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Significance of Vector Hysteresis Modeling in the Analysis of Variable Flux Reluctance Machines

Do˘ga Ceylan, Reza Zeinali, Bram Daniels, Konstantin O. Boynov, and Elena A. Lomonova

Abstract—This article presents the magnetostatic analysis of a 12/10 variable flux reluctance machine where the nonlinear magnetic characteristics of the soft-magnetic material are modeled using two different techniques: the single-valued magnetization curve and Jiles-Atherton vector hysteresis modeling. The root mean square and the peak local errors in the magnetic flux density calculated by the single-valued curve are found to be 0.23 T and 0.5 T, respectively. Moreover, the calculated torque under magnetic saturation with a single-valued curve exhibits over 5% error when compared to the Jiles-Atherton model, as it only models uni-directional material characteristics. Lastly, the modeled hysteresis loss of the applied two techniques is compared. The discrepancy between the two models is found to be 25% in magnetic saturation and reaches 48% for large dc-to-ac-field excitation ratios in the linear region.

Index Terms—Variable flux reluctance machine, magnetic characteristics, vector hysteresis, single-valued saturation curve.

I. INTRODUCTION

Correct computation of the magnetic flux density is critical for electromechanical systems to ensure that global parameters such as torque and efficiency are accurately determined. One of the biggest challenges in the computation of the magnetic flux density is to include the nonlinear magnetic characteristics of the soft-magnetic material under magnetic saturation. The most common approach is to apply a single-valued magnetization curve (SVC), i.e. virgin or $B-H$ curve, and a nonlinear solver such as the Newton-Raphson or fixed-point method. In [1], Maxwell’s equations for magnetostatics are solved iteratively in both finite-element and volume integration methods, where the SVC is employed to include magnetic saturation. Although the SVC is the fastest approach to simulate nonlinear magnetic properties, it assumes isotropic material without modeling the actual hysteresis behavior. Hence, computationally more expensive but more accurate models than the SVC have been developed which can take anisotropic magnetic hysteresis into account. While mathematical hysteresis models [2] ignore the physics of the magnetic material behavior, models based on phenomenological considerations, such as the Preisach [3], and Jiles–Atherton (JA) [4] hysteresis models, are often applied due to their high accuracy. In [5], the JA-model is selected over the Preisach model due to its lower computational cost and simpler implementation as well as for the easier identification procedure of the model parameters. Moreover, Bergqvist proposed the anisotropic version of the JA-model in [6] in order to define the relation between vector magnetic field and vector magnetization. Later, the proposed vector JA-model has been tested with alternating and rotating excitations and under different saturation levels in [7] and [8]. Bergqvist’s vector JA-model is commercialized and coupled with the finite-element method (FEM) of Comsol Multiphysics as reported in [9], which is used in this study to analyze a variable flux reluctance machine (VFRM).

The VFRM is of particular interest due to the permanent magnet-free structure, improved flux weakening capability [10], and sinusoidal flux linkage waveform, resulting in a low level of acoustic noise [11]. A VFRM consists of both ac- and dc-field windings through which a dc-biased magnetic field is created in the core of the machine, i.e. a magnetic flux density with a non-zero average. This is problematic for a model that applies a SVC as it results in unrealistic magnetic field distribution which results in inaccurate core loss and torque calculation. Therefore, this paper compares the effect of including a JA-based vector hysteresis model in the analysis of a VFRM.

II. BENCHMARK

A 12/10 6.25 kW VFRM with a rated speed of 1200 rpm is selected as the benchmark and illustrated in Fig. 1. The values of the radial geometric parameters $r_{st}$, $h_{ty}$, $h_{rt}$, air gap length, $h_{at}$, and $h_{sy}$ are 20, 20, 10, 1, 20, and 10 mm, while the tangential parameters $\theta_{ty}$, $\theta_{at}$, $\theta_{sr}$, and $\theta_{sy}$ are 25, 15, 15, and 15 degrees respectively. The stack length of the VFRM is 0.2 m and the iron material is NO27.
Fig. 2. Comparison of the optimized Jiles-Atherton hysteresis simulation model with the single-valued curve and measurements.

III. MODELING METHOD

The finite element method is used for the 2-D magneto-static analysis of the benchmark. The Dirichlet boundary condition is defined as indicated in Fig. 1, ignoring the leakage flux, while the periodic boundary condition is employed to decrease the number of degrees of freedom of the model. The model is developed in Comsol Multiphysics 5.6 and consists of 13932 triangular quadratic mesh elements resulting in 27993 degrees of freedom. The air gap is divided in 4 mesh layers to aid an accurate torque calculation. The nonlinear magnetic behavior of the electrical steel parts of the FEM model are described by two different characteristics: the SVC and the JA-model.

A. The Single-Valued Curve

The SVC of the NO27 laminated steel is measured in both rolling and transverse directions using an Epstein frame. The measurements are conducted under quasi-static excitation, i.e. the change of the flux density over time is limited to a maximum of 30 mT/s, such that the dynamic eddy current and excess fields are negligible. The saturation flux density is measured to be 1.48 T in the rolling direction and 1.32 T in the transverse direction due to the magnetic anisotropy of the material. The average of the measured SVCs in the two directions is used as the nonlinear magnetic characteristics of the iron. A Newton-Raphson based solver is used to couple the average SVC with the FEM model of the benchmark. The solver calculates the incremental permeability ($\mu$) from the SVC, and returns the Jacobian and the residual, as follows,

$$dB = \mu dH,$$

where $B$ and $H$ are magnitudes of the magnetic flux density, and magnetic strength, respectively. The Jacobian is updated on every iteration to improve the convergence of the nonlinear solver without scaling the residual.

B. The Jiles-Atherton Model

The JA-model in [9] is used to investigate the magnetic vector hysteresis property in the benchmark. The details of the used vector JA-model are presented in [6]. The JA-model includes five model parameters: the saturation magnetization ($M_s$), domain wall density ($a$), pinning loss ($k$), magnetization reversibility ($c$), and inter-domain coupling ($\alpha$). In the vectorized version of the JA-model, these model parameters exhibit different values in different directions. Before using the JA-model in the analysis of the benchmark, model parameters have to be optimized for the used soft-magnetic material. To identify these parameters, three measurements (a, b, c) are conducted in the rolling direction ($x$), and three measurements (d, e, f) are conducted in the transverse direction ($y$) as presented in Fig. 2. Measured $H$-field data is used as the excitation in a FEM model coupled with the JA-model to calculate the $B$-field. The FEM model used for the parameter identification consists of a single 2-D mesh element in magnetostatic. Model parameters are optimized for minimizing the discrepancy between $B$-field results calculated by the JA-model and measurements. The objective function ($\text{Obj}$) of the optimization is determined as the total error in the magnetic dissipated energy between the JA-model and measurements,
in the flux density between both models becomes less than 0.1 T where the flux density is larger than 1.5 T. Although the dc biased excitation does not generate minor loops under magnetic saturation, there is still a slight discrepancy in Fig. 4(c) in saturated iron parts. The reason for this slight discrepancy under magnetic saturation is that the average SVC is not able to model the magnetic anisotropy while the JA-model simulates hysteresis loops using different model parameters in the rolling and transverse directions. The RMS error of the magnetic flux density of the SVC, 

\[
\frac{1}{N} \sum_{k=1}^{N} (|B_{k,SVC}^x| - |B_{k,JA}^x|)^2 \leq 0.23 \text{T},
\]

is calculated as 0.23 T using, where \(N\) is the number of mesh elements in the iron region.

Effects of the discrepancy in the flux density on global parameters, such as the average torque and the hysteresis loss, are investigated. Different excitation levels are considered. \(J_{dc}\) is varied from 5 A/mm\(^2\) to 30 A/mm\(^2\) for three different \(J_{ac}\) values: 5, 10, and 15 A/mm\(^2\). Arkkio’s method [12] is selected as the torque calculation method to decrease the numerical error in both models with the SVC and the JA-model. Fig. 5(a) presents the torque generation of the benchmark under different excitation levels. The effect of magnetic saturation on the torque is observed in Fig. 5(a) for all three ac-field excitation levels. Fig. 5(b) demonstrates the error of the torque calculated by the SVC compared to the JA-model. It is observed that the SVC approximation results in less than 2% error in the torque calculation under a low level of excitation although the RMS error in the flux density is higher than 0.2 T. The reason for this is that the discrepancy in the flux density concentrates in unsaturated iron parts while it is relatively low in the air gap where the torque is calculated. Furthermore, Fig. 5(b) indicates that the error in the torque may reach 5% under the magnetic saturation since the average SVC can only model the uni-directional magnetic saturation while the JA-model has different saturation flux density values in the rolling and transverse directions.

Lastly, the SVC and JA-model are compared in terms of the hysteresis loss calculation. For the model with the SVC, the statistical loss separation theory of Bertotti is employed as discussed in [13] to estimate the hysteresis loss,

\[
P_{h,SVC} = f \rho \int W_h(\vec{B}) dV,
\]

where \(\vec{B}\) is the maximum value of the flux density in an electrical period, \(f\) is the excitation frequency selected as 200 Hz for 1200 rpm rotor speed, and \(\rho\) is the density of the NO27

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>OPTIMUM VALUES OF THE JILES-AHERTON MODEL PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>parameter</td>
<td>value</td>
</tr>
<tr>
<td>(M_{s,x}, M_{s,y}) [A/m]</td>
<td>(1.2 \times 10^6, 1.1 \times 10^6)</td>
</tr>
<tr>
<td>(a_x, a_y) [A/m]</td>
<td>37.5, 47.7</td>
</tr>
<tr>
<td>(k_x, k_y) [A/m]</td>
<td>30.9, 27.9</td>
</tr>
<tr>
<td>(c_x, c_y) [-]</td>
<td>(197 \times 10^{-3}, 107.6 \times 10^{-3})</td>
</tr>
<tr>
<td>(\alpha_x, \alpha_y) [-]</td>
<td>(95.2 \times 10^{-6}, 85.3 \times 10^{-6})</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>EMPIRICAL PARAMETER USED IN THE HYSTERESIS LOSS CALCULATION WITH RESPECT TO THE PEAK FLUX DENSITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B [T])</td>
<td>(W_h [W \cdot s \cdot kg^{-1}])</td>
</tr>
<tr>
<td>0.1</td>
<td>(2.4 \times 10^{-4})</td>
</tr>
</tbody>
</table>

IV. RESULTS

The benchmark in Fig. 1 is analyzed for different ac- and dc-field excitation levels. The root mean square (RMS) value of the ac-current density, \(J_{ac}\), and the dc-field excitation levels. The root mean square (RMS) suggested for the JA-model in [9].

The benchmark under different acexcitation levels. The effect of magnetic saturation on the torque is observed in Fig. 5(a) for all three ac-field excitation levels. Fig. 5(b) demonstrates the error of the torque calculated by the SVC compared to the JA-model. It is observed that the SVC approximation results in less than 2% error in the torque calculation under a low level of excitation although the RMS error in the flux density is higher than 0.2 T. The reason for this is that the discrepancy in the flux density concentrates in unsaturated iron parts while it is relatively low in the air gap where the torque is calculated. Furthermore, Fig. 5(b) indicates that the error in the torque may reach 5% under the magnetic saturation since the average SVC can only model the uni-directional magnetic saturation while the JA-model has different saturation flux density values in the rolling and transverse directions.

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\[
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\]

where \(\vec{B}\) is the maximum value of the flux density in an electrical period, \(f\) is the excitation frequency selected as 200 Hz for 1200 rpm rotor speed, and \(\rho\) is the density of the NO27
Fig. 3. $B$-$H$ characteristics along the radial direction in the middle of a stator tooth calculated by the single-valued curve and the Jiles-Atherton model for different dc-field excitation levels and 10 A/mm² root mean square ac-current density.

Fig. 4. Comparison of magnetic flux density distributions calculated by the single-valued curve ($|B_{SV C}|$) and the Jiles-Atherton model ($|B_{JA}|$).

Fig. 5. Comparison of torque generations calculated by the single-valued curve and the Jiles-Atherton model at different excitation levels.

![Fig. 6](image-url) Comparison of hysteresis losses calculated by the single-valued curve and the Jiles-Atherton model at different excitation levels.

V. CONCLUSION

A Jiles-Atherton-based vector hysteresis model to simulate the magnetic characteristics of a variable flux reluctance machine has been implemented. Its model parameters have been derived from measurements using an optimization procedure. Although the computational cost of the single-valued curve is less than the Jiles-Atherton model, it demonstrates a significant error in calculating the flux density for large dc-to-ac-field excitation ratios in the linear region of the magnetic characteristics. The discrepancy in the torque reaches 5% due to the magnetic anisotropy of the iron material. Moreover, the most considerable difference in calculated hysteresis loss between the two models occurred under low ac-field excitation and maximum dc-field excitation, resulting in a 48% discrepancy. Hence, employing the proposed vector hysteresis model is recommended to analyze the hysteresis loss in variable flux reluctance machines with a large dc-field excitation.
REFERENCES


VI. BIOGRAPHIES

**Doğa Ceylan** was born in 1992 in Izmir, Turkey. He received his B.Sc. and M.Sc. degrees from the Department of Electrical and Electronics Engineering, Middle East Technical University (METU), Ankara, Turkey, in 2016 and 2018, respectively. He is currently working towards the Ph.D. degree with the Electromechanics and Power Electronics Group at Eindhoven University of Technology, the Netherlands. His current research interest focuses on the modeling and control of saturated electrical machines. He also worked on electromagnetic launchers and pulsed-power sources.

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**Elena A. Lomonova** graduated (cum laude) in electromechanical and control systems from Moscow Aviation Institute (State University of Aerospace Technology), Moscow, Russia, and received the Ph.D. degree (cum laude) in 1993, working on powertrain and control systems for autonomous vehicles with multilevel power supply subsystems for on-board loads and laser equipment. She started her industrial career with the research and development company "Astrophysics," Moscow, Russia (1982–1987). Afterward, she moved to the Electromechanical and Control Systems Department, State University of Aerospace Technology (MAI), and was active in research, education, and industrial projects (1987–1997). In 1998, she was with the Delft University of Technology and joined the Eindhoven University of Technology in 2000. In March 2009, she was appointed a Full-Time Professor. She is currently a Full Professor and Chair of the Electromechanics and Power Electronics Group. Her chair focuses on fundamental and applied research on enabling energy conversion theory, methods, and technologies for high-precision, automotive, and medical systems. She is an author and co-author of more than 450 scientific publications and more than ten patents. Her research interests include various facets of advanced mechatronics, electromechanics, and electromagnetics, including rotary electrical machines and drives, and linear and planar actuation systems.