

A Macroscopic Magneto-Elastic Vector Hysteresis Model for Electromagnetic Device Simulations

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In this work, the Simplified Multiscale Model (SMSM) is integrated into the energy-based vector hysteresis framework and represents anhysteretic material behavior, enabling the inclusion of effects such as mechanical stress, magnetostriction, material anisotropy, and crystallographic texture into hysteretic simulations. This combination allows for detailed material information to be utilized while accounting for dissipative effects. This methodology is applied to a permanent magnet synchronous machine (PMSM), including rotor rotation and the influence of mechanical stresses, demonstrating its effectiveness in modeling complex magnetic phenomena in electric machines.

Index Terms—Computational electromagnetics, Energy-based vector hysteresis, Finite element analysis, Maxwell equations, Multiscale modeling, Numerical simulation

I. INTRODUCTION

THE accurate simulation of electrical devices, such as electric machines and transformers, requires advanced material models that account for effects like mechanical stress, magnetostriction, material anisotropy, and crystallographic texture. Standard models often fail to capture these complexities, necessitating more sophisticated approaches to ensure accurate predictions of material behavior and device performance.

This work integrates the Simplified Multiscale Model (SMSM) into the energy-based (EB) vector hysteresis framework, combining the SMSM's ability to model reversible (anhysteretic) material behavior under mechanical and magnetic excitations [1] with the EB's strengths in capturing dissipative effects, including anisotropic hysteresis behavior. A dissipative approximation, the Vector Play Model (VPM), serves as an efficient and explicit substitute for the full EB energy minimization problem [2]. Although approximate, the VPM exhibits minor differences from the full model while significantly reducing computational cost, especially when evaluating global properties like hysteresis losses.

In the following sections, we briefly discuss the integration of the anhysteretic SMSM into the VPM (denoted as SMSM+VPM) and then describe the finite element (FE) formulation employed for PMSM simulations.

II. SMSM+VPM MATERIAL MODEL

The SMSM [1] offers a computationally efficient approximation of the material behavior using the magnetic field strength $\mathbf{H}$ and mechanical stress tensor $\boldsymbol{\sigma}$ as an input. For algorithmic clarity, we represent SMSM as an operator

$$(\mathbf{M}, \epsilon^\mu) = \text{SMSM}(\mathbf{H}, \boldsymbol{\sigma}), \quad (1)$$

omitting material parameters from the notation for brevity. Detailed parameter descriptions can be found in [1].

On the dissipative side, the VPM approximates the full EB model's minimization by providing a quick update rule for the reversible field $\mathbf{H}_{\text{rev}}$ based on the new excitation $\mathbf{H}$, the previous reversible field $\mathbf{H}_{\text{rev,p}}$ and the pinning force κ :

$$\mathbf{H}_{\text{rev}} = \begin{cases} \mathbf{H}_{\text{rev,p}} & \text{if } \mathbf{H} - \mathbf{H}_{\text{rev,p}} \leq \kappa \\ \mathbf{H} - \kappa \frac{\mathbf{H} - \mathbf{H}_{\text{rev,p}}}{|\mathbf{H} - \mathbf{H}_{\text{rev,p}}|} & \text{otherwise} \end{cases} \quad (2)$$

Here, the direction of magnetization change ($\mathbf{M} - \mathbf{M}_{\text{prev}}$), with $\mathbf{M}$ as one output of $\text{SMSM}(\mathbf{H}, \boldsymbol{\sigma})$ is identified with the direction of the irreversible field, and the current reversible field is replaced by the previous one to achieve a rapid but accurate approximation of the dissipative behavior.

III. FINITE ELEMENT FORMULATION

In this work, the hysteretic reduced scalar potential formulation described in [3] is used. It can be summarized as the following minimization problem

$$\mathbf{H} = \underset{\mathbf{H} \in H(\text{curl})}{\text{argmin}} \left\{ \int_{\Omega} w_C(\vec{H}) \right\}, \text{ s.t. } \nabla \times \mathbf{H} = \mathbf{J}_i \text{ on } \Omega, \quad \mathbf{n} \times \mathbf{H} = \mathbf{0} \text{ on } \Gamma_H. \quad (3)$$

with the magnetic pseudo (because it includes dissipative parts) co-energy density functional w_C . Using variational principles, the following functional $\mathcal{F}$ can be defined

$$\mathcal{F}(\phi) := \int_{\Omega} \nabla \phi' \cdot \mu_0 (\mathbf{H} + \underbrace{\mathbf{M}(\mathbf{H})}_{\text{SMSM}(\mathbf{H}, \boldsymbol{\sigma})}) = 0 \quad \forall \phi' \in V, \quad (4)$$

where $\mathbf{M}(\mathbf{H})$ is the output of the SMSM operator. After applying the Newton Raphson scheme described in [3], the

TABLE I
POWER LOSS PER CYCLE (ONE 360° ROTATION OF THE STATOR FIELD),
EVALUATED IN THE ROTOR AND STATOR SEPARATELY.

	SMSM+VPM without stress (W)	SMSM+VPM with stress (W)	rel. difference (in %)
Rotor (without rotation)	1.662	1.759	5.512%
Stator (without rotation)	7.736	10.814	28.456%
Rotor (with rotation)	1.112	1.149	3.173%
Stator (with rotation)	16.160	20.148	19.796%

final weak form reads as: for a given source field $\mathbf{H}_s$, find $s \in V := \{u \in H^1(\Omega) : u = 0 \text{ on } \partial\Omega\}$

$$\int_{\Omega} \nabla \phi' \cdot \frac{\partial \mathbf{B}(\mathbf{H}_k)}{\partial \mathbf{H}_k} \cdot \nabla s = \int_{\Omega} \nabla \phi' \cdot \mathbf{B}(\mathbf{H}_k) \quad \forall \phi' \in V, \quad (5)$$

where s and $\mathbf{H}_k$ represent the Newton step and the field at iteration k , respectively and $\mathbf{B}(\mathbf{H}_k) = \mu_0(\mathbf{H}_k + \mathbf{M}(\mathbf{H}_k))$.

IV. NUMERICAL EXAMPLE

To highlight the importance of including mechanical stress states using the SMSM, a PMSM is considered (Fig.1). For the stress state, a mechanical simulation was conducted to model a press fit of the rotor and stator sheet onto a rod or casing by prescribing a radial displacement at the rotor's inner and stator's outer edge, resulting in the stress distribution shown in Fig. 2. Two simulations are carried out: one without rotor rotation and another with rotor speed $n_{\text{rotor}} = 1000 \text{ min}^{-1}$.

The stator windings carry a time-varying current density $\mathbf{J}_i(t) = J_i \sin(2\pi f t + \phi_i)$, where $\phi_i \in 0^\circ, 120^\circ, 240^\circ$, $J_i = 1.7515 \times 10^5 \text{ A/m}^2$, with $f = 50, \text{ Hz}$. The permanent magnets are set to a remanence of $B_r = 0.5 \text{ T}$.

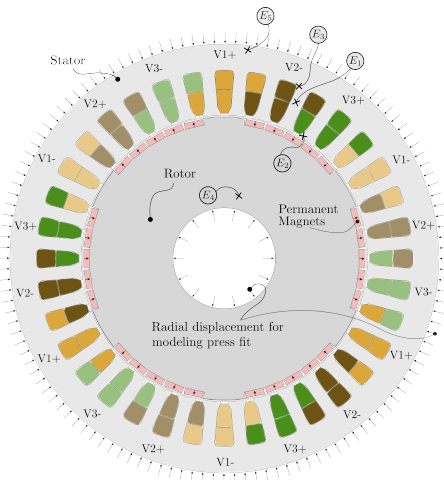


Fig. 1. Geometry of the simplified PMSM with $V_{1,2,3}$ as the three stator windings.

Table I reports the integrated hysteresis power loss over the stator and rotor regions. The inclusion of mechanical stress (via SMSM) shows a noticeable impact on hysteresis losses under both stationary and rotational conditions.

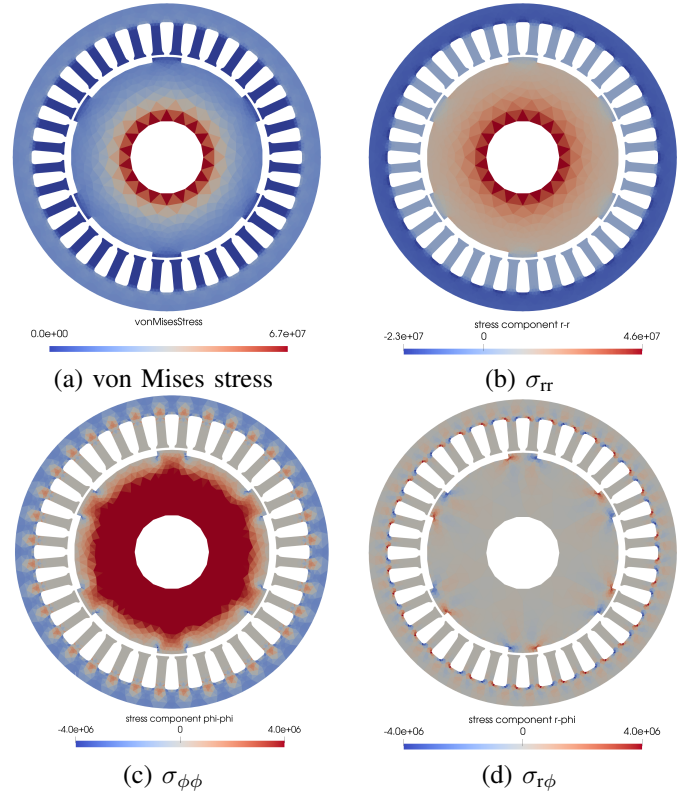


Fig. 2. Mechanical stress (in Pa) after prescribing a purely radial displacement at the rotor's inner and stator's outer edge.

V. CONCLUSION

The inclusion of mechanical stress significantly influences hysteresis losses under realistic operating conditions, as demonstrated in this work. Although SMSM+VPM introduces some computational overhead, it provides a path towards a more accurate use of material models in electromagnetic device simulations. Future work will involve using an extended SMSM model including effects such as crystallographic texture. However, increasing model complexity also elevates computational demands, and thus methods to accelerate the evaluation of the SMSM operator, such as constructing surrogate models, must be explored.

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