COMPARISON OF STATIC HYSTERESIS MODELS SUBJECT TO ARBITRARY MAGNETIZATION WAVEFORMS

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Abstract **– Critical to the accurate calculation of magnetization dynamics and iron losses in soft magnetic steel sheets is the description utilized to emulate the static hysteresis loop shape. This paper compares different static history independent hysteresis models (mathematical, behavioural as well as physical based ones) and a history dependent hysteresis model in terms of parameter identification effort and accuracy. The analysis shows that the resulting accuracy of the different hysteresis models is strongly dependent on the excitation waveform, i.e., smooth excitations, distorted flux waveforms, transients or steady-state regimes. This allows to select the most-suited hysteresis model for the sought for application and appraise the individual limitations.**

I. INTRODUCTION

Accurate modelling of soft magnetic hysteresis loops for arbitrary excitation regimes is essential in applied engineering. Adequate prediction of dynamic magnetization curves and power losses is critical for the improvement and design of various electromagnetic energy converters. Critical to accurate prediction is the static description of the hysteresis phenomena in soft magnetic steel sheets, i.e., the static hysteresis model. Most engineering applications demand the extension of a static hysteresis model by adding various dynamic terms, where different modelling approaches were developed. The prediction of extended dynamic models, however, depends heavily on the utilized static hysteresis model [1]. In particular, for arbitrary magnetization regimes it is essential that the static hysteresis model reflects the physical behaviour of the magnetization process as accurate as possible.

The development of static hysteresis models started almost a century ago. However, the complex underlying physical mechanisms as well as generally conflicting demands regarding accuracy, simplicity, and physical behaviour led to numerous very different modelling approaches. For engineering applications major driving forces are the ability to describe the various static hysteresis curves and loops and determine related energy loss due to magnetization processes.

Initially magnetic hysteresis loops were modelled using mathematical models, which can reproduce the magnetization curves well, but ignore underlying physics of the magnetic material behaviour. Such models instead rely on empirical techniques involving identification of their parameters. Representatives of this group are, e.g., the well-known Preisach model [2] and its successors or the Stop- and Play-models [3].

Later on, physically-based models such as the energy-based hysteresis models [4] were developed. Likewise, the field-separation principle advanced in [5] can be identified with the afore-mentioned descriptions of magnetic hysteresis. These energy-based descriptions obtain the hysteresis loop branches by the introduction of an offset along the *H*-axis. The advantage of these models is that they are consistent with the laws of irreversible thermodynamics. This is particularly interesting for engineers, who need reliable hysteresis models based on sound physical grounds.

One of the most cited and used model is the Jiles-Atherton (J-A) model [6]. The popularity of this model for engineering applications increased largely due to specific advantages such as relatively small number of parameters and good computational performance. However, for the J-A model, there are still shortcomings with the identification of the model's parameter and its stability [7]. Particularly when modelling distorted and irregular hysteresis loops, the deviation between modelled and measured loops is often not adequate.

As an alternative to the aforementioned models, transplantation type hysteresis models were proposed. Such models are based directly on measured major loops and/or first-order reversal curves and are good candidates for use in applied engineering. In this group the best known are the Zirka-Moroz (Z-M) hysteresis models, which are developed both in history independent as well as history dependent [8] versions. The history dependent version has a significant advantage over history independent models especially for applications with complex magnetization curves (e.g. PWM-like excitation waveforms in modern power electronics fed converters). The inclusion of the memory property can lead to physically correct magnetization curve predictions, but at the expense of the simplicity of the model.

Amongst the transplantation type of models also the Tellinen (TLN) hysteresis model can be considered [9]. Due to its promising blend of simple use, identification and implementation along with reasonable predictions it is also a good candidate for engineering use.

Large amount of developed hysteresis models leads to many possible choices for individual engineering application. Despite all the hysteresis models try to predict the same phenomena, they do this using completely different approaches. Consequently their internal mechanisms to predict intrinsic magnetization curves differ significantly also, despite similar prediction of major loops. The aim of this paper is therefore to provide a comprehensive analysis and comparison of most popular static hysteresis models in terms of identification, implementation, computational performance and accuracy.

II. STATIC HYSTERESIS MODELS

In this paper the so-called primal or inverse versions of discussed static hysteresis models are evaluated, where time-dependent magnetic flux density $B(t)$ plays the role of the independent variable. In this form the hysteresis models enable straightforward implementation in various extended model, such as e.g. FEM or the PMD model [10]. In this paper popular and promising representatives from discussed hysteresis models are evaluated: namely the Stop and Play models [3], the J-A hysteresis model [6], the GRUCAD hysteresis model [5], both the history independent and depended versions of the Z-M model [7] and the TLN hysteresis model [9].

III. IMPLEMENTATION AND PARAMETER IDENTIFICATION

The models were implemented using the Matlab/Simulink simulation software. This software package enables straightforward implementation and is popular in applied engineering. Effective calculation is obtained by using Matlab's variable step solver ode23tb (TR-BDF2 method).

When comparing the discussed models in terms of the identification, the J-A and GRUCAD model have the most challenging parameter identification, whereas the TLN, Z-M, Stop and Play model can be simply identified directly from standardized quasi-static measurements or alternatively from calculated loops using any other static hysteresis model. In this paper all the hysteresis models were identified based on a measured quasi-static major hysteresis loop of B_{max} = 1.5T.

IV. RESULTS

The discussed static hysteresis models were compared and evaluated under complex excitation waveforms. In this way, predictions of complex magnetization curves of individual hysteresis models are directly compared as well as evaluated versus measurements. Determination of the best fit between calculated curves and measurements is very challenging; to evaluate the goodness of fit graphical as well as numerical measures are used. The simpler and often more adequate approach is using graphical measures that easily display a wide range of relationships between magnetization curves of different models. In contrast to the graphical approach, various numerical measures should be used with care, as they often compress too much information into a single number and can quickly become useless or even misleading. For example, quantitative metrics such as losses cannot show where the deviation of different intrinsic magnetization curves is the biggest. In order to support the graphical evaluation in this paper the normalised root mean square (NRMS) deviations for individual magnetization curves are calculated also. In this way a comprehensive analysis that shows intrinsic mechanisms to predict magnetization curves of individual models is provided.

Differences between model predictions for PWM-like excitations are clearly visible in Fig. 1, where due to limited space only TLN, J-A, Z-M and Stop model magnetization curves are shown. It is quickly apparent that proposed analysis provides advantages as well as limitations of the discussed models.

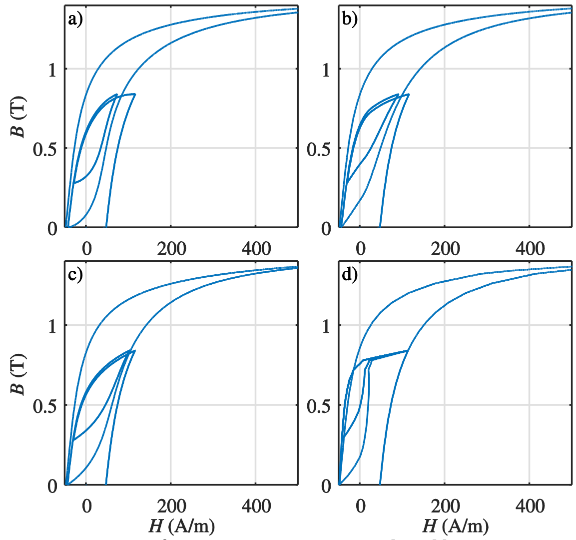

Fig.1. Comparison of magnetization curves predicted by: a) TLN model, b) J-A model, c) Z-M history independent model and d) Stop model

V. CONCLUSION

The presented analysis shows differences in intrinsic mechanisms to predict magnetization curves of the majority of the well-known static hysteresis models. The results are essential when selecting the most-suited hysteresis model for a specific application.

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