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Characterisation of soft magnetic materials by measurement: Evaluation of uncertainties up to 1.8 T and 9 kHz

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Magnetic measurements are indispensable for the characterization of soft magnetic material used e.g. in electrical machines. Characteristic values are used as quality control during production and for the parametrization of material models. Uncertainties and errors in the measurements are reflected directly in the parameters of the material models. This can result in over-dimensioning and inaccuracies in simulations for the design of electrical machines. Therefore, existing influencing factors in the characterization of soft magnetic materials are named and their resulting uncertainties contributions studied. The analysis of the resulting uncertainty contributions can serve the operator as additional selection criteria for different measuring sensors. The investigation is performed for measurements within and outside the currently prescribed standard, using a Single sheet tester and its impact on the identification of iron loss parameter is studied. https://doi.org/10.1063/1.4993294

I. INTRODUCTION

The behaviour of electrical machines during operation is influenced considerably according to the properties of the soft magnetic materials used. A specific material selection is therefore an essential component in the design of electrical machines. Thereby follows the necessity for measurement-technical characterization of soft-magnetic materials to obtain a more precise knowledge of the material behaviour during operation in terms of magnetisation and resulting iron loss.

Standardised characterisations of soft magnetic properties are performed according to IEC standards DIN60404. The three measuring instruments namely *Epstein frame* (*EPF*), *single sheet tester (SST)* and *ring core (RK)* described by the standards are commonly used to determine the magnetic material properties.[1,2] The test devices can be described as a transformer with open secondary terminals whose main inductance is formed by means of the material to be characterized. The aim of the measurements is to determine the magnetic properties as accurately, comparable and reproducibly as possible. Boundary conditions and accuracies currently defined in the standards are limited to a range of flux densities up to 1.5 T, a frequency of 400Hz, and a standard deviation in the range of 1.5% for non-oriented electrical Steel. The form factor (FF) is currently used as the sole evaluation criterion of the measurement quality.[1,2]

In current electrical machines, used e.g. as a traction drive, low losses and a low weight are particularly important. In order to achieve a high power density, machines with higher fundamental frequencies of 400 Hz to 1 kHz are constructed nowadays. Further, the current machine designs are magnetically highly utilised while operating with polarizations of 1.6T up to 1.9T close to the saturation of the soft magnetic material. In order to make a proper material selection according to the

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application, the material has to be characterised considering the specific frequency and flux density range. The material characterisation should be of high precision and reproducibility in and outside the current standard specifications.[3,4]

Already the use of different measuring systems lead to a systematic deviation in measuring results and problems in comparability between measurements systems as shown in Refs. 5 and 6. Various influencing factors in the measurements of soft-magnetic materials increase the uncertainty of the measurement in these areas. In order to quantify the resulting standard deviation or the expected uncertainty with rising frequency and flux density, these contributions are identified, analysed and evaluated using two different SST. The currently used watt-metric measuring method and the associated measuring set-ups for the characterization of soft magnetic materials, each have advantages and disadvantages with regard to accuracy, reproducibility and simplicity. For this reason, physical causes of measurement errors are identified from a literature study.

The paper is structured as follows, the determination of the combined uncertainty in the measurement of the specific losses is described in section II. Important uncertainty contributions of different measuring sensors are analysed and discussed over a wide polarisation and frequency range. In the following the impact of the resulting uncertainty intervals on identified magnetic loss parameters are studied in section III. A discussion on the results is given in section IV.

II. METHODOLOGY

A. Uncertainty determination

Measurements of magnetic properties as the specific losses are subject to systematic errors e.g. deviations in measuring equipment, which result into a particular uncertainty interval in each measured point. Influence parameters in the determination of the specific iron losses can be derived partly from the standard and the standardised formulation to derive the specific losses from measurement. Additional factors as the air flux compensation, temperature and polarisation level which influence the measured losses are summarised in an Ishikawa diagram and depicted in Figure 1.

In order to consider the identified influencing parameters in the determination of the specific magnetisation losses, compensation terms are introduced in (1) according to Ref. 7. Thereby, the measured parameters are scaled to the desired or predicted value x_p. The compensated loss calculation in (1):

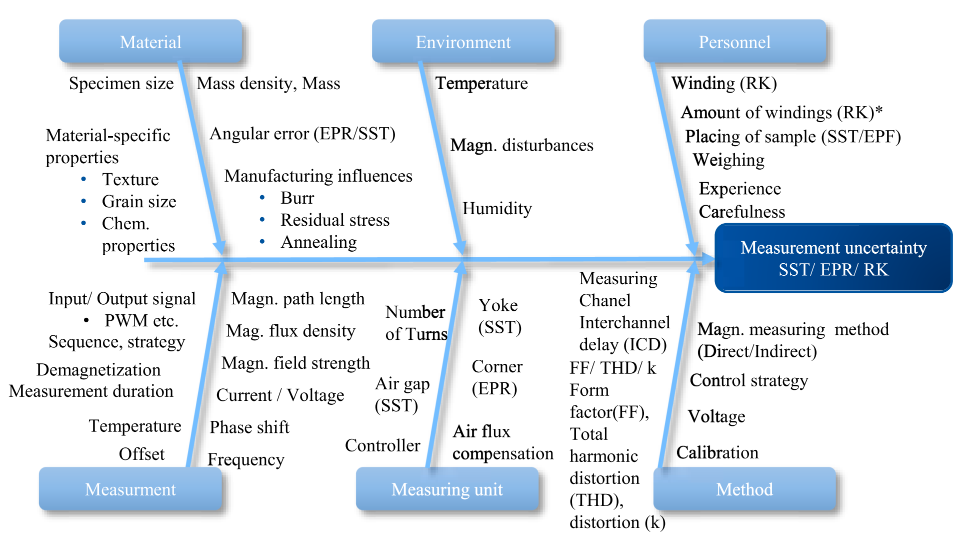


FIG. 1. Ishikawa diagram of parameters influencing the material characterisation.

$$P_s = \frac{(N_1/N_2)(U_1 R_m U_2 \cos(\varphi)/m)(4l/l_m)}{\beta(f/f_p)^2(FF/1.1107)^2 + (1-\beta)(f/f_p)} \cdot \left(\frac{fN_2 m\hat{J}_p(1+\gamma\mu_0\hat{H}/\hat{J}A_t/A)}{\overline{U_2}l\rho}\right)^{\alpha} - (T-T_p)\alpha_\tau \quad (1)$$

considers the primary and secondary windings N_1, N_2 of an EPF or SST primary and secondary voltage U_1, U_2, measuring shunt R_m, specimen mass m, length l, density ρ and cross section A, the mean magnetic path length l_m, frequency f, effective area of the secondary winding A_t, maximum magnetic field strength $\hat{H}$, maximum predicted polarisation $\hat{J}_p$, temperature T and temperature coefficient α_τ. Further, the influence of the formfactor FF, a phase error φ between primary and secondary voltage and the error of air flux compensation γ can be taken into account.

To cope with a varying frequency f from the predicted one f_p a constant proportionality of β is introduced based on loss separation according to Jordan.[7,8] In addition the strong influence of the maximum polarisation $\hat{J}$ is considered by using the exponent α as correction of the deviation in the resulting specific losses due to the polarisation. It is defined as:

$$\alpha = \frac{\partial P_s}{\partial \hat{J}} \frac{\hat{J}}{P_s} \quad (2)$$

and can be derived from the measured specific losses. Both α, the influence of polarisation the specific losses and β, the proportionality factor considering the influence of the frequency on the specific losses, are identified for each measured polarisation. This is due to the fact, that with rising frequencies and high polarisations, the performed loss calculation would lead to a rising model error.

For the quantification of the combined standard uncertainty two different methods are described according to Ref. 9. On the one hand the type A evaluation of uncertainties is the method of evaluation by statistical analysis of series of observations. On the other hand the type B evaluation in terms of a scientific judgement based on all available information. The type A observation characterise the dispersion of the observed quantities around the mean. For type B evaluation an inside into measuring system and a mathematical model considering the influence factors is necessary.

To calculate the combined standard uncertainty according to[9] type B evaluation, the sum of the partial derivations of each parameter in (1) has to be considered as follows:

$$u_c^2(P_s) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i)\ . \quad (3)$$

The resulting mathematical description of the combined standard uncertainty follows as written in (4).

It is nearly impossible to measure the exact desired polarisation J_p or twice exact the same point. Hence, the combined standard uncertainty of the measured specific iron losses u_{c,P_s} at a desired polarisation J_p can be derived by linear regression, where J_p and $P_{s,p}$ are the desired reference points. The linear regression can be derived from repeated measurements under the assumption that the derivation around the desired measuring point is small and therefore a linear approximation valid. The derivation of repeated measurements around the desired point in terms of the linear regression is considered within the first column of (4). It is summarised in the following as uncertainty contribution $u(y_p)$.

$$\begin{aligned} u_{P_s}^2 &= u^2(c_0) + (\hat{J}_p - \hat{J}_0)^2 u^2(c_1) + 2(\hat{J}_p - \hat{J}_0)^2 \cdot u^2(c_0)u^2(c_1)r(c_0, c_1) \\ &+ P_s^2 \cdot \left(\left((1-\alpha)\frac{u(U_2)}{U_2}\right)^2 + \frac{u(U_1)}{U_1}\right)^2 + (\tan(\varphi))^2 + \left(\frac{\alpha A_t \mu_0 \hat{H}}{A\hat{J}} u(\gamma)\right)^2 \\ &+ \left(\frac{u(R_m)}{R_m}\right)^2 + \left((1-\alpha+\beta)\frac{u(f)}{f}\right) + \left(2\beta\frac{u(FF)}{F}\right)^2 + \left((\alpha-1)\frac{u(m)}{m}\right)^2 \\ &+ \left((1-\alpha)\frac{u(l)}{l}\right)^2 + \left(\frac{u(l_m)}{l_m}\right)^2 + \left(\frac{\alpha u(\rho)}{\rho}\right)^2 + (\alpha_{\tau,rel} u(T))^2 \Bigg) \end{aligned} \quad (4)$$

TABLE I. Uncertainty contributions related to the used measurement equipment.

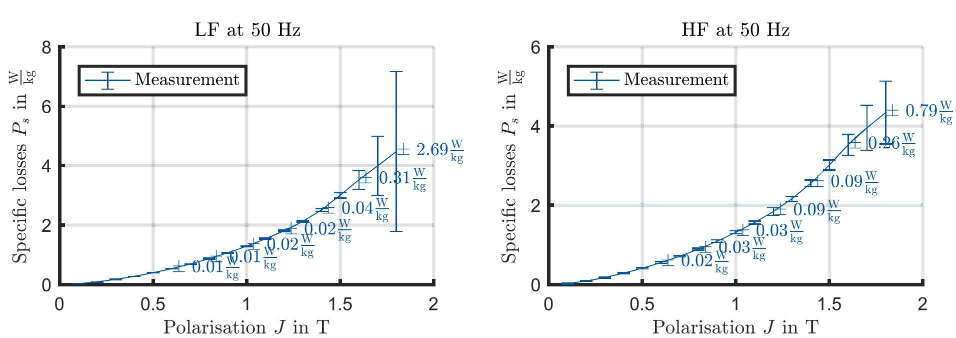
Parameter	x_i	Uncertainty $u(x_i)$
Primary voltage	U_1	$0.5\text{mV}/\sqrt{3}$
Secondary voltage	U_2	$0.5\text{mV}/\sqrt{3}$
Measuring shunt	R_{meas}	$0.5{\times}10^{-3} \times R_{meas}\ /\ \sqrt{3}$
Phase angle	φ	$0.02°/\sqrt{3}$
Frequency	f	$0.5 \times 10^{-3}\ /\sqrt{3}$
Formfactor	FF	$\lvert FF - FF_{nom}\rvert/2$
Air flux compensation	γ	$1 \times 10^{-3}\ /\sqrt{3}$
Density	ρ	8kg/m^3
Length	l	$0.5\text{mm}/\sqrt{3}$
Mean magnetic path length	l_m	$0.3\text{mm}/\sqrt{3}$
Mass	m	$0.2\text{g}/\sqrt{3}$

The quantification of the different influence factors are conducted according to type B evaluation using manufacturer's specifications. The specific values used for the evaluation are listed in Table I. A normal distribution of values is assumed according to Ref. 9.

B. Uncertainty contributions

Present time electrical machines are designed at rising fundamental frequencies and magnetic polarisation levels. Therefore, material characterisation has also to be conducted at magnetic polarisation and frequency levels above the interval presently covered by the standard. Hence, a quantification of the uncertainty contributions resulting from the magnetic characterisations is important for an assessment of the material model and its parameters. Consistently, the uncertainty contributions are analysed over a wide magnetic polarisation range J up to 1.8T and frequency range f up to 9kHz. Futhermore, the sensitivity of the different contributions can be analysed within the measured spectrum.

In the following the different loss contributions are analysed quantitatively and qualitatively. Based on the compensated loss calculation (1), the derived description of the uncertainty in measurement of the specific losses (4) and the values is collected in Table I. Two different measuring sensors are used for the material characterisation. The considered SST differ in the amount of primary and secondary windings. Both SST have a transformation ratio of one. The first SST, in the following named *LF* has 300 windings and is preferably used for quasi static measurements. The second SST, in the following named *HF* has 50 windings and is preferably used at higher frequencies. In Figure 2 a comparison of the resulting measured magnetic losses at 50Hz and the corresponding uncertainty contributions are depicted dependent on the magnetic polarisation. In case of the LF in Figure 2(a) the resulting absolute uncertainty is smaller compared to the HF in Figure 2(b) at lower magnetic polarisation levels. With rising magnetic polarisation



(a) (b)

FIG. 2. Measured specific losses and corresponding calculated uncertainty at 50 Hz of two different measuring sensors.

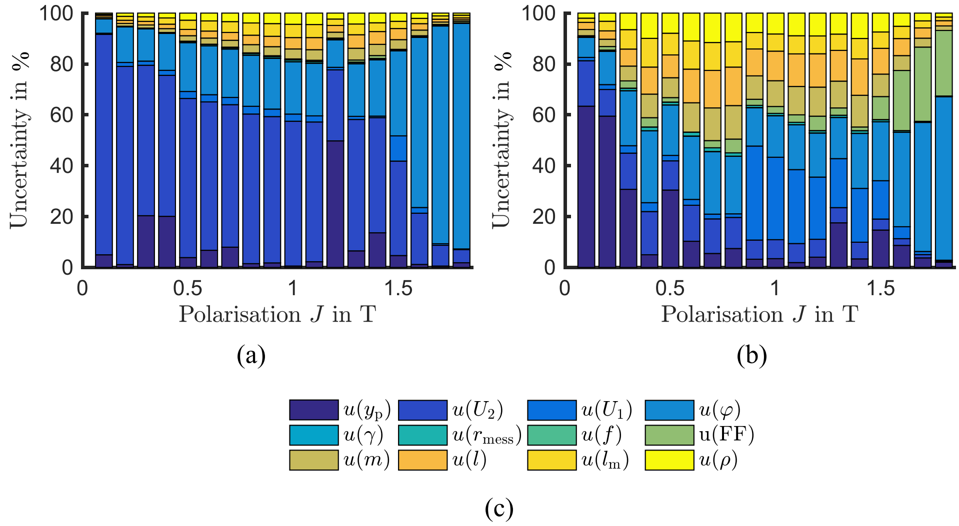


FIG. 3. Relative share of uncertainty contributions to the calculated combined uncertainty of a SST with 50 windings at (a) 50 Hz and (b) 1 k Hz.

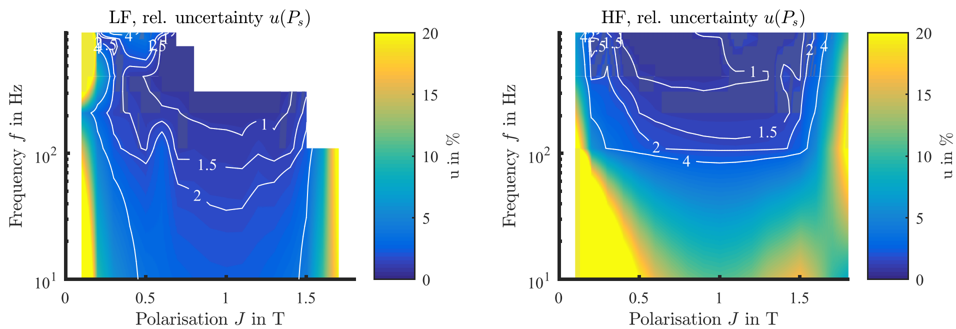
the combined uncertainty in measured losses of LF increases strongly above 1.5T compared to the LF.

In order to exemplarily analyse the sensitivity and influence of the different uncertainty contributions on the combined uncertainty of the HF SST, two frequencies are exemplarily selected. Figure 3 depicts the relative contributions at 50Hz and 1kHz considering the HF measuring sensor. As a result of the analysis on the different uncertainties, two main contributions, namely the Form factor FF and the phase angle φ can be found. Beside theses, at low frequencies and magnetic polarisation levels demonstrated in Figure 3(a), a significant contribution can be found in terms of the secondary voltage levels. If the voltage level U_2 is low when compared to the measuring interval, the uncertainty contribution can prevail.

The uncertainties are calculate considering at least three repetitions of the same measurements. Therefore, the statistical influence of random measuring deviations can be taken account by using the calibration factor y_{p} of the repetitions. By considering repeated measurements a strong influence can exemplarily be found at a magnetic polarisation of $J = 1.2$ T depicted in Figure 3(b). In the specific measuring point a high relative uncertainty contribution results due to the deviation in repeatedly measured specific losses. At low frequencies the impact of the phase angle increases significantly with rising magnetic polarisation levels especially above $J = 1.5$ T. In accordance with (1) a linear dependency of measured specific losses and the phase angle can be found within an interval of the measured phase angles considering a specific magnetic polarisation value.

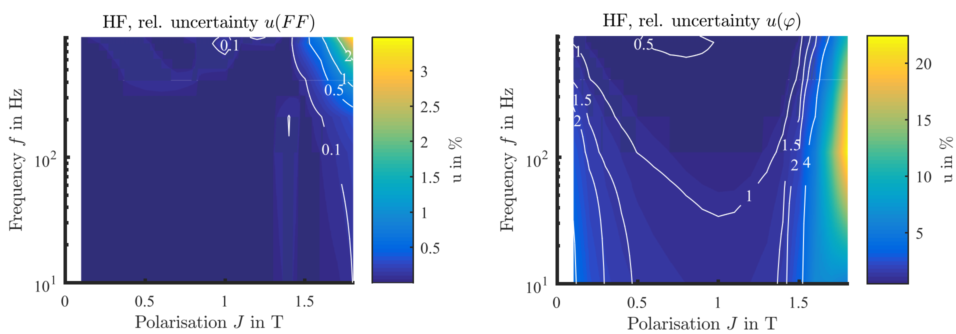
Due to the need of characterising material properties under magnetic polarisation and frequencies levels also above the currently defined standards, the combined standard uncertainty and its contributions are analysed within a broad frequency and polarisation spectrum. In Figure 4 the resulting combined standard uncertainty of the used LF, and HF SST are depicted up to 1.8T and 9 kHz. It becomes apparent that the HF results in a high uncertainty due to the low secondary voltage and the phase angle, in case of low polarisation and frequency levels. While the LF is preferable used at low frequencies a frequency independent boundary can be found at 1.5T and below 0.2 T. In case of the HF a frequency dependency can be seen within the polarisation range of 0.2T up to 1.5 T. Measured magnetic losses at polarisation levels above and below this interval are prone to high specific uncertainties.

During measurements the form factor is kept within the boundaries defined by the standard. Thereby its uncertainty contribution is small across the entire frequency and polarisation spectrum, as depicted in Figure 5(a). As discussed earlier the phase angle, depicted in Figure 5(b) is a key



(a) (b)

FIG. 4. Calculated combined uncertainty of a SST with (a) 300 windings (LF) and (b) 50 windings (HF).



(a) (b)

FIG. 5. Calculated uncertainty contribution of (a) phase angle and (b) of the Form Factor to the measured specific losses.

aspect to be considered for magnetic characterisation outside the standard. Its significant uncertainty contribution at polarisation levels above 1.5T is an inherent effect of the open transformer method.

III. IMPACT OF THE COMBINED UNCERTAINTY ON IRON LOSS PARAMETERS

The influence of the measured magnetic properties on the material model in terms of the loss parameters is analysed on the basis of the identified resulting uncertainty. Iron loss calculations in (5) are performed according to the material model in Ref. 10. The iron losses are separated into the contributions of static hysteresis losses P_{hyst}, eddy current losses $P_{\text{classical}}$, excess losses P_{excess} and saturation losses P_{sat}.

$$\begin{aligned} P_{\text{IEM},5} &= P_{\text{hyst}} + P_{\text{classical}} + P_{\text{excess}} + P_{\text{sat}} \\ &= a_1 \cdot B^{\alpha+\beta \cdot B} \cdot f + a_2 \cdot B^2 \cdot f^2 \\ &\quad + a_2 \cdot a_3 \cdot B^{2+a_4} \cdot f^2 + a_5 \cdot B^{1.5} \cdot f^{1.5} \end{aligned} \tag{5}$$

The impact of the measuring uncertainty on the loss parameters is determined by considering the minimum $u(P_\text{s})_-$ and maximum values $u(P_\text{s})_+$ of each interval of the combined uncertainty calculated in (4). The loss parameters are identified at different frequencies and polarisation levels as described in Ref. 10. To analyse the sensitivity of the uncertainty on the resulting loss parameters, the identification is done using the measured values $P_{\text{s,meas}}(f, B)$ it self and the measured values considering the upper $u(P_\text{s})_+$ and lower boundary's $u(P_\text{s})_-$ of the interval as written in (6).The result of the identification is depicted in Figure 6 and the according values are shown in Table II.

$$P(f, B) = P_{\text{s, meas}}(f, B) \pm u_{P_\text{s}}(f, B) \tag{6}$$

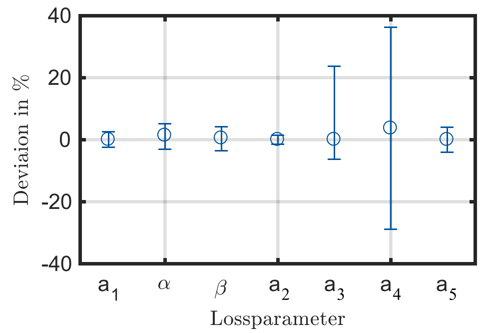


FIG. 6. Relative impact of uncertainty on iron loss parameters.

Hysteresis losses are identified at quasi static conditions. The impact of the measuring uncertainty on the measured losses is determined using the type A evaluation according to Ref. 9. It is the statistical analysis in terms of the standard uncertainty of mean from independent observations. For the identification of the uncertainty on the hysteresis loss parameters a_1, α and β each magnetic polarisation point is measured at least 25 times. The measurements are current controlled using a fixed delta of flux density $\frac{dB}{dt}$. The impact on a_1 are rather small, while loss parameter α is mostly influenced by the uncertainties. Due to the used method of least square error, the uncertainties at higher polarisation have a larger impact on the identification process. This can be seen in the exponents α and β which more prone to the resulting uncertainties.

In this paper the classical eddy current loss parameter a_2 is estimated analytically. Consistently, the uncertainty of the loss parameter using (3) can be described by (7). The resulting uncertainty interval is very low, implying the applicability of the analytical description. Especially at high frequencies, the analytical description is inaccurate and numerical calculations are necessary, to estimated eddy current losses and resulting uncertainties more precisely. As shown in Ref. 11 for polarisation levels up to approximately 1.1T, the analytical description results in an overestimation and at higher polarisation levels in an underestimates of the resulting eddy current losses.

$$u_c^2(a_2) = a_2^2((2\frac{u(d)}{d})^2 + (\frac{u(\rho_{\text{el}})}{\rho_{\text{el}}})^2 + (\frac{u(\rho)}{\rho})^2) \tag{7}$$

The identification of loss parameter a_5 are performed at low frequencies and in the linear magnetisation range. As demonstrated in Figure 4(b) the total combined uncertainty of the HF measuring sensor is high at low frequency and polarisation levels. This results into a high interval and uncertainty of parameter a_5.

Saturation losses and loss parameters a_4 and a_5 are a mathematical compensation of the inaccurate eddy current description at high frequencies and polarisation levels. They can be identified at a single frequency above 400Hz and high polarisation levels or to minimize the overall error in the loss description at high frequencies. In this paper, saturation losses are identified at 400Hz and polarisation levels above 1.4 T. As depicted in Figure 4 the combined uncertainties at both measuring sensors is very prone to polarisation levels above 1.5 T. This results in a high relative

TABLE II. Resulting loss parameters and corresponding uncertainty.

Parameter	a_i	Value	Lower boundary	Upper boundary
Hysteresis	a_1	$16.62 \cdot 10^{-3}$	$16.21 \cdot 10^{-3}$	$17.03 \cdot 10^{-3}$
Hysteresis	α	1.36	1.42	$1.31 \cdot 10^{-3}$
Hysteresis	β	0.49	0.47	0.50
Classical	a_2	$136.5 \cdot 10^{-6}$	$134.49 \cdot 10^{-6}$	$138.45 \cdot 10^{-6}$
Excess	a_5	$339.63 \cdot 10^{-6}$	$353.58 \cdot 10^{-6}$	$325.91 \cdot 10^{-6}$
Saturation	a_3	$29.26 \cdot 10^{-3}$	$31.10 \cdot 10^{-3}$	$22.37 \cdot 10^{-3}$
Saturation	a_4	3.67	2.48	4.85

uncertainty especially in case of the exponent a_4 as depicted in Figure 6. As mentioned before, eddy current losses are calculated analytically. The analytical description is inaccurate with rising polarisation and frequency level, which influences significantly the identification of the saturation losses.

IV. CONCLUSIONS

In this paper the resulting uncertainty contributions within the characterisation of no-oriented soft magnetic materials is analysed. Two SST's with different amount of windings are used as exemplary measuring sensors. It is demonstrated, that the evaluation of the resulting uncertainties can be used as an additional selection criteria for different measuring sensors. Beside the Form Factor as standardised quality criterion, the phase angle is a key aspect to be considered in terms of the resulting uncertainties of the measured specific losses. The increasing phase angle at polarisation levels above 1.5 T is an inherent effect due to the measuring principle of an open transformer.

The impact of the calculated uncertainties within the identification of iron loss parameters is studied. It is found that a high relative uncertainty interval results in case of the saturation loss parameters. On the one hand, this is due to the fact of an analytical eddy current parameter which results in larger inaccuracies with rising frequency and polarisation. On the other hand, the identification interval of the saturation losses is subject to high uncertainties, mainly due to the increased magnetic polarisation.

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