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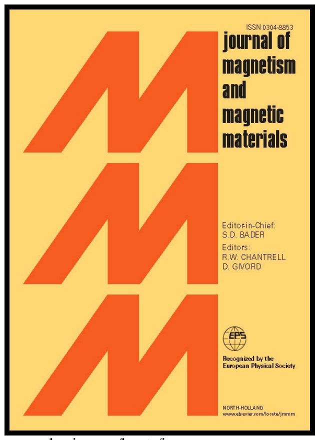

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Energy-Based Ferromagnetic Material Model with Magnetic Anisotropy

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Abstract

Non-oriented soft magnetic materials are commonly assumed to be magnetically isotropic. However, due to the rolling process a preferred direction exists along the rolling direction. This uniaxial magnetic anisotropy, and the related magnetostriction effect, are critical to the accurate calculation of iron losses and magnetic forces in rotating electrical machines. This paper proposes an extension of an isotropic energy-based vector hysteresis model to account for these two effects.

Index Terms: Hysteresis modeling, magnetic anisotropy, magnetostriction, thermodynamics.

I. INTRODUCTION

Non-oriented soft magnetic materials are widely used as a basic constituent in rotating electrical machines. Although their qualification seems to indicate them to be magnetically isotropic, they exhibit actually, due to the rolling process, a magnetically preferred direction that leads to anisotropy in both the magnetic and elastic behavior [1]. A variety of vector hysteresis models have been developed to simulate the magnetization process under rotational field. Many of them are vector extension of well-established uniaxial scalar models; the vectorization being realized by superposition of a number of scalar models oriented over different directions [2], [3], and [4]. In contrast, the model presented in this paper builds on an isotropic energy-based vector hysteresis model [5-7], which is inherently a vector model and offers readily a complete theoretical framework to include magnetic anisotropy, magnetostriction, and characteristic features of magnetic hysteresis such as the wiping-out property or rotational hysteresis.

II. ENERGY-BASED FERROMAGNETIC MATERIAL MODEL

The proposed model builds on the thermodynamic representation of hysteresis proposed in [5-8] and gets some inspiration from the kinematic hardening theory of plasticity discussed in [9-11].

A. Magnetic state variables

To appropriately account for the susceptibility of empty space, the magnetic flux density b is represented as a sum of two components (1): an empty space magnetic polarization $J_0 = \mu_0 h$ (with μ_0 the magnetic permeability of vacuum), which is always present, and a material magnetic polarization J, associated with the presence of microscopic moments attached to the atoms of a material body.

$$b = J_0 + J \tag{1}$$

B. Energy conservation

The ferromagnetic material model follows from the expression of the conservation of energy in the material

$$\mathbf{h}\cdot\dot{\mathbf{b}} = \dot{U} + D \tag{2}$$

where U is the internal energy density, $\mathbf{h}\cdot\dot{\mathbf{b}}$ the rate of magnetic work, and $D \geq 0$ a non-negative dissipation functional. Note that the terms of the energy conservation equation have actually the dimension of power.

C. Internal energy and anhysteretic saturation

The internal energy U is a function of the state variables of the system and is composed of two terms. The first term depends on J_0 and accounts for the energy of empty space. The second term u(J, …) accounts for the energy stored in matter and depends on J and possibly on other nonmagnetic state variables (strain, entropy, …). The variation in time of the internal energy, holding non-magnetic state variables constant, writes

$$\dot{U} = \frac{\mathbf{J}_0}{\mu_0}\cdot\dot{\mathbf{J}}_0 + \partial_{\mathbf{J}} u\left(\mathbf{J},...\right)\cdot\dot{\mathbf{J}}. \tag{3}$$

The second term can be regarded as the power delivered to the state variable J by a magnetic field h_r called reversible magnetic