, Germany
ABB, Ludvika, Sweden
AK Steel, Middletown, USA
Baosteel, Shanghai, China
WISCO, Wuhan, China
NOTE The numerical order used in Figures 9 to 20 does not correspond to the order of this list.

6.2 Circulation of the samples and measurement procedure

Two conventional grain-oriented (CGO) and three high-permeability (HGO) electrical steel sheets, taken from the production line, were delivered, both as 500 mm × 500 mm SST sheets and 305 mm × 30 mm Epstein strips, by Thyssenkrupp Electrical Steel Isbergues (TKES) to the pilot laboratory (INRIM). The mass and cross-sectional areas of the individual SST sheets and of the Epstein samples (32 strips for each alloy) were determined by TKES, and their values were adopted by all partners.

The circulation of the samples (listed in Table 2) took about one year, at the end of which INRIM repeated the whole set of measurements. The second round of measurements by INRIM had the scope of verifying any possible damage to the samples or drift of the material properties during circulation. Since the repeated measurements of INRIM are assumed to be correlated with those made at the start, they were excluded from the statistical analysis (they are nevertheless available for any further analysis).

The following quantities were measured, according to the IEC 60404-3 (SST 92) and IEC 60404-2 (Epstein) standards, at the frequencies f = 20 Hz, 40 Hz, 50 Hz, 60 Hz, 80 Hz, 100 Hz and peak polarization values J_p = 1,3 T, 1,5 T, 1,7 T, 1,8 T: specific power loss P_s, specific apparent power S_s, associated peak value of the field strength H_p, and the polarization J_{800} for H = 800 A/m. The measurements were carried out, following demagnetization at 50 Hz, at the temperature 23 °C ± 2 °C. Repeatability was checked, for all the previous quantities, at 50 Hz by making five successive measurements without intervening demagnetization. INRIM gathered all the results by the partners, which were assumed to have appropriate traceability of measurements to the SI standards, and performed the related statistical analysis.

Table 2 – Circulated grain-oriented electrical steel test samples

Code	Type	Nominal density kg/m^3	Thickness mm
Sample No. 1	CGO (M120-27S)	7 650	0,254
Sample No. 2	CGO (M130-30S)	7 650	0,289
Sample No. 3	HGO (M100-27P)	7 650	0,260
Sample No. 4	HGO (M105-30P)	7 650	0,286
Sample No. 5	HGO (M85-23P) laser scribed	7 650	0,217

6.3 Results and analysis of the measured quantities

Data analysis in a comparison exercise basically aims at the determination of a reference value for each measured quantity and its expanded uncertainty, which identifies the 95 % confidence level around such a value [16] [17]. In particular, by denoting with y_i the best estimate of the i-th laboratory and with $u_c(y_i)$ the related combined uncertainty, the reference value is obtained as a weighted mean, see Formula (2):

$$<< y >> = \sum_{i=1}^{N} g_i y_i \tag{2}$$

obtained by averaging the best estimates y_i of the N laboratories once they have been assigned a weight factor, see Formula (3):

$$g_i \propto (1/u_c^2(y_i)) \tag{3}$$

In the present comparison, however, a significant number of laboratories could not provide defined uncertainty values with their best estimates. The unweighted mean as shown in Formula (4):

$$< y > = \sum_{i=1}^{N} y_i / N \tag{4}$$

was consequently assumed as the reference value. This is an acceptable option, because the objective of the exercise is more one of assessing the measurement reproducibility than one of providing a 95 % level of confidence interval around the true value of the investigated quantity. We shall thus define in the following the degree of reproducibility of the SST and Epstein methods through the dispersion of the best estimates y_i around $<y>$ and the associated standard deviation $\sigma(y)$. By defining the reproducibility $R(y)$ as the standard deviation of the lab-to-lab differences, it is obtained as shown in Formula (5):

$$R(y) = \sqrt{2} \cdot \sigma(y) \tag{5}$$

Given our inability to identify the outliers from knowledge of weighted mean and calculation of the so-called normalized error [17], it was decided to exclude the best estimates falling outside a $\pm\, 2\sigma$ interval around $<P>$ (or $<S>$). In Figures 9, 10, and 11, examples of scattering of results around the reference values $<P>$ and $<S>$ are shown. They refer to a CGO and two HGO samples.

The reported values of power loss P and apparent power S refer to the SST (left) and Epstein (right) measurements in the CGO sample No. 2 at J_p = 1,7 T and f = 50 Hz. A few S outcomes do not appear here, because they fall outside the ± 2σ band around the reference value. They are discarded as outliers. The labelling of the laboratories does not correspond to the order of listing in Table 1. The source of any specific figure of P and S is kept undisclosed, except for the pilot laboratory PL.

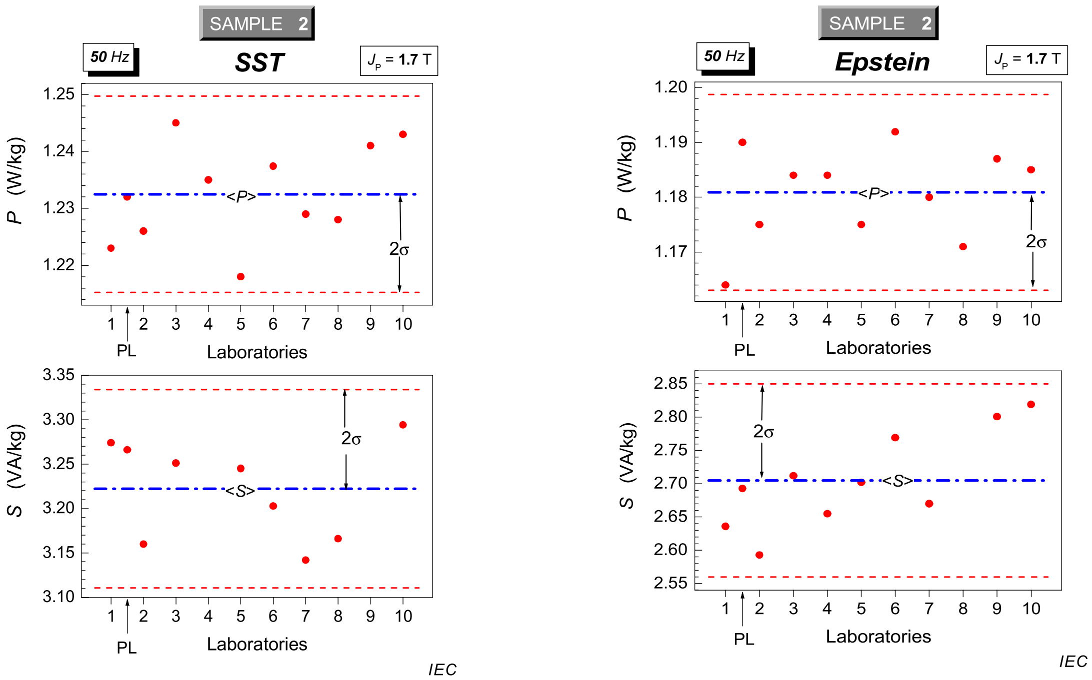


Figure 9 – Example of scattering of the laboratories' best estimates around the reference value (CGO sample No. 2, unweighted average, dash-dotted line)

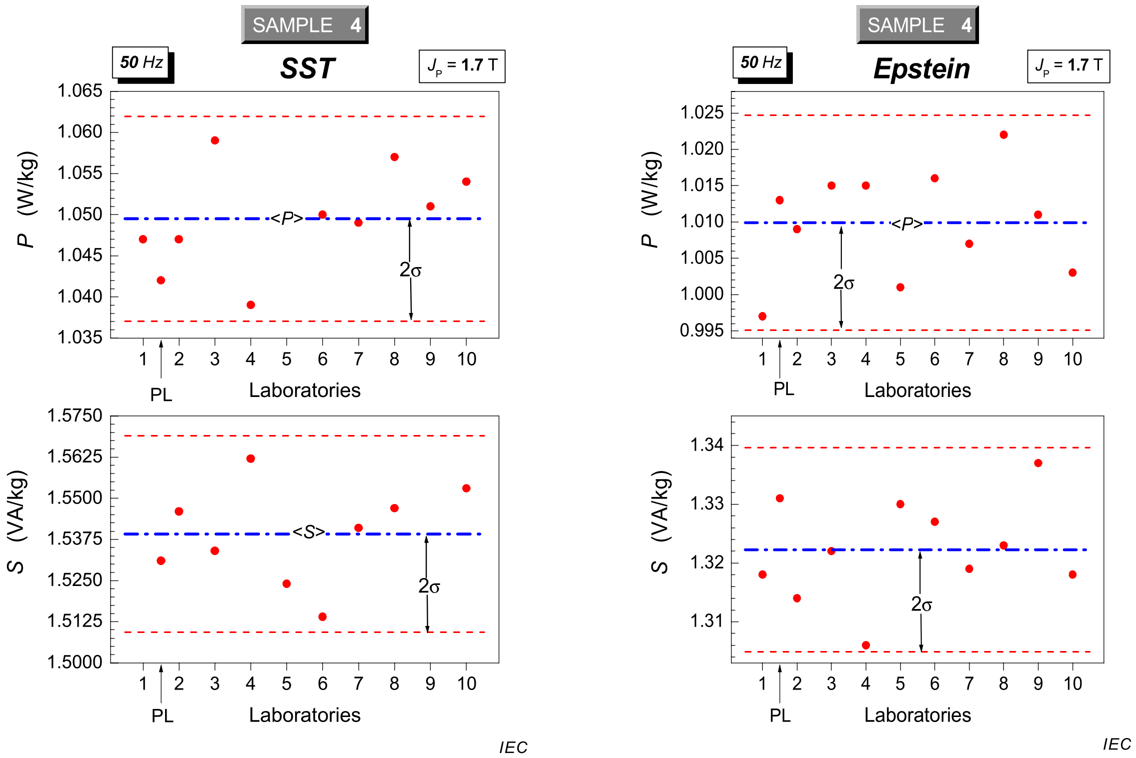


Figure 10 – Example of scattering of the laboratories' best estimates around the reference value (HGO sample No. 4, unweighted average, dash-dotted line)

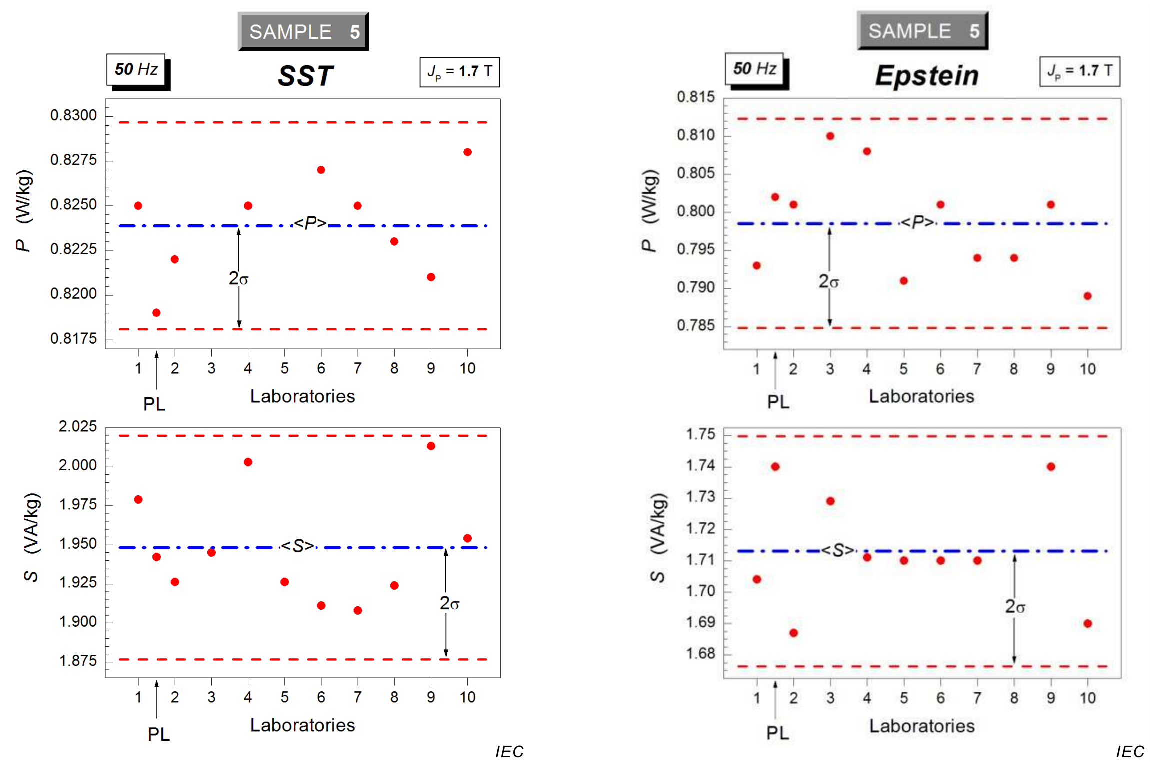
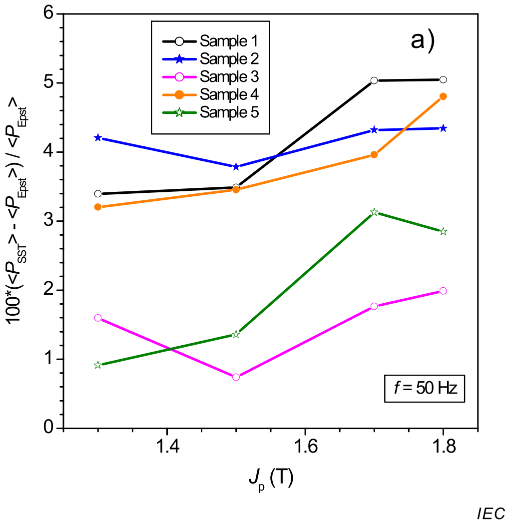
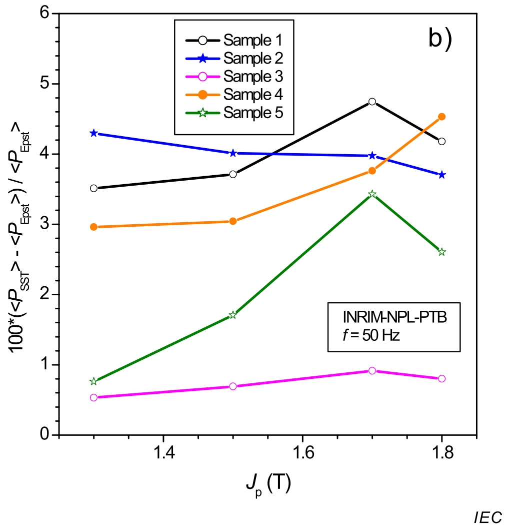


Figure 11 – Example of scattering of the laboratories' best estimates around the reference value (HGO sample No. 5, unweighted average, dash-dotted line)

Table 3 provides the whole set of reference values <*P*> and <*S*> at 50 Hz, and Table 4 the associated standard deviations. It is confirmed that the usual finding of SST figures is higher than the Epstein ones. It is also confirmed, according to previous literature [3] [6], that the related difference $\delta P_{SE}(J_p) = (\langle P_{SST}\rangle - \langle P_{Epst}\rangle) / \langle P_{Epst}\rangle$ exhibits large scattering upon different samples, as illustrated in Figure 12.



a) All Laboratories



b) The European metrological laboratories

NOTE The outliers have been found according to the 2σ rule. 40 outliers were found out of the 880 measured values (4 P_{SST}, 7 P_{Eps}, 18 S_{SST}, 10 S_{Eps} outliers). 95,5 % of the provided figures were then retained for the statistical analysis. Note that 30 out of 40 outliers were generated in three of the eleven participating laboratories.

Figure 12 – Samples No. 1 to No. 5: ratio of SST to Epstein power loss reference values $\delta P_{SE}(J_p) = (\langle P_{SST}\rangle - \langle P_{Epst}\rangle) / \langle P_{Epst}\rangle$ at 50 Hz versus peak polarization

Table 3 – Reference values at 50 Hz for the power loss P and the apparent power S

Sample	J_p (T)	$\langle P_{SST} \rangle$ W/kg	$\langle P_{Epst} \rangle$ W/kg	$\langle S_{SST} \rangle$ VA/kg	$\langle S_{Epst} \rangle$ VA/kg
No. 1	1,3	0,579	0,560	0,764	0,696
No. 2		0,619	0,594	0,786	0,714
No. 3		0,509	0,501	0,611	0,567
No. 4		0,580	0,562	0,688	0,632
No. 5		0,442	0,438	0,700	0,657
No. 1	1,5	0,801	0,774	1,210	1,080
No. 2		0,85	0,819	1,220	1,092
No. 3		0,682	0,677	0,840	0,771
No. 4		0,779	0,753	0,975	0,862
No. 5		0,597	0,589	1,070	1,002
No. 1	1,7	1,189	1,132	3,410	2,730
No. 2		1,232	1,181	3,270	2,640
No. 3		0,922	0,906	1,370	1,170
No. 4		1,050	1,010	1,530	1,320
No. 5		0,824	0,799	1,950	1,710
No. 1	1,8	1,540	1,466	11,28	8,290
No. 2		1,562	1,497	10,71	8,570
No. 3		1,129	1,107	2,490	1,840
No. 4		1,287	1,228	2,850	2,160
No. 5		1,047	1,018	3,640	3,20

Table 4 – Standard deviations associated with the reference values at 50 Hz for the power loss P and the apparent power S (Table 3)

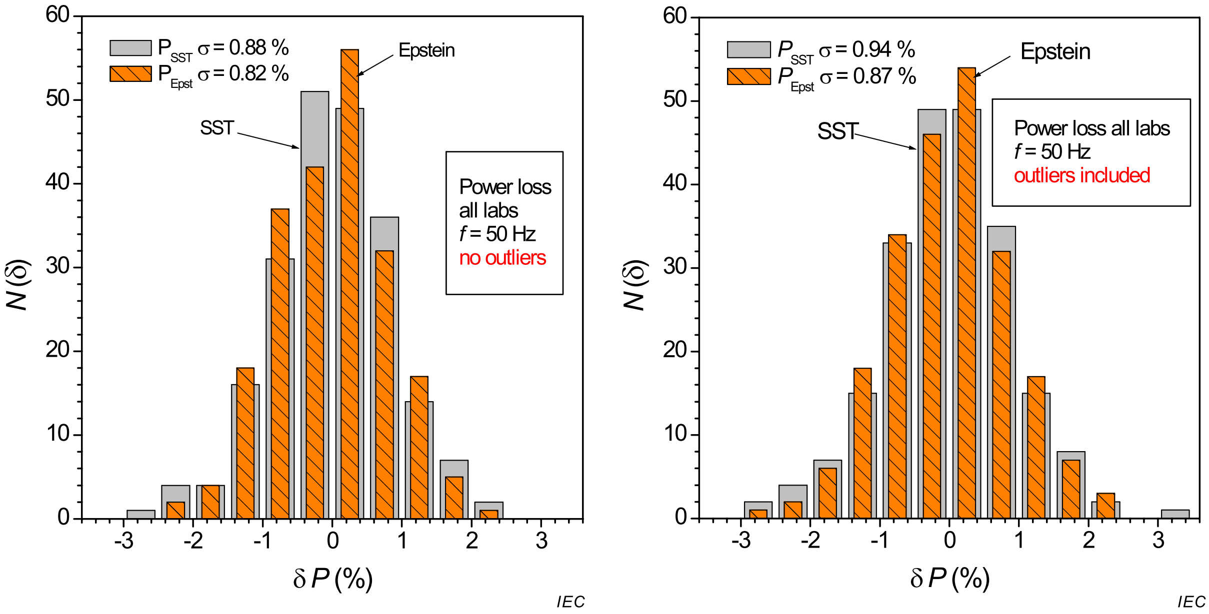
Sample	J_p T	σ(<P_{SST}>) (%)	σ(<P_{Epst}>) %	σ(<S_{SST}>) %	σ(<S_{Epst}>) %
No. 1	1.3	0,896	0,561	1,92	0,761
No. 2		0,873	0,482	2,02	0,684
No. 3		1,19	0,861	2,87	0,961
No. 4		1,02	0,912	2,69	0,795
No. 5		1,12	0,790	2,14	0,698
No. 1	1.5	0,783	0,384	1,17	0,410
No. 2		0,823	0,315	1,22	0,822
No. 3		1,12	0,664	2,62	0,494
No. 4		0,978	0,569	2,46	0,812
No. 5		1,08	0,996	1,77	0,760
No. 1	1.7	0,822	0,787	4,54	3,38
No. 2		0,696	0,754	3,98	2,69
No. 3		0,52	0,889	1,31	1,42
No. 4		0,592	0,738	1,25	0,660
No. 5		0,345	0,857	1,84	1,07
No. 1	1.8	1,50	1,13	3,26	5,11
No. 2		1,14	0,99	2,54	5,29
No. 3		0,695	1,62	1,80	3,87
No. 4		0,663	0,835	2,09	2,05
No. 5		1,03	0,928	2,09	2,37

The thicker sample No. 4 fits in with the upper group of CGO samples which corresponds to its higher power loss values, see Table 3. This group shows good agreement with the δP_{SE} curve given in Annex C of IEC 60404-3:1992/IEC 60404-3:1992/AMD1:2002 (see Figure 2 and Figure 6). As to the position of the curves for samples No. 3 and No. 5, it is referred to in 5.4.

The reference values for J_{800}, the polarization at H = 800 A/m, and the related standard deviations are given in Table 5.

Table 5 – Reference values at 50 Hz of the polarization at H = 800 A/m J_{800} and standard deviation of the distribution of the laboratories' best estimates

Sample	$J_{800,SST}$ T	σ_{SST} %	$J_{800,Epst}$ T	σ_{Epst} %
No. 1	1,818	0,337	1,840	0,411
No. 2	1,822	0,334	1,837	0,363
No. 3	1,920	0,347	1,934	0,338
No. 4	1,913	0,337	1,927	0,273
No. 5	1,905	0,369	1,907	0,305



a) without outliers **b) outliers included**

NOTE The histograms show the distribution of the differences $\delta(P_i) = (P_i - \langle P \rangle) / \langle P \rangle$.

Figure 13 – Overall dispersion (all labs, J_p values, and samples) of the laboratories' best estimates P_i of the power loss at 50 Hz around their reference values

We have considered the whole matrix of reference values $\langle P \rangle$ and $\langle S \rangle$ at 50 Hz shown in Table 3 and the associated distributions of the laboratories' best estimates P_i and S_i. In particular, the relative differences $\delta(P_i) = (P_i - \langle P \rangle) / \langle P \rangle$ and $\delta(S_i) = (S_i - \langle S \rangle) / \langle S \rangle$ for each sample and J_p value have been taken, and the standard deviation of their distributions has been derived. As shown in Figures 13, 14, 15, 16, the SST and Epstein distributions, showing close behaviours, approximately fit a Gaussian function. After excluding the outliers, we obtain the standard deviations $\sigma(P)_{SST}$ = 0,88 % and $\sigma(P)_{,Epst}$ = 0,82 % for the power loss, $\sigma(S)_{SST}$ = 2,20 % and $\sigma(S)_{Epst}$ = 2,15 % for the apparent power.

It is noted, comparing the previous histograms with those of Figure 17, that the reproducibility is much improved when the analysis is restricted to the European metrological laboratories (INRIM, NPL, PTB). The standard deviations associated with these narrower distributions are

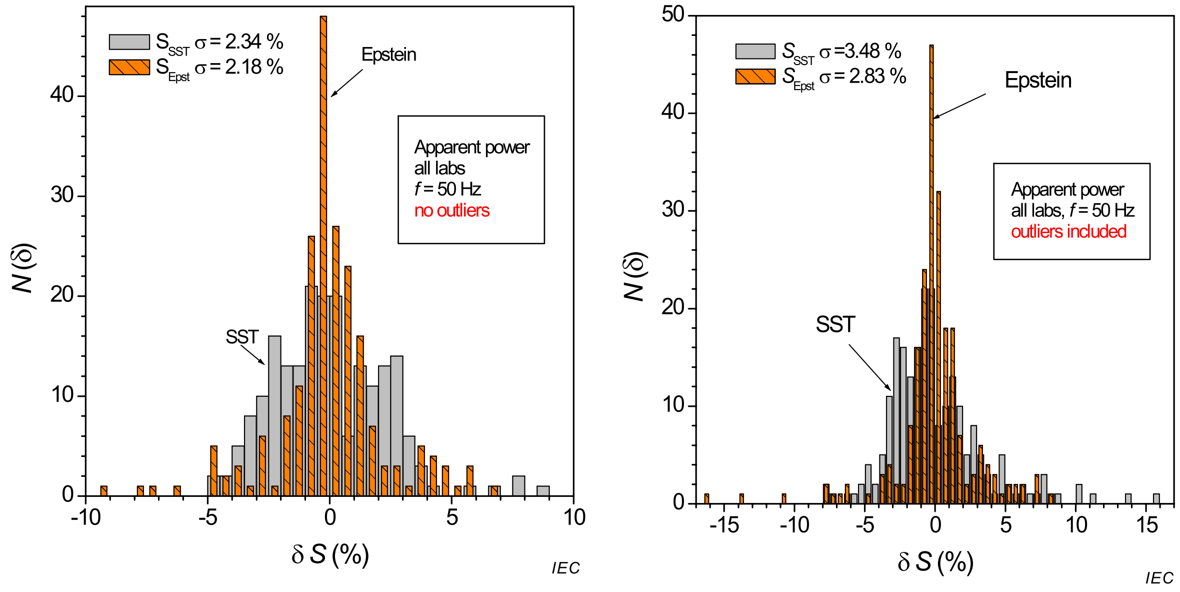
$\sigma(P)_{SST}$ = 0,42 %,

$\sigma(P)_{Epst}$ = 0,55 %,

$\sigma(S)_{SST}$ = 1,19 %,

$\sigma(S)_{Epst}$ = 0,82 %.

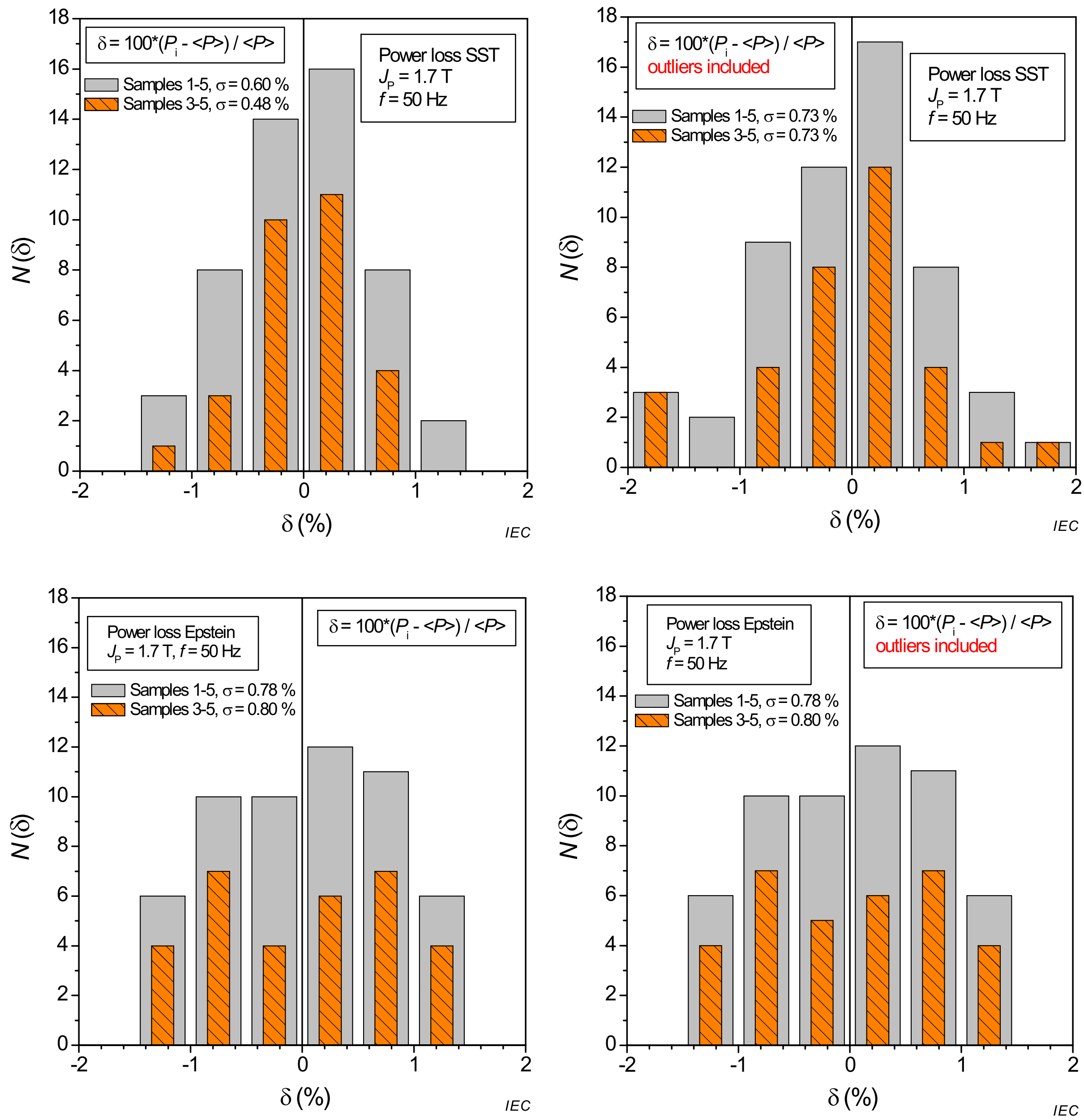
Again, little difference is observed between SST and Epstein dispersions. It is stressed that the present results compare favourably with the outcomes of a comparison carried out on 15 different grain-oriented steel sheets by the same laboratories in the year 2000 at J_p = 1,5 T and J_p = 1,7 T, as shown in Table 6.



a) without outliers **b) outliers included**

NOTE The histograms show the distribution of the differences $\delta(S_i) = (S_i - \langle S \rangle) / \langle S \rangle$.

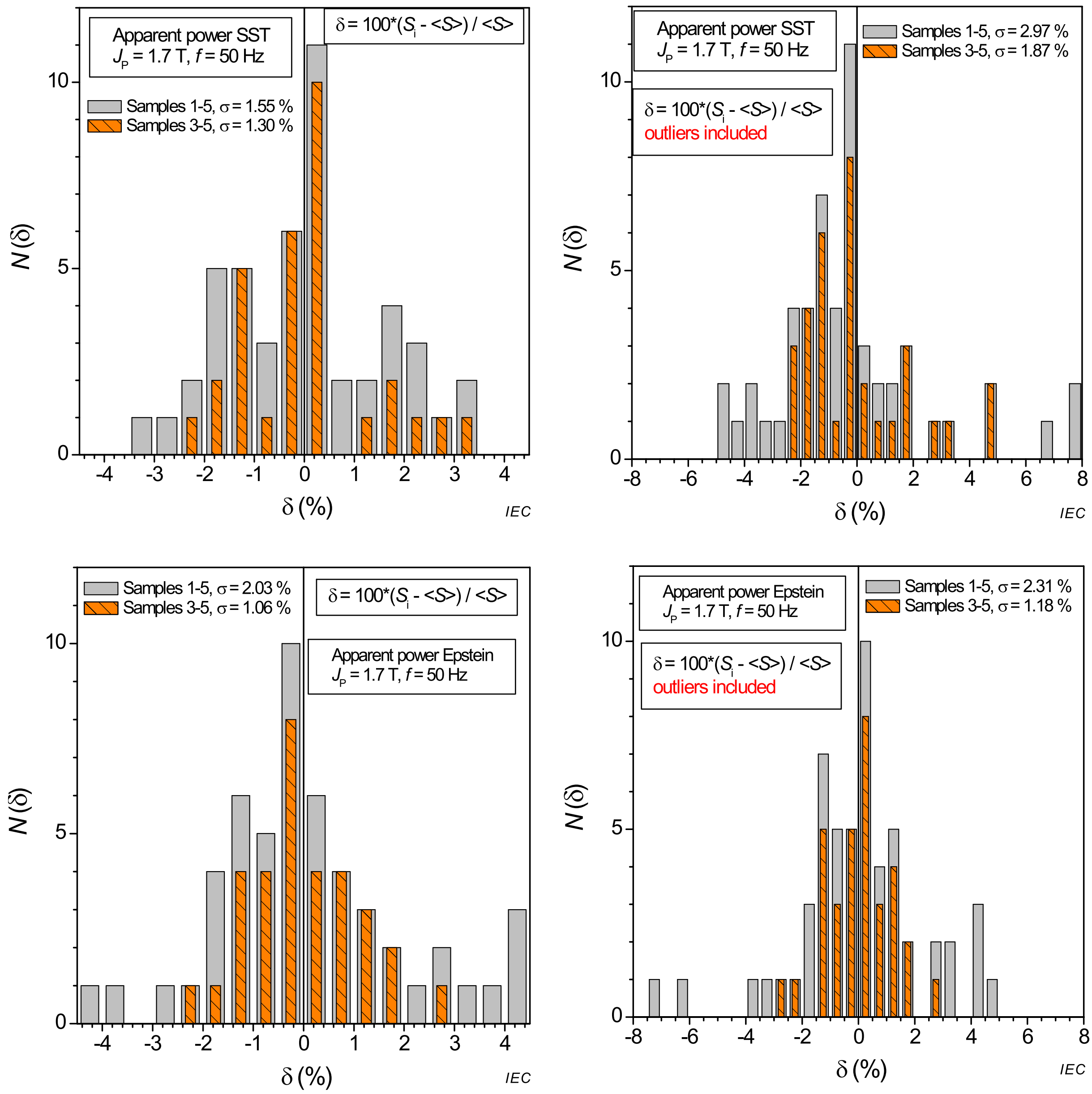
Figure 14 – Overall dispersion (all labs, J_p values, and samples) of the laboratories' best estimates S_i of the apparent power at 50 Hz around their reference values, with and without outliers



a) without outliers **b) outliers included**

Figure 15 – Dispersion around the reference value of the laboratories' best values of the power loss P measured at 50 Hz by the Epstein and the SST methods at 1,7 T

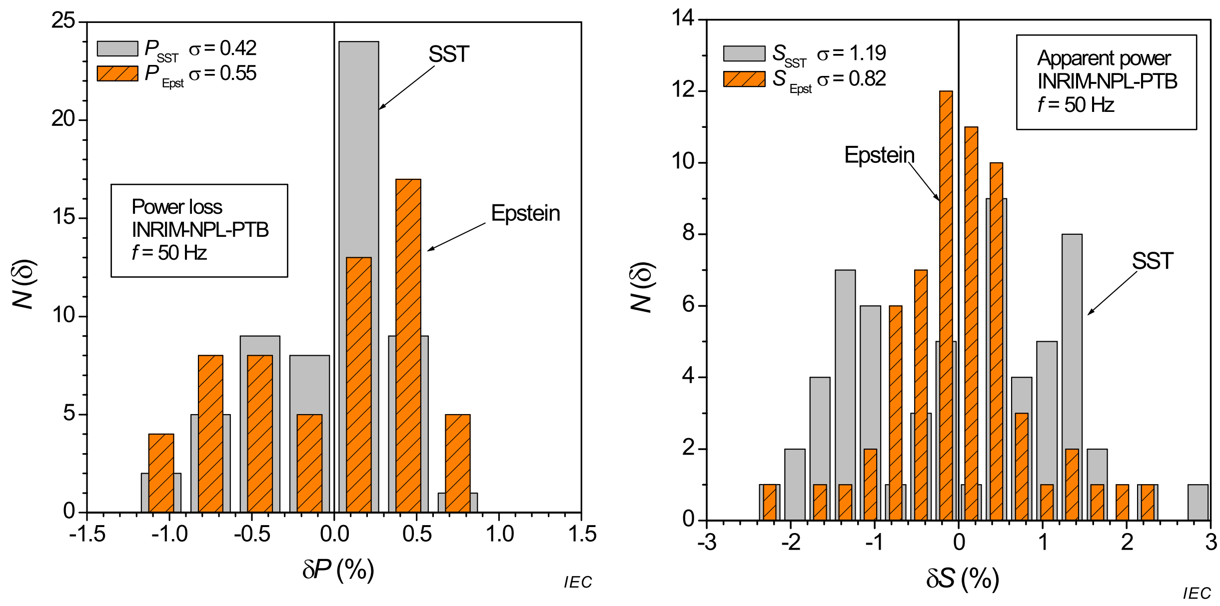
All samples and all laboratories are considered. The outliers are included in the dispersion histograms shown on the right hand side of Figure 15. The high-permeability GO samples are labelled as No. 3, No. 4, and No. 5. Even considering the outliers, the dispersion of P found with the SST method compares well with that associated with the Epstein method. Note, however, that no outliers are found among the Epstein results.



a) without outliers **b) outliers included**

NOTE The histograms show the distribution of the differences $\delta(P_i) = (P_i - \langle P \rangle) / \langle P \rangle$.

Figure 16 – Dispersion around the reference value of the laboratories' best values of the apparent power S measured at 50 Hz by the Epstein and the SST methods at 1,7 T



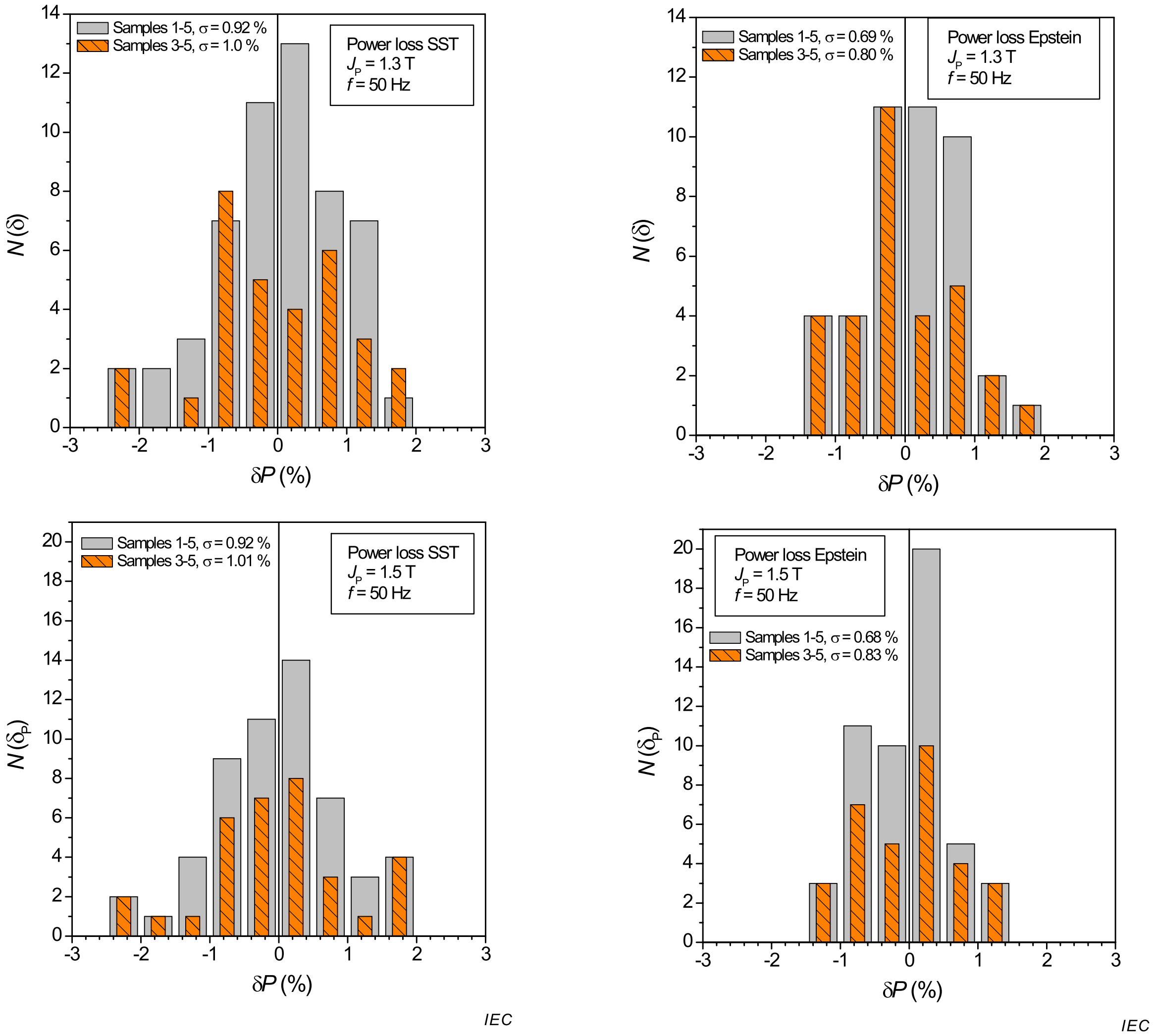
a) power loss **b) apparent power**

NOTE The histograms show the distribution of the differences $\delta(P_i) = (P_i - \langle P \rangle) / \langle P \rangle$.

Figure 17 – Overall dispersion (European metrological laboratories only, all J_p values and samples) of the laboratories' best estimates P_i of the power loss at 50 Hz around their reference values, with and without outliers

Table 6 – Relative standard deviations of 50 Hz power loss P and apparent power S distributions around their reference values

	$\sigma(P)_{SST,00}$ %	$\sigma(P)_{SST,14}$ %	$\sigma(P)_{Epst,00}$ %	$\sigma(P)_{Epst,14}$ %	$\sigma(S)_{SST,00}$ %	$\sigma(S)_{SST,14}$ %	$\sigma(S)_{Epst,00}$ %	$\sigma(S)_{Eps,14}$ %
1,5	0,61	0,33	0,50	0,55	1,15	1,00	0,39	0,55
1,7	0,75	0,43	0,62	0,55	2,18	1,11	1,31	1,08
NOTE Comparison of the measurements of INRIM, PTB, and NPL. Exercise on 15 different g-o. steel sheets performed in the year 2000 [15] (index 00)), with the present measurements (index 14).								



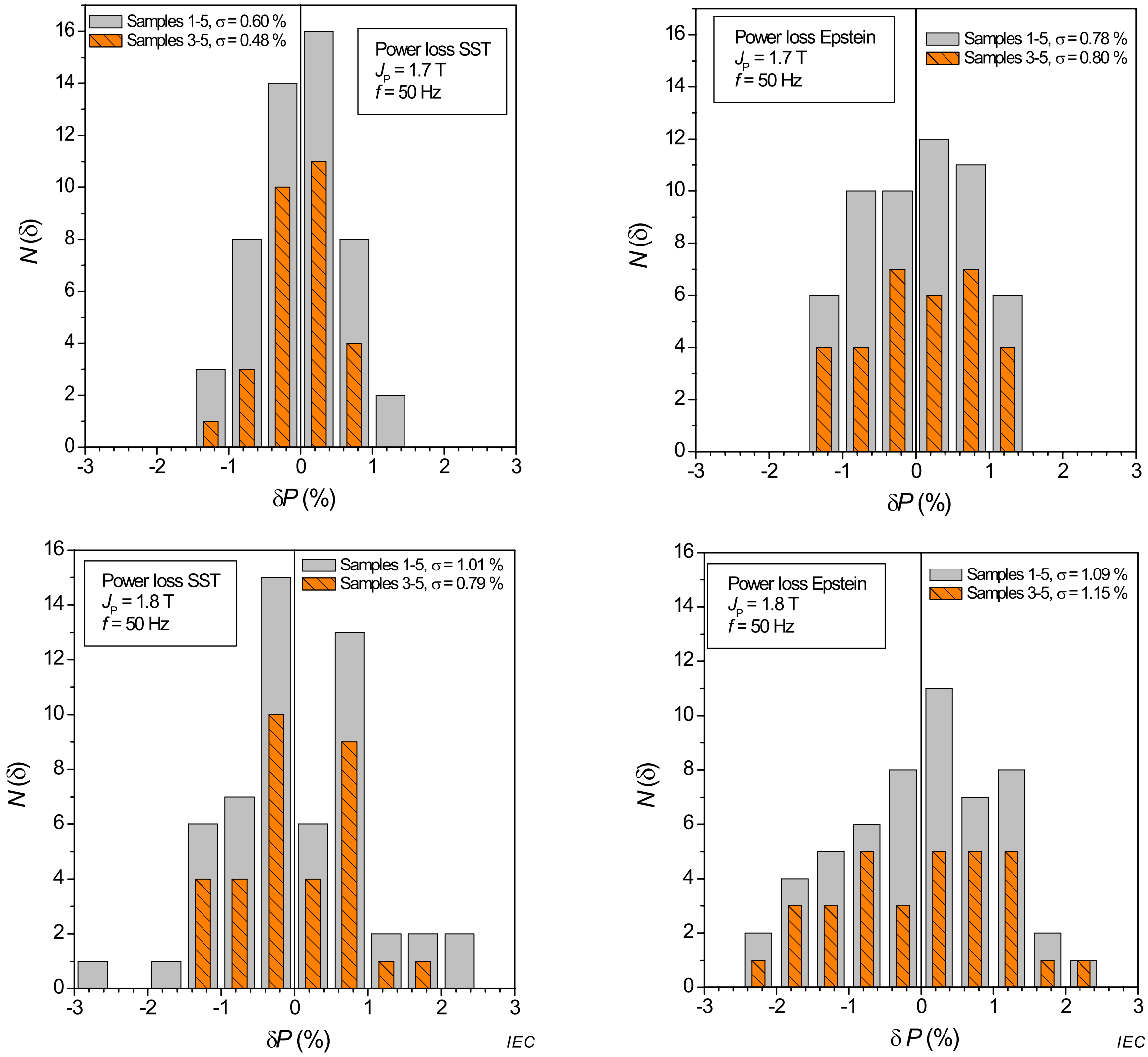
a) SST power loss **b) Epstein power loss**

NOTE The frequency of the relative differences δP_i are shown for two of the four investigated J_p levels, 1,3 T and 1,5 T. The response of the HGO samples, No. 3, No. 4 and No. 5, is separately put in evidence.

Figure 18 – Dispersion of the laboratories' best estimates of SST (a) and Epstein (b) power loss at 50 Hz

The overall distributions of the differences $\delta(P)$ and $\delta(S)$ at 50 Hz given in Figure 12 can be decomposed in the sub-ensembles associated to the different values, thereby achieving the evolution of the distributions and their standard deviations $\sigma(P)$ and $\sigma(S)$. Figures 18 and 19 show, for example, the power loss dispersion versus J_p.

These figure, besides confirming the relatively close behaviours of the SST and Epstein power loss dispersions, show that the minimum standard deviation $\sigma(P)$, of the order of 0,5 %, is observed for the SST measurements at J_p = 1,7 T. This also happens to be the condition where the SST apparent power attains minimum dispersion.



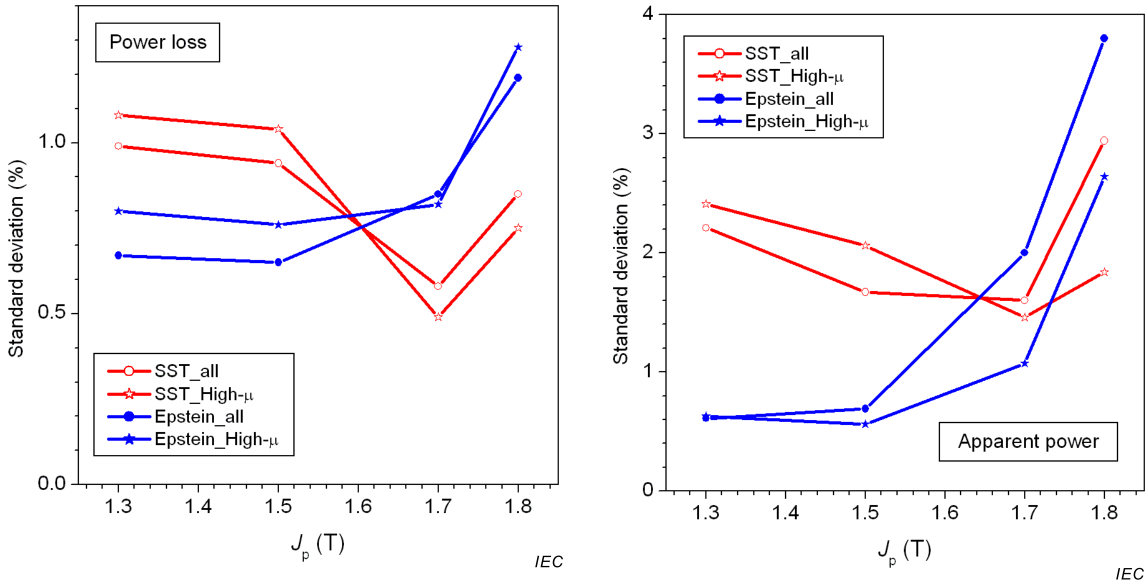
a) SST power loss **b) Epstein power loss**

NOTE The frequency of the relative differences δP_i are shown for two of the four investigated J_p levels, 1,7 T and 1,8 T. The response of the HGO samples No. 3, No. 4 and No. 5 is separately put in evidence.

Figure 19 – Dispersion of the laboratories' best estimates of SST (a) and Epstein (b) power loss at 50 Hz

Figure 20 is the aggregation of Figures 18 and 19. It shows the reproducibility of the SST and Epstein measurements of the laboratories presented in the form of the dispersion parameter σ which is its inverse. In the low polarization range, we have parameters with the SST which form a more stochastic situation, i.e. we can suppose different multipole intensities and distributions at the individual yoke-sample transitions of the different SSTs involved, whilst the Epstein frame forms a more deterministic system in this region. In higher polarization regions, eddy currents harmonize and equalize the performance of the SSTs. However, the Epstein frame dispersion is continuously formed by the stochastic stacking variation.

In this context, it is also remarkable that the SST reproducibility increases when confined to the HGO samples whereas the Epstein reproducibility decreases slightly, probably caused by the larger impact of stacking variations when grains are larger.



a) Power loss **b) Apparent power**

NOTE The response of the HGO samples No. 3 to No. 5 is separately put in evidence.

Figure 20 – Dispersion of the laboratories' best estimates, represented by the standard deviation σ of SST (red) and Epstein (blue) power loss (a) and apparent power (b) at 50 Hz, versus the peak value of the polarization, J_P, summarizing Figures 18 and 19

Thus, the measured magnetic loss and apparent power reproducibility is chiefly determined by the properties of the magnetic circuit. This is especially true in the polarization range up to 1,7 T. At the highest polarization value J_p = 1,8 T and beyond, the main contribution to the dispersion of the results comes probably from the measurement systems and their different capabilities in handling signals with very small phase difference φ of the fundamental waves, i.e. low cos(φ), and of the high dynamic range.

Exhaustive physical explanations elaborated by F. Fiorillo can be found in the paper published recently by the INRIM experts [8].

The participants of this comparison exercise have also measured the power loss and apparent power at the frequencies 20 Hz (partly), 40 Hz, 60 Hz, 80 Hz and 100 Hz. The results show the well-known increase of values with increasing frequency, whilst the SST to Epstein ratio decreases slightly. Insofar these results are not really relevant regarding the normative issue of the 50 Hz-reference values. These measurements were preferably to gain experience with the impact of SST yokes and thus are dealt with in connection with the treatment of this matter in 5.3.

6.4 Conclusions of the international comparison

An extended international comparison on the measurement of power loss and apparent power in grain-oriented steel sheets has demonstrated the close reproducibility properties of the single sheet testing (SST) and Epstein measuring methods. In particular, the dispersion of the laboratories' best estimates at 50 Hz exhibits, with both methods, a standard deviation lower than 1 % for the power loss and slightly higher than 2 % for the apparent power through the peak polarization range 1,3 T to 1,8 T. Narrower distributions are obtained by restricting the comparison to the European metrological laboratories.

The main sources of lab-to-lab scattering of the power loss figures are believed to be with the stochastic properties of the magnetization process at low inductions and the resolution and signal handling capability of the different measuring setups at high inductions. It is observed that minimum dispersion is attained at 50 Hz to 60 Hz and J_p = 1,7 T, which is the testing regime typically adopted for the standard characterization of the grain-oriented materials, where the industrial setups are optimized.

The local discontinuities of the magnetic circuit at the yoke-sample interface, fluctuating from lab to lab, may somewhat contribute to the widening of the SST power loss distribution towards the lower J_p values, but they are especially detrimental for the dispersion of the apparent power figures, given the pre-eminent role of the associated demagnetizing fields. The reduction of the differential permeability at high inductions, beyond about J_p = 1,7 T, engenders a large uncertainty in the corresponding determination of the peak field value, besides posing resolution problems in the integration process. This becomes the main reason for the observed corresponding increase of the dispersion of the laboratory estimates, being especially dramatic for the apparent power.

7 Summary and conclusions

Former attempts at specifying SST reference values for grading high permeability grain-oriented (HGO, P-type) electrical steel sheet, referencing Epstein measurements, were insufficient. Whilst in-house reproducibility at manufacturers with stable material production and Epstein sample preparation may gain even pretty good values in this way, it shows considerable dispersion when applied to the global metrological situation. The presented comparison elucidated the background: it appears that, very probably, the Epstein sample preparation and stacking contributes to the dispersion which is not reflected in single inter-comparisons where identical Epstein samples are circulated through the participating laboratories and Epstein strips are numbered to guarantee the same position in all Epstein frames involved. The fact that SST and Epstein methods show good to excellent reproducibility values each, whilst the SST/Epstein ratio, considered for different comparisons, i.e for those with different sample pairs, scatters considerably, suggests the conclusion drawn above. This conclusion seems to be particularly relevant for large-grain high-permeability materials.

The results of the international comparison presented in Clause 6 provide good backing to the proposed adoption of SST as an independent method, not traceable to the Epstein method, in the definition of the specification standards of high permeability grain-oriented materials. It is indeed confirmed by the present measurements that the SST to Epstein power loss ratio suffers large scattering across the investigated steel sheets, casting doubts on the use of such a ratio to grade the SST tested materials in terms of reconstructed Epstein figures.

Whilst preliminary studies (Clause 5) seemed to indicate a correlation between increased inter-lamination conductivity of the SSTs' yokes and increase of measured power loss, the stringent IEC RRT exercise (Clause 6) did not confirm these findings. Likewise, no influence of this conductivity on the ratio of loss values measured at 100 Hz and 40 Hz, P100/P40, could be detected which fits with the fact that even enormous differences in the yokes' inter-lamination conductivity had no visible impact on the excellent reproducibility found for the HGO material. Therefore, the influence of the variation of the yokes' properties on the dispersion of power loss measurements seems to have been overvalued in the past. However, this phenomenon should be investigated and studied further in future.

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