# Iron-Loss Modelling based on a Loss-Separation Approach in Modelica

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**In many electromagnetic energy conversion processes, transformers or electric machines are controlled with modern power converters at high frequencies up to a range of several 10 kHz. Such operation modes lead to not negligible, distinct iron losses in the flux-leading laminated core. For estimating iron losses, no universally valid equation is available covering transient effects and nonlinear magnetization processes at the same time for a wide frequency range. Sophisticated models in 2D and 3D are available but these hysteretic models are computationally very intensive when applied in a finite elements method (FEM).**

**This work presents a 1D iron-loss model, which allows estimating the static and dynamic hysteresis losses during the electromagnetic energy conversion processes with low computational effort. The model is based on a loss-separation approach, in which the different magnetization-loss mechanisms are interpreted corresponding to an analogous mechanical model. The proposed approach is implemented in Modelica; the model setup and the simulations are performed in Dymola. The validation of the developed iron-loss model is performed with measurements conducted on an Epstein frame.**

***Index Terms*— Electromagnetic energy conversion, iron losses, static and dynamic hysteresis losses, loss-separation approach, Modelica.**

## I. INTRODUCTION

POWER transformers, generators and electric machines show already good energy efficiency compared to thermodynamic energy conversion applications. Nevertheless, loss optimization is still an important issue, since pulsed operation modes at high frequencies lead to considerable iron losses in the laminated core. Many approaches use empirical formulas to estimate these iron losses. However, such empirical formulas have only a limited range of validity and so far, no universally valid equation is available covering characteristic physical effects like higher harmonics (evoking eddy losses) and nonlinear magnetization processes (e.g. hysteretic effects) at the same time for a wide frequency range [1]. To overcome this issue, physical and parametrizable iron-loss models are required but hysteretic models are computationally very intensive when applied in a Finite Elements Method (FEM). This paper introduces a physical and parametrizable iron-loss model based on a loss-separation approach, in which the different magnetization loss mechanisms are interpreted corresponding to an analogous mechanical model [2]. This approach is suitable to be implemented as 1D loss model in Modelica using Dymola [3].

## II. MODEL STRUCTURE

The physical modeling is based on the description of the behavior of spatial areas in ferromagnetic materials (so called magnetic domains) when an external magnetic field is applied to a probe. In a simplified theory the domain structure consist only of antiparallel adjacent domains separated by their domain walls. When an external magnetic field is applied, the domain walls start to bend firstly. If the external magnetic field is further intensified, the number of domains in direction of the field increase while the antiparallel domains decrease. This displacement of the domain walls is not occurring continuously but jerkily and when the magnetic field is turned-off, the borders remain in their new positions. This leads to the static hysteretic effect and the energy spent for moving the domain walls is irreversibly lost. However, if the applied external magnetic field is increased instead, then all field-parallel domains are maximized and the antiparallel areas are minimized in their dimensions. This leads to a saturation of the ferromagnetic material. If the external magnetic field applied to a ferromagnetic probe alternates, additional irreversible dynamic losses (so called eddy losses) arise in the magnetic material representing the dynamic hysteresis losses.

### A. Loss-separation approach

The magnetization effects addressed above can be modeled properly with an analogous mechanical loss model by using a loss-separation approach. This requires distinguishing between the irreversible static and the dynamic hysteresis losses. Thereby, a dry mechanic friction force describes the force, which moves a domain wall jerkily (i.e. static hysteretic effect), whereas mechanic damping elements model the viscosity-like dynamic friction losses. To consider also the saturation effect and the reversible anhysteretic behavior, a modified mechanic spring element with nonlinear (e.g. arctangent) characteristics is introduced [4]. Fig. 1 (left) illustrates the analogous mechanical loss model. The amount of the displacement of the mechanical oscillating system (i.e. the position) and its derivative (i.e. the velocity) correspond to the magnetization $M$ in T and its rate of change $\dot{M}$, respectively. The impressed force on the bottom node corresponds to an externally applied magnetic field (strength) $H$ in A/m. The external field can be split into three associated magnetic field strengths denoting $H_r$ as the internal anhysteretic field, $H_e$ as field strength originating from the local dynamic eddy losses and $H_f$ originating from the quasistatic dissipation due to the domain wall movements.

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Hence the loss-separation approach enables to estimate the irreversible dynamic and static iron losses. Equation (1) shows the differential equation based on the first law of thermodynamics expressing the occurring power densities.

$$\dot{W}_{\mathrm{u}} = \dot{W}_{\mathrm{w}} + \dot{W}_{\mathrm{q}} \tag{1}$$

The internal power density on the left hand in (1) origins from the stored internal energy in the spring element. In (1) on the right hand side, the first term is the developed convertible power which origins from the applied external magnetic field. The second term describes the dissipation, determining the dynamic and static hysteresis losses as written in (2)

$$\dot{W}_{\mathrm{q}}(M) = -\lambda\left(\dot{M}\right)^{2} - \kappa\left|\dot{M}\right|, \tag{2}$$

implying $H_e = \lambda\,\dot{M}$ and $H_f = \kappa\,sign(\dot{M})$ [2]. In order to improve the model behavior for different magnetic materials, several hysteresis cells can be connected in series whereupon the amplitudes $\lambda$ and $\kappa$ are the crucial material parameters to be identified. A suitable parameter-identification approach used in this work is introduced in [1].

### B. *Model implementation in Modelica using Dymola*

Fig. 1 (right) depicts the arrangement of e.g. three analogous mechanical hysteresis cells to a lossy permeance in Dymola. All circuit elements except the developed hysteresis cells are available in the Magnetic library [5] of the Modelica Standard Library (MSL). The hysteresis cells are modeled in the style of their equivalents available in the Mechanics-MSL [6], but with substituted variables, however. Further details about the model implementation are presented in the full paper.

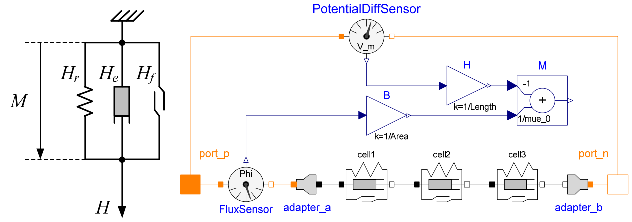

Fig. 1. Analogous mechanical loss model based on a loss-separation approach (left) and Dymola implementation of the analogous mechanical loss model (right).

## III. SIMULATION RESULTS AND VALIDATION ON AN EPSTEIN TEST FRAME

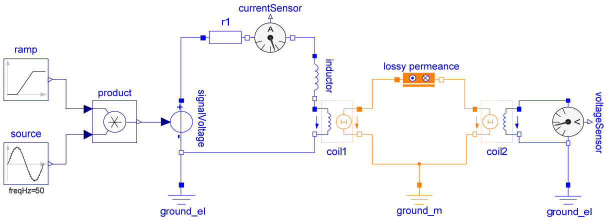

Fig. 2. Dymola application of the lossy permeance in the Epstein frame model.

Fig. 2 depicts the implementation of the lossy permeance model in an Epstein frame implemented in Dymola and parameterized for an iron sheet (type M400-50A) with standard quality [7]. The simulation set-up enables different operation modes e.g. pure sine mode or converter operation mode. The simulation results for two different operation modes, shown in Fig. 3 (left: sine-operation mode, right: 2-level-converter mode), emphasize that internal loops and minor loops phenomena are reflected correctly. The static and dynamic iron losses, implemented and calculated according (2), are available as output quantities during the simulation run. To validate the simulation results gained for the iron sheet type M400-50A, Epstein frame measurements [8] were performed for sine-operation mode and 2-level-inverter mode.

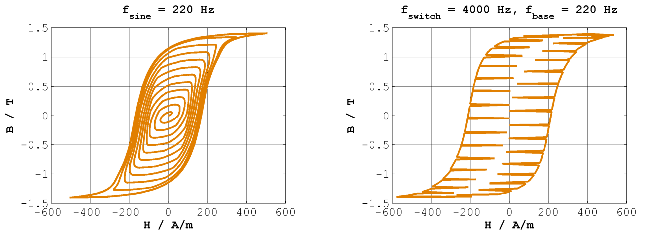

Fig. 3. Simulated internal loops under sine-operation mode (left) and simulated minor loops under 2-level-converter mode (right).

Further details about the set-up and the conducted measurements on the Epstein frame, the applied parameterization method as well as the estimated iron losses and the quality of the gained simulation results compared to measured data are discussed in the full paper.

## IV. CONCLUSION

Up to now, no commercial FEM-tool for the calculation of losses in ferromagnetic materials is available, which considers saturation as well as dynamic and static hysteretic effects at the same time with low computational effort. This paper outlines the application of a physical and parametrizable iron-loss model based on an analogous mechanical loss-model approach. Using Modelica as object-oriented description language, a 1D model is set-up in the simulation environment Dymola. The model is then used to simulate the iron losses for a standard quality iron sheet during different operation modes. The gained simulation results are compared and validated with measurements conducted on an Epstein frame. With the proposed model approach, transient effects as well as hysteresis behavior and hence iron losses can be considered correctly and with less computational effort.

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