

An Efficient Hysteresis Loss Evaluation Considering Magneto-Elastic Effects using the Stepwise Monotonic Hysteresis Model

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In this paper, the stepwise monotonic hysteresis model is used to evaluate the hysteresis losses in synchronous machines under the influence of mechanical stress, thereby needing only a single magnetostatic simulation. The mechanical stress is considered by using a magneto-elastic vector hysteresis model within the finite element formulation. The loss evaluation is applied on a permanent magnet synchronous machine affected by a mechanical stress state induced by manufacturing. The results are compared to a full transient model and show a good agreement while only needing a fraction of the computational time related to a transient simulation.

Index Terms—Computational electromagnetics, Energy-based vector hysteresis, Finite element analysis, Loss models

I. INTRODUCTION

IN synchronous machines, it is of importance to consider the magnetic material behavior in the iron yoke. Crucial losses are due to the hysteresis effect. Simulating the magnetic field strength $\mathbf{H}$ and the magnetic flux density $\mathbf{B}$ under the influence of the hysteretic effect can be time-consuming. Moreover, precise material models require to model even more complicated phenomena such as the influence of mechanical stress on the iron yoke, which increases the computational cost. There exist various methods to evaluate the hysteresis loss that avoid that. One prominent approach is to calculate the losses in a post-processing step using empirical models, like the Steinmetz or Bertotti formulae [1]. Another approach is to execute an anhysteretic finite element simulation and put the obtained values for $\mathbf{H}$ into a parametrized hysteresis model that is decoupled from the actual simulation [2]. The most straightforward method is to simulate every single time step using a *Full Transient Model* (FTM) where the hysteresis model is incorporated into the Finite Element (FE) Formulation [3]. However, these methods either can not or have to be extended to cope with mechanical stress [4], do not include the hysteresis model in the simulation or are computationally costly. In this paper, a magneto-elastic vector hysteresis model being the combination of the *Simplified Multiscale Model* (SMSM) and the *Vector Play Model* (VPM) is briefly described. It is used in combination with the *Stepwise Monotonic Hysteresis Model* (SMHM) to evaluate the hysteresis loss needing only a single magnetostatic simulation. The method is demonstrated on a permanent magnet synchronous machine and compared to the FTM.

II. MAGNETO-ELASTIC VECTOR HYSTERESIS MODEL

In this work, the SMSM in combination with the VPM is used to simulate the magnetic behavior under the consideration of mechanical stress, magnetostriction, material anisotropy, and

crystallographic texture [5]. The SMSM takes local variations of $\mathbf{H}$ and the mechanical stress $\boldsymbol{\sigma}$ as inputs and approximates the material as a collection of magnetic domains, initially randomly oriented, to obtain the magnetization $\mathbf{M}$. This gives the anhysteretic characteristics of the material. To model the dissipation, the VPM is used. It takes the information about the anhysteretic curve and approximates the energy-based hysteresis model by applying the following update rule for the reversible part of the magnetic field strength $\mathbf{H}_{\text{rev}}$

$$\mathbf{H}_{\text{rev}} = \begin{cases} \mathbf{H}_{\text{rev,p}} & \text{if } \mathbf{H} - \mathbf{H}_{\text{rev,p}} \leq \kappa \\ \mathbf{H} - \kappa \frac{\mathbf{H} - \mathbf{H}_{\text{rev,p}}}{|\mathbf{H} - \mathbf{H}_{\text{rev,p}}|} & \text{otherwise,} \end{cases} \quad (1)$$

where p indicates the previous time step and κ is the pinning force that counteracts the magnetization of the material. To obtain $\mathbf{M}$, the reversible magnetic field strength and the mechanical stress is put into the SMSM

$$\mathbf{M} = \text{SMSM}(\mathbf{H}_{\text{rev}}, \boldsymbol{\sigma}). \quad (2)$$

III. STEPWISE MONOTONIC HYSTERESIS MODEL

This method takes the core idea of [6] stating that for synchronous machines in stationary operation, the magnetic field rotates at the mechanical speed ω_m . Hence, the angular position φ and time t are related by $\varphi = \omega_m t$. Accordingly, the discrete time evolution of the magnetic field strength $\mathbf{H}(r, \varphi, t_n) = [H_r \ H_\varphi]^\top$ can be expressed in polar coordinates by results of a single magnetostatic simulation

$$\mathbf{H}(r, \varphi, tn) = \mathbf{H}(r, \varphi_0 - n\varphi_{\text{pitch}}, t_0) \quad (3)$$

$$t_n = t_0 + nt_{\text{pitch}} \quad (4)$$

$$n = 1, 2, \dots, N_{\text{slot}}, \quad (5)$$

where $t_{\text{pitch}} = \varphi_{\text{pitch}}/\omega_m$ and the pitch angle $\varphi_{\text{pitch}} = 2\pi/N_{\text{slot}}$. To overcome interpolation issues, for a stator with N_{slot} slots, a single slot pitch is meshed, which is the reference

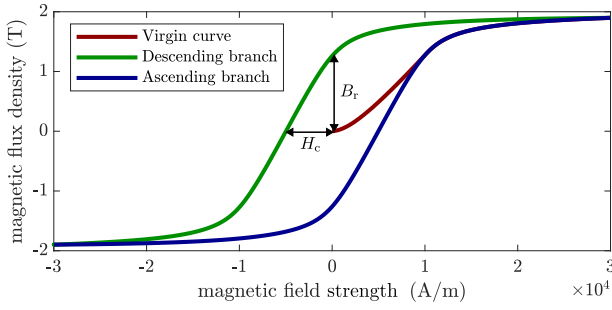


Fig. 1. Hysteresis loop subdivided in three parts: the virgin curve, the descending branch and the ascending branch.

slot with reference angle φ_0 , and is copied N_{slot} times. Then, features the same mesh and $\mathbf{H}$ can be evaluated without mesh interpolation. The actual SMHM is divided into three steps: In step 1, a single magnetostatic simulation is executed using the material model described in Section II within the FE formulation. This yields a magnetic field distribution where all field values lay on the virgin curve (Figure 1, red line). In step 2, $\mathbf{H}(r, \varphi, t_n)$ is evaluated by using (3) in all elements of the reference slot pitch. In step 3, the stationary hysteresis behavior is determined. The maximum values define the reversal points on the virgin curve and thus the first-order reversal curves (FORCs) (Figure 1, green line, blue line). This can be done since as long the magnetic field strength changes monotonically, the FORCs are independent of the waveform of $\mathbf{H}$. This gives the corresponding values of $\mathbf{B}$. The hysteretic power loss P_{hyst} is then evaluated by integrating the energy density $w_{\text{hyst}} = \int_C \mathbf{H} \cdot d\mathbf{B}$ over the stator domain and divided by the time span of one rotor rotation.

IV. NUMERICAL RESULTS

A 6-pole 26-slot permanent magnet synchronous machine (PMSM) serves as an example (Figure 2). A mechanical stress is introduced by the press fit of the stator within the housing and the rotor onto the shaft. This stress distribution is calculated for prescribed radial displacements of the outer surfaces of the stator and rotor, yielding the stress state shown in Figure 2. The motor is excited by a current $I = 19.8$ A at 50 Hz, corresponding to a synchronous speed of 1000 rpm. The permanent magnets have a remanence $B_r = 0.5$ T. The mesh has 21370 triangular elements. The proposed SMHM combined with the magneto-elastic vector hysteresis model is compared to a *Full Transient Model* (FTM) from and the *Bertotti Model* (BM) concerning its accuracy and computational efficiency. The comparison for the considered PMSM is shown in Table I. For both cases with and without stress, the SMHM attains a technically sufficient accuracy at a substantial lower computational cost. Moreover, the results illustrate the importance of taking the stress configuration into account.

V. CONCLUSION

The *Stepwise Monotonic Hysteresis Model* yields accurate results in a fraction of time compared to the *Full Transient Model* as it needs only a single magnetostatic simulation of the synchronous machine. It is shown that the *Stepwise Monotonic Hysteresis Model* can deal with the inclusion of a mechanical

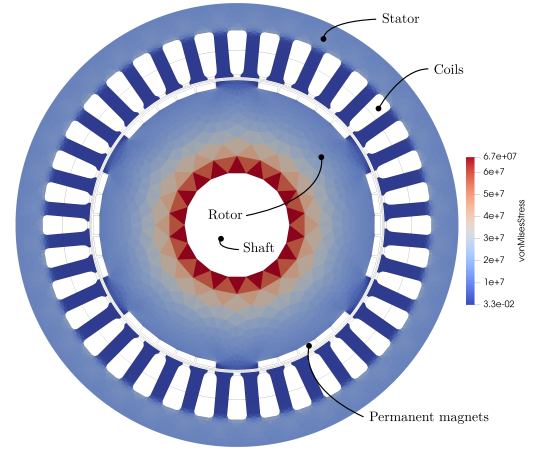


Fig. 2. Considered 6-pole, 36-slot permanent magnet synchronous machine and mechanical stress state expressed by the von Mises stress in Pa.

TABLE I
EVALUATED POWER LOSS FOR EACH METHOD.

Method	Unit	BM	FTM	SMHM
$P_{\text{hyst}, \sigma=0}$	W	11.40	16.16	14.15
$P_{\text{hyst}, \sigma=\sigma_{\text{sim}}}$	W	18.48	20.15	20.25
$t_{\sigma=0}$	sec	208.34	10335.33	203.86
$t_{\sigma=\sigma_{\text{sim}}}$	sec	174.35	10582.76	175.05

stress state by using the *Simplified Multiscale Model* in the description of the behavior of the magnetic material. This results in a more general evaluation of the hysteresis losses in synchronous machines.

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