Advanced Iron-Loss Estimation for Nonlinear Material Behavior

Daniel Eggers, Simon Steentjes, and Kay Hameyer

RWTH Aachen University, Aachen 52062, Germany

The aim of an optimal design of electrical machines requires the accurate prediction of iron losses for various operating points. For this purpose different iron-loss models have been proposed which intent to describe the loss inducing effects. The most used iron-loss prediction formulas are either physically based, but nevertheless only valid for linear material behavior at low frequencies and low magnetic flux densities, or grounded on a pure mathematical description of the material behavior, that is not more than interpolated measurements. This paper presents a modified loss equation with semi-physically based parameters as well as a first try to explain the nonlinear loss component.

***Index Terms*—High frequency iron losses, magnetic losses, measurement loss prediction, nonlinear material behavior, soft magnetic materials.**

I. INTRODUCTION

THE accurate prediction of iron losses for various operating points is still troublesome for an optimal design of electrical machines. The best motor design yields high utilization of the soft magnetic material used. This yields high magnetic flux densities and therefore saturation inside the magnetic core of the machine. Modern electrical machines, e.g. employed as traction drives in full electrical vehicles are operated at frequencies in the range of 500 Hz or even higher. Therefore, the loss estimation must be capable to deliver sufficient accurate results in this range of basis frequency as well.

This paper is organized as follows: At first, the Bertotti loss-equation as well as the 4 parameter iron-loss prediction formula is presented. Thereon the physically based parameter identification procedure of the specific parameters for three common non grain oriented (NO) soft magnetic materials and the mathematical based identification of the nonlinear parameters are described. The identified parameters for these three soft magnetic materials, M235-35A, M270-35A and M800-50A, are presented and the ability of iron-loss estimation of both models is compared. Ongoing a first physical interpretation of the parameters describing the nonlinear material behavior is attempted. Finally the results are discussed and an outlook is given.

II. METHODS OF IRON-LOSS PREDICTION

In practice the iron-loss estimation is very often performed by empirical models such as the Steinmetz-Model or more physical based models such as the Bertotti-Model [1]

$$P_{Bertotti} = k_{hyst}B^{\alpha}f + k_{eddy}B^2f^2 + k_{excess}B^{1.5}f^{1.5} \quad (1)$$

which describes the total iron losses as a contribution of hysteresis, eddy current and excess losses. The Bertotti-Model contains the magnetization frequency f, the maximum value of the magnetic flux density B and the material specific parameters $k_{hyst}, \alpha, k_{eddy}, k_{excess}$. By solving Maxwell's equations the parameter for the eddy current losses can be described as

$$k_{eddy} = \frac{\pi^2 d^2}{6\rho\rho_e} \quad (2)$$

with the sample-specific characteristics: thickness d (m), density ρ $(\mathrm{kg/m^3})$ and electric resistivity ρ_e $(\Omega\mathrm{m})$.

The Bertotti-Model is valid for linear material behavior, i.e. the material is not in saturation so that permeability can be considered to be constant near this operation point. By a rule of thumb it can be said that (1) is valid for magnetic flux densities $B \leq 1.2$ T and frequencies $f \leq 400$ Hz.

Because of the inaccurate iron-loss prediction with (1) for nonlinear material behavior, the IEM-Formula [2]

$$P_{IEM} = a_1B^2f + a_2B^2f^2(1 + a_3B^{a_4}) + a_5B^{1.5}f^{1.5} \quad (3)$$

has been developed. The parameters a_1–a_5 were identified by a pure mathematical fitting procedure done on measured data sets of iron losses.

To consider the impact of higher frequencies, a correction factor F_{skin} [3] is used in the eddy current term. So the additional term $a_3B^{a_4}$ just represents the nonlinear material behavior which is investigated in this paper. Considering F_{skin} in (1) and (3) the modified loss equations are as follows

$$\begin{aligned} P_{Bertotti} &= k_{hyst}B^{\alpha}f + F_{skin}k_{eddy}B^2f^2 \\ &\quad + k_{excess}B^{1.5}f^{1.5} \quad (4) \\ P_{IEM,5} &= a_1B^{\alpha}f + F_{skin}a_2B^2f^2(1 + a_3B^{a_4}) \\ &\quad + a_5B^{1.5}f^{1.5}. \quad (5) \end{aligned}$$

III. PARAMETER IDENTIFICATION

In contrast to [2] where the parameters of both loss models were identified by a mathematical approximation of the measured curves for different frequencies, the parameter identification is done in line with the physically interpretation of the phenomena. The identification of the hysteresis parameter k_{hyst} and the exponent of the magnetic flux density α are performed using dc-measurements. Those were carried out on a standard Epstein

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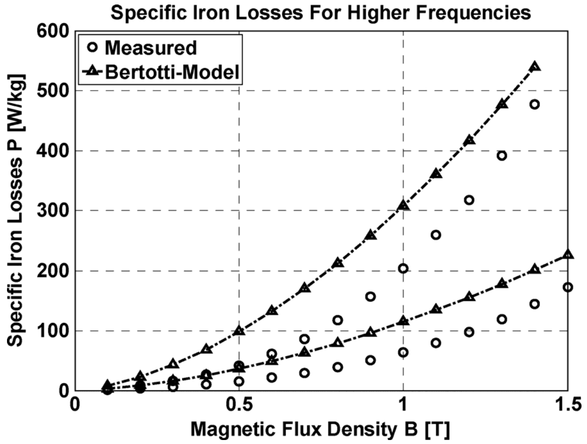

Fig. 1. Comparison of the predicted iron losses by the Bertotti-model (4) and measurements at 500 Hz (low) and 1000 Hz (top) for M800-50A.

frame with 700 windings and 12 strips of the soft magnetic material, each 280 mm × 30 mm, under test with sinusoidal uniaxial magnetic flux densities.

The eddy-current parameter k_{eddy} is identified via (2) using the material characteristics known from the material data sheet provided by the manufacturer.

The excess loss parameter k_{excess} is determined from measurements at $f = 5$ Hz using the same configuration as described for k_{hyst}. For this frequency the eddy current losses are not dominant and the excess loss term is easily separated.

With these parameters (4) has been used for loss estimations at frequencies of 500 Hz and 1000 Hz. Fig. 1 shows the comparison of these results for the material M800-50A with the measurements. It is obvious that the calculated iron losses overestimate the measured ones. This is caused by the large proportion of excess losses for high frequencies predicted by (4). The correction factor F_{skin} reduces the exponent of the frequency in the eddy current term to 1.5, so it is the same power as the excess term, but k_{excess} is approximately ten times higher than k_{eddy}. This means that following (4) the excess term is the dominant contribution of losses for lower and middle magnetic flux densities. This is an unphysical interpretation of loss composition at high frequencies for that eddy current losses should be dominant.

Using (5) to identify the nonlinear loss component by subtracting the estimated losses from the measured losses leads to a negative loss component, which means a generation of power.

Therefore (5) was modified by removing the excess loss component, resulting in

$$P_{IEM,4} = d_1 B^{\alpha} f + F_{skin} d_2 B^2 f^2 \left(1 + \frac{d_3 B^{d_4}}{F_{skin}}\right) \quad (6)$$

so the parameters d_3 and d_4 are determined from the iron-loss estimation error (7). The nonlinear loss component P_{nl} is just the difference between the measured and calculated eddy current and hysteresis losses

$$P_{nl} = P_{Measured} - k_{hyst} B^{\alpha} f - F_{skin} k_{eddy} B^2 f^2. \quad (7)$$

The measurements for the identification of the parameters were performed in a frequency range from 500 Hz to 2000 Hz on two Epstein frames with 100 and 40 windings for sinusoidal uniaxial magnetic flux densities. The Epstein frame with 100 windings was used for frequencies from 500 Hz up to 1500 Hz and the frame with 40 windings from 1500 Hz upwards.

TABLE I
IDENTIFIED PARAMETERS FOR THE MATERIALS

	M235-35A	M270-35A	M800-50A
k_{hyst}, d_1	$13.877\cdot10^{-3}$	$11.745\cdot10^{-3}$	$37.272\cdot10^{-3}$
k_{eddy}, d_2	$44.766\cdot10^{-6}$	$50.340\cdot10^{-6}$	$174.948\cdot10^{-6}$
k_{exces}	$0.524\cdot10^{-3}$	$0.447\cdot10^{-3}$	$6.031\cdot10^{-3}$
d_3	0.168	0.262	0.307
d_4	2.945	2.969	2.975
α	1.979	1.992	1.776

Table I presents the identified parameters for three non grain oriented (NO) materials.

The loss estimations of both loss-models (4) and (6) using these parameters for three frequencies of 500 Hz, 1000 Hz and 5000 Hz are shown in Figs. 2, Fig. 3 and Fig. 4. The improved loss prediction by the 4-parameter-formula (6) within the parameter identification range is obvious. For loss estimations out of the parameter identification range (Fig. 4), the accuracy for M235-35A and M270-35A is improved. The predicted losses for M800-50A are not in the desired range of accuracy. Based on these results it can be declared that the parameter identification is sensitive to the used parameter identification range because of the mathematical identification of the nonlinear loss component. For example, the parameter identification for M800-50A using measured losses up to 5000 Hz leads to the parameters $d_3 = 0.863$ and $d_4 = 2.959$. With these parameters, a better agreement is achieved for high frequency losses and a reduced for low frequency losses over the whole magnetic flux density range. Within this, a recommended frequency range for loss estimation due to the identified parameters cannot be given yet. According to [5], variable coefficients for different frequencies would help to fulfill the aimed accuracy of loss prediction, but this would increase computing effort for a numerical FE-Simulation compared to a loss model with constant parameters.

Figs. 5 and 6 present the relative estimation error with respect to the measured iron losses. For the material M235-35A, the accuracy increases at higher magnetic flux densities in the identification range. For the magnetic flux density range of electrical machine applications, $B \leq 1.2$ T, the estimation error is almost zero for 500 Hz and 1000 Hz. The relative error of (6) at 5000 Hz is underneath the error of (4) within this magnetic flux density range. According to Fig. 6, the relative error of (6) is still below the error of (4) but already in an unsatisfactory high level for 5000 Hz (~50%). The error for both lower frequencies is from $B \leq 0.5$ T onwards less than 20%, which is still a good loss estimation.

IV. NONLINEAR LOSS COMPONENT

The nonlinear loss component depends on the behavior of the permeability which is influenced by both, high frequencies above the limiting frequency f_G [4] and high magnetic flux densities leading to magnetic saturation.

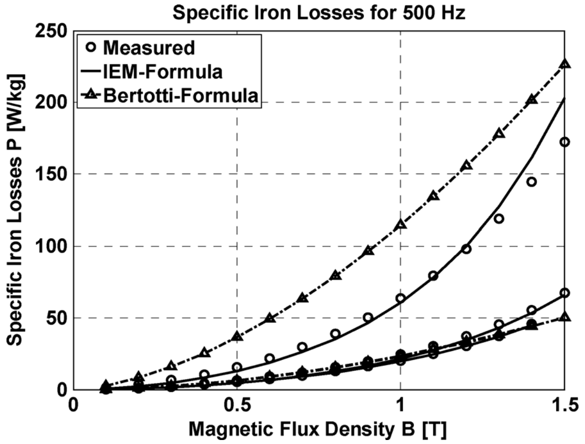

Fig. 2. Comparison of the 4-parameter-IEM-formula (6) with measurements and the Bertotti-formula (4) for a frequency of 500 Hz for M235-35A (low), M270-35A (middle) and M800-50A (top).

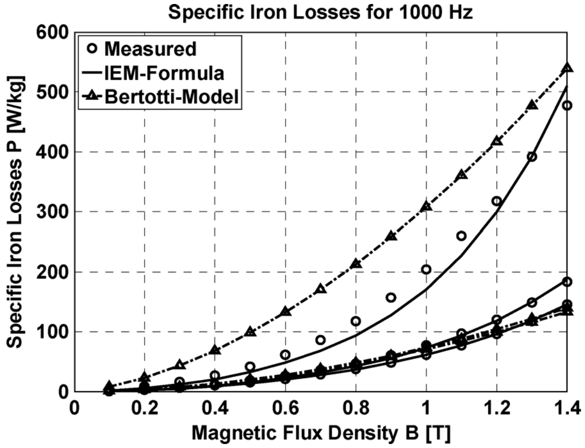

Fig. 3. Comparison of the 4-parameter-IEM-formula (6) with measurements and the Bertotti-formula (4) at a frequency of 1000 Hz for M235-35A (low), M270-35A (middle) and M800-50A (top).

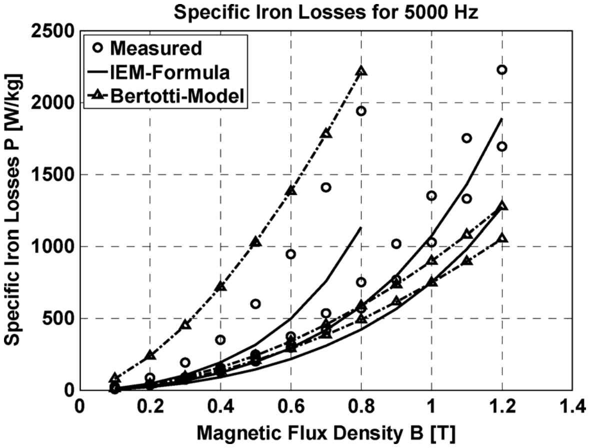

Fig. 4. Comparison of the 4-parameter-IEM-formula (6) with measurements and the Bertotti-formula (4) at a frequency of 5000 Hz for M235-35A (low), M270-35A (middle) and M800-50A (top).

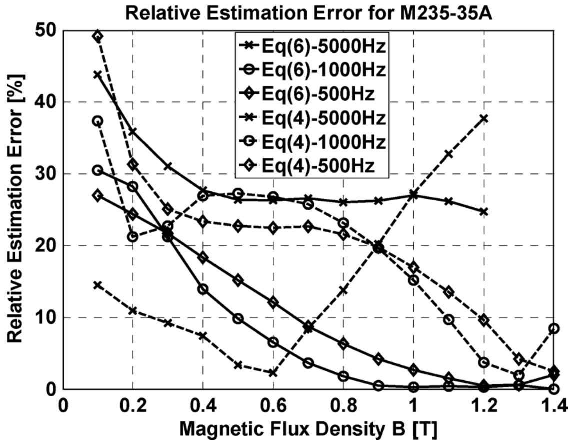

Fig. 5. Relative estimation error for the NO material M235-35A for different magnetic flux densities and frequencies.

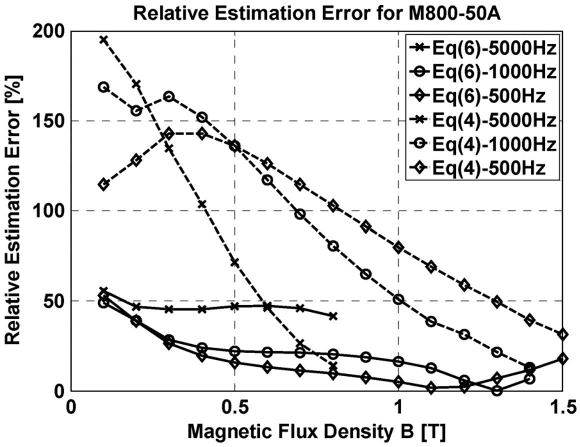

Fig. 6. Relative estimation error for the NO material M800-50A for different magnetic flux densities and frequencies.

The nonlinear losses for the three materials are estimated by (7) and presented in Figs. 7, 8 and 9. For low magnetic flux densities the loss estimation at high frequencies of (4) is accurate for M270-35A. Due to a frequency-dependent magnetic flux density, the material behavior becomes nonlinear and the additional loss component becomes more relevance [6]. This behavior is identified for M270-35A. Because of the very low limiting frequency of $f_G \approx 200$ Hz, M800-50A is already for the observed frequencies very sensitive to the nonlinear losses and shows therefore a high nonlinear loss component yet at a magnetizing frequency of $f = 500\ \mathrm{Hz}$ (Fig. 9).

Having a look on the nonlinear parameters (Table I), the exponent of the high order term, d_4, seems to be constant. This means that the course of the nonlinear losses is the same for the investigated materials. This supposition can be confirmed by Figs. 7–9.

For d_3, the weighting factor of the course of the nonlinear losses, no correlation with the measureable material characteristics like thickness and mass density can be identified. No relationship between the permeability at these high frequencies and the parameters is found. Also the residual magnetic flux density, known from measurements, cannot be associated with the parameter d_3.

A possible influence of the grain size needs to be investigated in upcoming research. Another starting point for further research is the influence of the alloy content, especially the rate of silicon and aluminum per cent by volume, as well as imperfections.

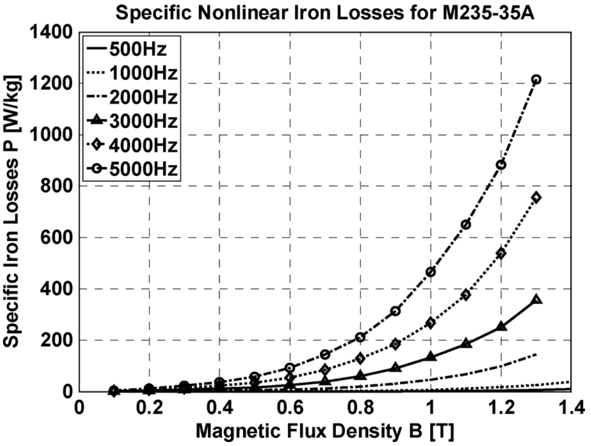

Fig. 7. Progress of the nonlinear loss component for M235-35A for different magnetic flux densities and frequencies.

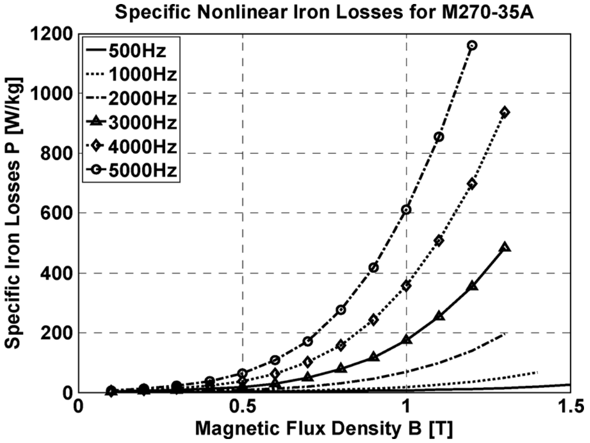

Fig. 8. Progress of the nonlinear loss component for M270-35A for different magnetic flux densities and frequencies.

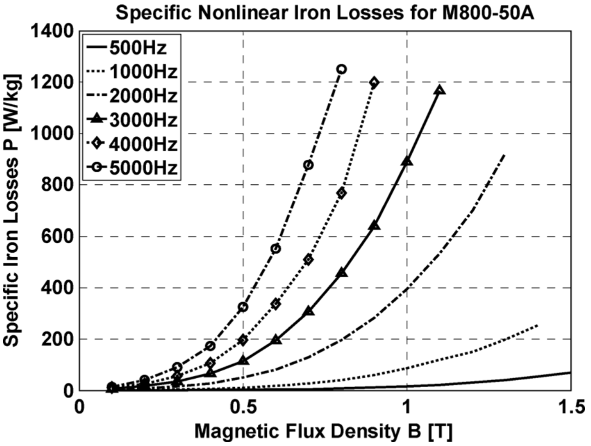

Fig. 9. Progress of the nonlinear loss component for M800-50A for different magnetic flux densities and frequencies.

The manufacturing process of the soft magnetic material is another interesting aspect, which should be added to the model in the future. The internal stress caused by punching and welding [7], [8] leads to a reduction of flux conductivity, which means a reduction of the permeability, and saturation as well as an increasing of the hysteresis losses. Further research will aim to describe this hysteresis loss increase, modifying (6) by an additional parameter depending on the relative cutting edge length.

Moreover, with respect to operating conditions of electrical machines, the extension of (6) with existing approaches for harmonics [9], [10] and rotational magnetization [11] needs to be investigated in the future.

V. CONCLUSIONS

A variation of an iron loss estimation formula for an investigation of the nonlinear loss component is presented. The parameter identification procedure is performed by the physical interpretation of the common loss components hysteresis, eddy current and excess as well as by mathematical fitting to the nonlinear loss contribution.

It was shown that the excess term of the common loss models overestimates the losses for high frequencies.

The 4-Parameter-IEM-Formula results with semi-physical identified parameters in a good approximation of the measured losses of the non grain oriented materials M235-35A, M270-35A and M800-50A in the investigated frequency range.

A first approach to physically interpret the parameters, modeling the nonlinear loss, was presented and leads to an exclusion of a simple mathematical correlation of thickness and mass density.

Upcoming research will aim the coherence of the nonlinear loss parameters as a function of material properties like grain size, resistivity or alloy content.

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