OVERVIEW AND COMPARISON OF IRON LOSS MODELS FOR ELECTRICAL MACHINES

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Abstract—One important factor in the design process and optimization of electrical machines and drives are iron losses in the core. By using new composite materials and low-loss electrical Silicon-Iron (SiFe) steels, the losses in the magnetic flux conducting parts of the machine can be reduced significantly. However, it is necessary to have accurate but also easy implementable iron loss models to take the loss effects into account, preferable already during the first design steps and simulations of new electrical machines. The goal of this paper is to give an overview of available iron loss models and to summarize and compare certain models for analytical and numerical machine design methods.

Index Terms—Eddy currents, electrical steel sheets, electromagnetic iron losses, excess losses, hysteresis losses, hysteresis models, permanent magnet machines.

I. Introduction

HIGH efficient electrical machines play a key role in the ongoing climate discussions to reduce the energy consumption and to improve the efficiency, in order to meet the new European Commission Regulation (EC) No 640/2009 concerning the efficiency for electric motors [1]. Furthermore, intensive research in high efficient electrical drive systems is conducted for future traction applications, where wide speed ranges and high power densities are demanded. Especially permanent magnet synchronous and brushless DC machines are ideally suited for these high efficiency applications, but also induction machines have a high potential for further energy savings. There are several ways to improve the efficiency and to reduce the losses in these machines. One key factor is the electromagnetic iron losses, which occur mainly in the stator teeth and yoke as well as in the rotor yoke. In field weakening operation of traction machines, iron losses can even become the major loss component.

From a physical point of view, the losses in conducting ferromagnetic materials are all based on Joule heating [2]. Losses due to spin relaxation are negligible for electrical machines, because their impact is significantly only at frequencies in the MHz range and above. Thus, both hysteresis and eddy current losses are caused by the same physical phenomena: every change in magnetization (which also occurs at DC magnetization) is a movement of domain walls and creates (microscopic and macroscopic) eddy currents which, in turn, create Joule heating. The fact that hysteresis losses also arise at almost zero frequency is due to the fact that even if the macroscopic magnetization change is very slow, the local magnetization inside the domains is changing rapidly

and discrete in time, which generates eddy current losses [2]. Therefore, it should be kept in mind that the engineering approach of loss separation into different loss types (the so-called hysteresis losses, eddy current losses and excess losses for example) is an empirical approach, trying to separate the different physical influences due to frequency and flux density variations in electromagnetic systems, rather than explaining the physical phenomena directly. Nevertheless, empirical iron loss models have in most cases shown good correlation with measurements. Since these empirical models allow a fast iron loss calculation, they are mainly used in machine analysis models nowadays.

To predict the iron losses during a machine design process, the engineer can choose from a wide range of different iron loss models for electrical machines. The first part of this paper provides an overview of the factors which influence the iron losses during assembly and manufacturing processes and points out models taking these effects into account. The second part of this paper discusses the development of different iron loss models in more detail and compares the models in terms of possible flux density waveforms (i.e. time variations), rotating field consideration, needed material data and accuracy.

II. Influencing factors for iron losses

One demand when investigating iron losses is the need of measurement results and technical data of the used electrical steels. The needed data is depending on the used iron loss model. But even if one focuses on the same catalog type of electrical steel sheets, the iron losses will vary in reality due to non-isotropic effects, different alloy composites, contamination during the manufacturing process and uncertainties of the measured magnetic properties [3]. Since these variations are mainly small compared to the average accuracy of the iron loss models, they are mostly neglected. However, the catalog values of the material determine just the maximum guaranteed values of the magnetic properties and losses in the material. Therefore, manufactures provide often also typical average values, which are much closer to the real values and thus more suitable to use in iron loss calculations. Nevertheless, if exact values are needed, especially for large machines in the MW range, the delivery certificates for the lamination rolls provided from tests by the manufacturer should be applied.

More attention should be paid to influences which occur during the manufacturing process of the magnetic circuit of an electrical machine. Even if the presented analytical models give more or less reasonable results and fit loss measurement

data (typically obtained by Epstein frame measurements) quite well, the accuracy can be drastically reduced when it comes to the loss determination in finally assembled machine cores.

Cutting and punching the iron sheets influence the material properties and create inhomogeneous stress inside the sheets, which in turn influences the hysteresis curve by shearing. The effect is depending on the alloy composite, whereas the grain size in the sheets seems to be the main influencing factor, especially for operating ranges between $0.4\,\mathrm{T}$ to $1.5\,\mathrm{T}$ [4], [5]. The influenced region in the sheet due to cutting and punching goes up to $10\,\mathrm{mm}$ in distance from the cutting edge, where the permeability is significantly decreased [6], [7]. This reduction in permeability increases the iron losses in the material. Especially for geometric parts smaller than $10\,\mathrm{mm}$ in width (small stator teeth for example), the punching process can have a significant influence on the iron losses and therefore has to be considered in the loss calculation [8]. A formula for estimating the iron losses in the teeth of induction machines is developed in [9]. A way to regard the cutting edge influences in design tools is presented in [10], [11]. It should be mentioned that the width of the electric sheets for standard loss measurements in the Epstein frame is $30\,\mathrm{mm}$ and thus not suitable for material and loss investigations of small sheet parts.

An important point to consider is that it is possible to recover the magnetic material characteristics up to a certain degree by a stress-relief annealing after the process of machining [6], [12]. This annealing process is mainly applied to machines with small geometrical dimensions where the cutting edges account for a significant part of the geometry. Depending on the used cutting technology, the annealing is more effective before or after the cutting process [13]. Further, the cutting and punching process damages the thin insulation layer which can lead to short circuits between several sheet layers.

Similar deteriorations as for cutting and punching effects are obtained due to the stacking and welding process during the machine core assembly. Especially the welding process deteriorates the material properties of the assembled core which, in turn, generates higher iron losses [14], [15], [16].

The deterioration effects on the material due to both processes, cutting and assembling, are investigated for an electrical permanent magnet machine in [17]. An approach for a posteriori estimations of the manufacturing process of induction machines by measurements is presented in [18].

Table I gives an overview of influencing loss parameters where P_{hyst} denotes the hysteresis losses, P_{ec} the classical eddy current losses and P_{exc} the excess losses. J_{s} and H_{c} are the saturation magnetization and the coercive field strength, respectively.

III. Iron loss models overview

Figure 1 gives an overview of the most often used methods for determining iron losses. One group of models is based on

Table I
INFLUENCE OF DIFFERENT FACTORS ON SIFE STEEL SHEETS PROPERTIES [11], [19], [20].

Influencing Factor	P_{hyst}	P_{ec}	P_{exc}	J_{s}	H_{c}
Grain size (d_{grain} ↗)	↘		↗		↘
Impurities (↗)	↗			↘	↗
Sheet thickness (d ↗)	↘	↗			↘
Internal stress (↗)	↗				↗
Cutting/punching process	↗			↘	
Pressing process		↗			
Welding process	↗				
Alloy content (%Si ↗)		↘		↘	

the Steinmetz equation (SE) [21]:

$$p_{\mathrm{Fe}} = C_{\mathrm{SE}}\, f^{\alpha}\, \hat{B}^{\beta} \qquad (1)$$

where $\hat{B}$ is the peak value of the flux density in the sheet. The three coefficients C_{SE}, α and β are determined by fitting the loss model to the measurement data. Since (1) assumes purely sinusoidal flux densities, there are nowadays several modifications used to take into account also non-sinusoidal waveforms. They will be investigated in more detail in Section IV .

In [22], an extension to (1) is presented by Jordan where iron losses are separated into static hysteresis losses and dynamic eddy current losses:

$$p_{\mathrm{Fe}} = p_{\mathrm{hyst}} + p_{\mathrm{ec}} = C_{\mathrm{hyst}}\, f\, \hat{B}^{2} + C_{\mathrm{ec}}\, f^{2}\, \hat{B}^{2} \quad (2)$$

In this approach, it is assumed that the hysteresis losses are proportional to the hysteresis loop of the material at low frequencies ($f \to 0$). The eddy current part of the losses p_{ec} can be calculated with the help of Maxwell's equations. This leads to

$$p_{\mathrm{ec}} = \frac{d^{2}\left(\dfrac{dB(t)}{dt}\right)^{2}}{12\,\rho\,\gamma} \qquad (3)$$

where $B(t)$ is the flux density as a function of time, d is the thickness of the electric sheet, ρ its specific resistivity and γ the material density. Equation (2) has been proven correct for several Nickel-Iron (NiFe) alloys but lacks accuracy for SiFe alloys [23]. For this reason, an empirical correction factor η_{exc}, called the excess loss factor (often also referred to as anomalous loss factor), was introduced by Pry and Bean [24]. It extends (2) to

$$p_{\mathrm{Fe}} = p_{\mathrm{hyst}} + \eta_{\mathrm{a}}\, p_{\mathrm{ec}} =$$
$$C_{\mathrm{hyst}}\, f\, \hat{B}^{2} + \eta_{\mathrm{exc}}\, C_{\mathrm{ec}}\, f^{2}\, \hat{B}^{2} \qquad (4)$$

with $\eta_{\mathrm{exc}} = \frac{p_{\mathrm{ec\_measured}}}{p_{\mathrm{ec\_calculated}}} > 1$. For thin grain oriented SiFe alloys, η_{exc} reaches values between 2 and 3 [23].

Another approach to improve (2) is to introduce an additional loss term p_{exc} to take into account the excess losses as a function of the flux density and frequency. It separates the iron loss formula p_{Fe} into three terms, the static hysteresis
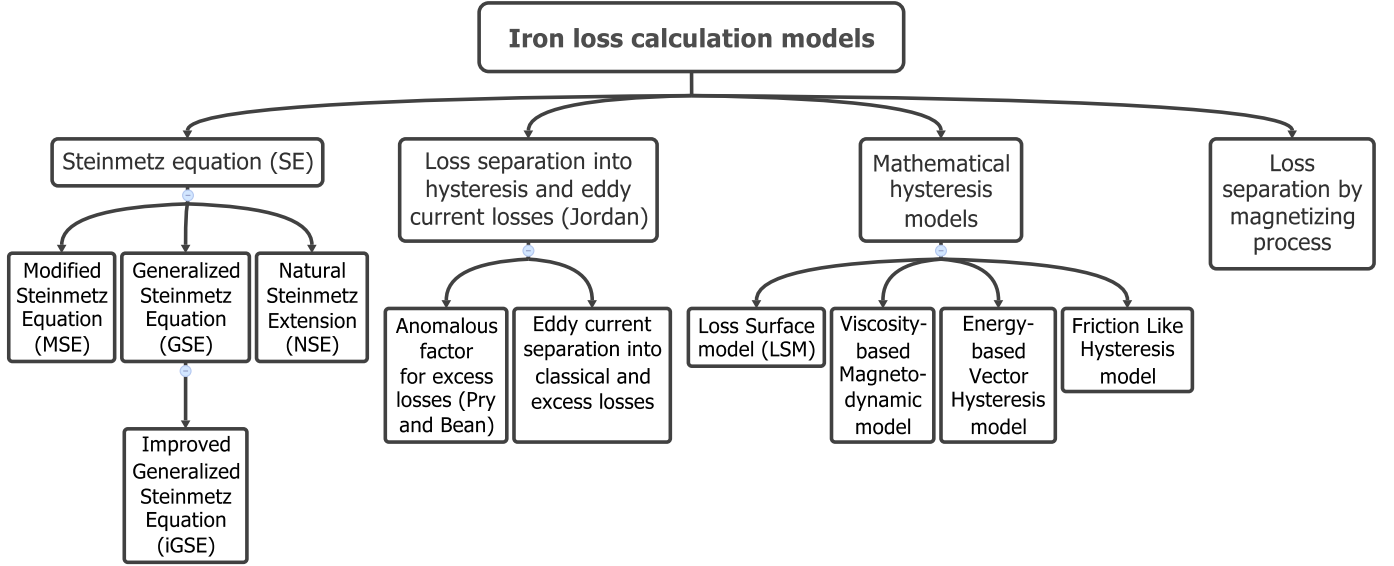
Figure 1. Model approaches to determine iron losses in electrical machines.

losses p_hyst, dynamic eddy current losses p_ec and the excess losses p_exc:

$$p_\text{Fe} = p_\text{hyst} + p_\text{ec} + p_\text{exc} =$$
$$C_\text{hyst}\, f\, \hat{B}^2 + C_\text{ec}\, f^2\, \hat{B}^2 + C_\text{exc}\, f^{1.5}\, \hat{B}^{1.5} \tag{5}$$

Since the excess losses in (5) are still based on empirical factors, Bertotti developed a theory and statistical model to calculate the iron losses by introducing so called magnetic objects, which led to a physical description and function of the loss factor C_exc in terms of the active magnetic objects and the domain wall motion [25], [26], [27], [28]:

$$C_\text{exc} = \sqrt{S\, V_0\, \sigma\, G} \tag{6}$$

where S is the cross sectional area of the lamination sample, $G \approx 0.136$ a dimensionless coefficient of the eddy current damping and σ the electric conductivity of the lamination. V_0 characterizes the statistical distribution of the local coercive fields and takes into account the grain size [27]. It has to be noted that this loss separation does not hold if the skin effect is not negligible [29]. A recently study on the properties of the coefficients from Bertotti's statistical model is presented in [30].

Next to the loss separation into static and dynamic losses, there are also further analytical approaches available for determining iron losses in electrical steel sheets. Several approaches focus on the iron losses created due to rotational magnetization (also called rotational losses) in the sheets [31], [32], [33], [34], [35]. It has to be mentioned that these physical loss behavior is not regarded in the previous presented models. An often applied loss model, which takes into account these losses due to rotational magnetization, is the loss separation model after the magnetizing processes. This means that the losses caused by linear magnetization, rotational magnetization and higher harmonics are added up to determine the total iron losses [36]:

$$p_\text{Fe} = C_1\, p_\text{a} + C_2\, p_\text{rot} + C_3\, p_\text{hf} \tag{7}$$

where p_a are the losses caused by linear magnetization, p_rot the losses caused by rotational magnetization and p_hf the losses caused by higher harmonics. C_x are empirical material and geometric dependent factors from measurements and curve fittings.

It should be noted that in electrical machines the iron losses caused by rotational magnetization occur mainly at the tooth heads/tips and in the intersection areas between the teeth and the yoke. In the larger parts of the machine, in the middle of the teeth and in the middle of the yoke, the magnetization is only linear. Thus from the electrical machine point of view, this loss separation model after the magnetizing process does not give any advantages in the machine parts where linear magnetization is clearly dominating.

Another possibility to regard iron losses due to rotational magnetization is by introducing a further correction factor. This is done in [37], where a rotational loss factor due to rotational magnetization and the loss separation model from Bertotti are combined:

$$p_\text{Fe} = a_2\, \hat{B}^2\, f + (a_1 + a_4\, \hat{B}^{a_3})\hat{B}^2\, f^2 \tag{8}$$

where $a_1 = C_\text{ec}$ and $a_2 = C_\text{hyst}(1 + \frac{B_\text{min}}{B_\text{max}}(r-1))$, with r the rotational hysteresis factor and B_min and B_max the minimum and maximum values of $B(t)$ over one period. The term a_4 and the exponent a_3 are used to get an accurate representation of the iron losses at large fields by introducing a higher order of the flux density B. Thus, they are called high order loss factors. Further, a_3 is depending on the lamination thickness. The excess loss term C_exc is negligible compared to the other terms in this model and thus not considered in (8).

Another iron loss model for permanent magnet synchronous machines, which takes into account the magnetization in different directions, is presented in [38]. Here the loss determination

is also separated into the iron losses occurring in the teeth and the one occurring in the yokes of the machine. The waveform of the flux densities in the different machine parts are assumed to be piecewise linear. This means the change rate of the flux density becomes a function of the number of phases and poles per pole and phase.

Calculating the iron losses by applying Fourier analysis to the magnetic field H and magnetic flux density B is proposed and investigated in [39], [40]:

$$p_{\mathrm{Fe}} = \sum_{n=1}^{\infty} \pi \left(f\, n \right) \hat{B}_n\, \hat{H}_n\, \sin \phi_n \qquad (9)$$

Here f is the fundamental frequency in Hz, $\hat{B}_n$ and $\hat{H}_n$ the peak values of the nth harmonic and ϕ_n the angle between $\hat{B}_n$ and $\hat{H}_n$. It should be mentioned that neglecting the phase difference under distorted waveforms, especially for the lower harmonics, can lead to errors of more than 30% [40]. Investigations on correction factors for flux waveforms with higher harmonics in induction machines is presented in [41].

For situations where the complete B-H hysteresis loop is available from measurements, it is possible to use the Preisach-model or Jiles/Atherton-model to calculate the hysteresis loop for arbitrary flux density waveforms [42], [43], [44]. It is also possible to regard minor-loops and DC premagnetization by using modifications of these models. They are described in more detail in Section V.

IV. Approaches based on the Steinmetz equation

As mentioned, the classical Steinmetz equation (1) is only valid for sinusoidal flux densities. Thus, several modifications were developed in the last decades to extend the classical Steinmetz equation also for non-sinusoidal waveforms of the flux density caused by power electronic circuits.

It should be pointed out that all the modifications of the Steinmetz equation in the following paragraphs have the well known problem that the Steinmetz coefficients vary with frequency. Thus, for waveforms with high harmonic content, it can be difficult to find applicable coefficients which give good results over the full frequency range of the applied waveform. Furthermore, it should be mentioned that the history of the flux density waveform, which also has an impact on the iron losses, is neglected in the following presentation of the modified Steinmetz equations.

One improvement to the Steinmetz equation for core loss calculation with arbitrary waveforms of the flux density is called *Modified Steinmetz Equation* (MSE) [45], [46]. The idea behind the MSE is to introduce an equivalent frequency which is depending on the macroscopic remagnetization rate dM/dt. Since the remagnetization rate is proportional to the rate of change of the flux density dB/dt, the equivalent frequency based on this change rate is defined as

$$f_{\mathrm{eq}} = \frac{2}{\Delta B^2\, \pi^2} \int_0^T \left(\frac{dB}{dt} \right)^2 dt \qquad (10)$$

with $\Delta B = B_{\max} - B_{\min}$. Combining (10) with the Steinmetz

equation (1) yields

$$p_{\mathrm{Fe}} = C_{\mathrm{SE}}\, f_{\mathrm{eq}}^{\alpha-1}\, \hat{B}^{\beta}\, f_{\mathrm{r}} \qquad (11)$$

where p_{Fe} is the specific time-average iron loss, $\hat{B}$ the peak flux density and f_{r} the remagnetization frequency ($T_{\mathrm{r}} = 1/f_{\mathrm{r}}$). C_{SE}, α and β are the same fitting coefficients as in (1). A DC-bias premagnetization can also be taken into account by introducing a second correction factor. This factor includes two more coefficients which have to be resolved from measurements at different frequencies and magnetizations. A disadvantage of the MSE is that it looses accuracy for waveforms with a small fundamental frequency part.

Another, and also newer modification of the Steinmetz equation is the so called *Generalized Steinmetz Equation* (GSE), described and also compared to the MSE in [47]. This modification of the Steinmetz equation is based on the idea that the instantaneous iron loss is a single-valued function of the flux density B and the rate of change of the flux density dB/dt, without regarding the history of the flux density waveform. A formula is derived which uses this single-valued function and connects it to the Steinmetz coefficients. This yields

$$p_{\mathrm{Fe}} = \frac{1}{T} \int_0^T C_{\mathrm{SE}} \left| \frac{dB}{dt} \right|^{\alpha} |B(t)|^{\beta-\alpha}\, dt \qquad (12)$$

An advantage of the GSE compared to the MSE is that the GSE has a DC-bias sensitivity without the need of additional coefficients and measurements. Further, the GSE can also be used for deriving an equivalent frequency or equivalent amplitude which can be applied in the classical Steinmetz equation (similar to the MSE). For this purpose, different approaches are proposed in [47].

A disadvantage of the GSE is the accuracy limitation if the third or a closely higher harmonic part of the flux density becomes significant, thus if multiple peaks are occurring in the flux density waveform. Because of the minor loops in the hysteresis loop, it can be necessary to take into account analytical hysteresis loss models at this point of operation. To overcome this problem, the previously derived GSE is optimized to the so called *improved Generalized Steinmetz Equation* (iGSE) [48]. The idea of the iGSE is to split the waveform in one major and one or more minor loops to regard the minor loops of the hysteresis loop for the loss calculation. Therefore, in [48], a recursive algorithm is presented which divides the flux density waveform into major and minor loops and calculates the iron losses for each determined loop separately by

$$p_{\mathrm{Fe_x}} = \frac{1}{T} \int_0^T C_{\mathrm{SE}} \left| \frac{dB}{dt} \right|^{\alpha} |\Delta B|^{\beta-\alpha}\, dt \qquad (13)$$

where ΔB is the peak-to-peak flux density of the current major or minor loop of the waveform. A disadvantage of the iGSE is that it does not have the DC-bias sensitivity like the GSE because the iGSE is a function of ΔB instead of $B(t)$.

A similar approach to the iGSE has been published as the *Natural Steinmetz Extension* (NSE) [49], where also the peak-to-peak value of the flux density value ΔB is taken into

account:

$$p_{\mathrm{Fe}} \; = \; \left(\frac{\Delta B}{2}\right)^{\beta-\alpha} \frac{C_{\mathrm{SE}}}{T} \int_0^T \left|\frac{dB}{dt}\right|^\alpha \, dt \qquad (14)$$

In this approach, the waveform is not divided into major and minor loops. Instead it is directly applied to the waveform of the whole period (minor loops in the hysteresis loop are neglected). Thus, it focuses on the impact of rectangular switching waveforms (like PWM).

To sum up the different approaches based on the Steinmetz equation and their coefficients, it can be pointed out that they offer a simple and fast way to predict the iron losses without the need for previous loss measurements of the used material. The Steinmetz coefficients are either directly supplied by the manufactures or can be easily obtained by curve fitting from the manufactures measurement curves. The drawbacks of the introduced approaches are that the Steinmetz coefficients are known to vary with frequency and that the accuracy is in average lower compared to the accuracy of the Preisach hysteresis loss models. Especially at low frequencies, the losses are mainly caused by the hysteresis effect and thus become more or less independent on the waveform. Further, it should be mentioned that only the MSE was investigated for lamination steel sheets of electrical machines [45]. The other Steinmetz based models were designed with a focus on ferrites at higher frequencies and, to the authors' knowledge, they are not tested for SiFe alloys, which are mainly used in electrical machines.

V. Hysteresis models

To obtain a higher accuracy of the iron loss prediction, mathematical hysteresis models can be used if measurements of full hysteresis curves of the investigated material or even more parameters are available. Next to the well documented classical hysteresis models from Preisach [50], [51] and Jiles/Atherton [52], there are several improved and modified iron loss models applicable to steel sheets and complete electrical machines proposed in the literature. Generally, they require more measurements and material data of the electrical steel sheets but also give better results in terms of accuracy and allow more complex simulations compared to the simpler Steinmetz models. Some applicable improved and modified hysteresis models are amongst others the dynamic Preisach model, the Loss Surface model, the Magnetodynamic Viscosity Based model, the Friction Like Hysteresis model and the Energy Based Hysteresis model. They are discussed in more detail in the following. Since a detailed description of the Preisach model is beyond the scope of this paper, the reader is referred to relevant literature [51].

The dynamic Preisach model extends the classical Preisach model by introducing a rate dependent factor for each elementary rectangular loop of the hysteresis model [51], [53], [54]. This rate dependent factor takes the delay time of the induction $B(t)$ behind the magnetic field $H(t)$ into account. In this way, it is possible to regard the enlargement of the hysteresis loop with increasing frequency and, thus, also model the excess losses by using a dipole function that can take every

value between -1 and $+1$ (in the classical Preisach model the dipole function can just become -1 or $+1$). The function for determining the dipole values is a function of the material and determined from dynamic hysteresis measurements. In [55], [56], the dynamic Preisach model for iron loss calculations in electrical machine cores is compared for different numerical implementations using the finite-element method.

Another dynamic and scalar hysteresis model, the Loss Surface model, is presented in [57]. The magnetic field H is determined as a characteristic surface function

$$S \; = \; H(B, \frac{dB}{dt}) \; = \; H_{\mathrm{stat}}(B) \; + \; H_{\mathrm{dyn}}\left(B, \frac{dB}{dt}\right) \qquad (15)$$

separated into a static and a dynamic part. B is the magnetic flux density and dB/dt its rate of change. The model connects the magnetic field H on the sheet surface with the flux density B in the thickness of the sheet. The static part is modeled by the classical (static) Preisach model (rate-independent), which is determined by measurements of the major loop and first order reversal curves. The dynamic part is modeled by two linear analytical equations describing the low and high values of the flux density derivatives after subtracting H_{stat}. Both linear equations are connected by a second order polynomial to connect them steadily. This model is also implemented in the finite element software Flux (Loss Surface model) for a number of common electrical steels [58].

A similar model to the Loss Surface model is the Magnetodynamic Viscosity based model [59]. It is also based on a static (rate-independent) Preisach hysteresis model but uses a viscous type differential equation for describing the delay time between the induction $B(t)$ and the magnetic field $H(t)$. This differential equation determines the shape of the dynamic part of the loop and the dynamics of the model to take the excess losses into account. The needed material data for this model are the static major hysteresis loop and first order reversal curves, as well as two dynamic loops together with the sheet thickness and its resistivity.

The Friction like Hysteresis model (an approach based on hysteresis vectors with dry friction like pinning) uses the properties from the Preisach model as well as from the Jiles/Atherton model [60]. It is assumed that the magnetization is a superposition from the contribution of a large number of particles. The free energy of these particles is assumed to be summed up by the virgin curve behavior for the constitution law between the magnetic field H and the magnetization M as well as a ripple. This ripple represents the influence of domain wall movements and bendings which leads to the minor loops and the hysteresis behavior. The model is tested and investigated in more details in [61].

A similar method is described in [62] and applied in [63]. The hysteresis behavior is modeled based on an energy approach where the magnetic dissipation from the macroscopic point of view is represented by a friction-like force. In this way, the stored magnetic energy as well as the dissipated energy are known at all times. Since this vector model is purely phenomenological, it can also be used for 3D numerical analysis of rotational hysteresis losses.

Table II
COMPARISON OF INVESTIGATED IRON LOSS MODELS.

Iron loss model	Complex waveforms	Rotating field	Material prior knowledge	Accuracy
Steinmetz Equation (SE)	−	−	small	low
Modified Steinmetz Equation (MSE)	+	−	small	low-medium
Improved Generalized Steinmetz Equation (iGSE)	+	−	small	low-medium
Static/Dynamic Loss Separation model	−	−	medium	medium
Dynamic Preisach model	+	−	high	good
Loss Surface model	+	−	high	good
Magnetodynamic Viscosity Based model	+	−	high	good
Friction Like Hysteresis model	+	+	high	good
Energy Based Hysteresis model	+	+	high	good
Loss separation after magnetizing processes	+	+	model dependent	model dependent

VI. Results

There is a wide range of models available for determining iron losses in electrical machines. These models differ in several aspects and are designed for different purposes. The models based on the Steinmetz equations and the loss separation models (Jordan, Bertotti) are preferable and best suited for fast and rough iron loss determinations as well as comparison of different materials for a certain electrical machine. They can be easily integrated in finite-element simulations (post-processing) where the time variation of the flux density $B(t)$ is determined for every element.

In contrast to this, the complex hysteresis loss models are more suitable for an exact iron loss determination in the machine design and evaluation process. These models need much more knowledge about the material data or prior material measurements as well as more information about the flux density waveforms in the machine. Furthermore, the integration into finite-element software is more complicated (especially if it is part of the solving process), but the results have generally also a higher accuracy.

Table II gives an overview of the presented iron loss models in terms of possibility for complex (higher harmonics) and non-sinusoidal flux density waveforms, rotating fields consideration, necessary knowledge about the material and the relative accuracy of the model in general.

VII. Conclusion

In this paper, useful information for regarding iron losses in electrical machines were presented. The aim is to provide machine designers and system engineers with ideas for integrating suitable iron loss models into the machine design process and simulations. Several models based on different approaches and of different complexity and field of applications were discussed and compared. The results were summed up to give the electrical engineers an overview and help for choosing a suitable model for the machine design and simulation processes.

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