

Implementation of Energy based Hysteresis Model in LTspice for power electronics applications

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Circuit type simulation softwares are routinely used in power electronics systems to analyze a large variety of topologies and parameter combinations (duty cycle, frequency, input/output voltages, ...). The inductors present in such systems very often contain magnetic cores exhibiting a significant hysteresis behaviour. Accurate hysteresis models are therefore needed to predict magnetic quantities and losses in those cores. This paper shows how to implement the Energy-Based hysteresis model into the LTspice software, in order to account for hysteresis phenomena in the magnetic cores of inductor components in transient simulations. Some results are compared with measurements on a DC/DC buck converter for frequencies not too high in order to neglect dynamic losses of the core.

Index Terms—magnetic hysteresis, saturation magnetization, Power Electronics, Transient Response

I. INTRODUCTION

MAGNETIC hysteresis is a fundamental phenomenon in magnetic materials, characterized by a dependence of magnetization on the history of the applied magnetic field. Accurate modeling of this behavior (Jiles Atherton (JA) model [1] or Preisach model (PM) [2]) is critical for numerous applications, including power electronics, electromagnetic devices, and magnetic storage systems. When a sufficient number of cells (parameters) are selected, the Energy-Based Hysteresis Model [3] has been proven to be highly accurate. Moreover robust identification protocols [4], [5], [6] exist for that model that have proven their efficiency [7]. The inverse EB model has been implemented successfully into a circuit type simulation software and compared to FE simulations in [8]. This article proposes a new implementation where the direct EB model is used and compare it with experiments on a power electronics application.

II. METHODS

A. Energy based hysteresis model

The EB hysteresis model [3] decomposes the excitation field $\mathbf{h}$ into a reversible $\mathbf{h}_{re}$ and an irreversible part $\mathbf{h}_{ir}$:

$$\mathbf{h} = \mathbf{h}_{re} + \mathbf{h}_{ir} \quad (1)$$

A better accuracy is obtained by representing $\mathbf{h}_{re}$ as the weighted sum of $\mathbf{h}_{re0k}$ contributions of a certain number of cells N ($\mathbf{h}_{re} = \sum_{k=1}^N \omega_k \mathbf{h}_{re0k}$) with $\omega_k \geq 0$ the weights associated with the k cell, which verify a partition of unity relationship $\sum_{k=1}^N \omega_k = 1$. As the excitation magnetic field $\mathbf{h}$ changes in time, it is modified by application of the following update rule:

$$\mathbf{h}_{re0k} = \begin{cases} \mathbf{h}_{re0k} & \text{if } \|\mathbf{h} - \mathbf{h}_{re0k}\| < \kappa_k \\ \mathbf{h} - \kappa_k \cdot \frac{\mathbf{h} - \mathbf{h}_{re0k}}{\|\mathbf{h} - \mathbf{h}_{re0k}\|} & \text{otherwise} \end{cases} \quad (2)$$

where κ^k is the pinning field of the cell k . The magnetization $\mathbf{M}$ is given by

$$\mathbf{M} = M_{an}(\|\mathbf{h}_{re}\|) \cdot \frac{\mathbf{h}_{re}}{\|\mathbf{h}_{re}\|} \quad (3)$$

where $M_{an}(\|\mathbf{h}_{re}\|)$ is a scalar anhysteretic function. Here, we used the classical Langevin function.

$$\mathbf{b} = \mu_0(\mathbf{M} + \mathbf{h}) \quad (4)$$

Finally the flux density $\mathbf{b}$ is computed by (4). The parameters to be identified for the EB model are thus (ω_k, κ_k) , M_s and h_0 . This can be done from unidirectional measurements and Table I gives the identified parameters for a N30 ferrite material.

TABLE I
FERRITE N30 MATERIAL PARAMETERS

Cell	κ_k (A/m)	ω_k	Cell	κ_k (A/m)	ω_k
1	0	0.423	2	8.92	0.373
3	23.3	0.142	4	40.6	0.063
5	188	0.005			
	M_s (A/m)	310983		h_0 (A/m)	10.89

B. Implementation in LTspice

Here, we chose to use the permeance-capacitance analogy firstly introduced by Karnopp[9] and then reused by other authors like [10] and [11]. The Table II shows the analogy between electrical and magnetic quantities.

With this analogy, coils linking electric and magnetic quantities can be easily represented by two coupled current controlled voltage sources. Linear magnetic cores which can be viewed as flux tubes can be represented by a constant capacitor whose value is the permeance of the flux tube. If the core is non-linear and/or hysteretic, one can represent the core by the equivalent of a non-linear charge capacitance depending on the voltage.

TABLE II
ELECTRICAL VERSUS MAGNETIC MAGNITUDES

Electric	Magnetic
Voltages u [V]	Magneto-motive force mmf [A.t]
Current i [A]	magnetic flux derivative $\frac{d\phi}{dt}$ [Wb/s]
Charge q [C]	magnetic flux ϕ [Wb]
power $p = u \cdot i$ [W]	power $p = mmf \cdot \phi$ [W]

Indeed, the charge ϕ of a core with a cross section A_e and a mean path length ℓ is (5)

$$\phi = A_e \cdot B(H_{stat}) \quad (5)$$

With $B(H_{stat})$, calculated by the EB model. Replacing H_{stat} by the magnetomotive force of the core divided by ℓ , one obtains the equivalent of the "current-voltage" law of the magnetic core (6).

$$\frac{d\phi}{dt} = A_e \frac{d}{dt} \left(B \left(\frac{mmf}{\ell} \right) \right) \quad (6)$$

This principle is shown on the Fig. 1 thanks to current and voltage behavioural sources. B13 reads the magnetomotive force ($mmf = F_+ - F_-$) applied to the core and divide by the length (Lm) to obtain H_{stat} . H_{stat} is used to compute the equations of the EB model thanks to mathematical functions available in LTspice. The result B is multiplied by $Sec = A_e$ (source (B15)) and is derived thanks to an ideal inductance of 1 H. The potential $dphi = \frac{d\phi}{dt}$ is then used by the B1 current source to impose the $\frac{d\phi}{dt}$ through the core. The resistor R2 is here just to authorize the serial connection between several cores.

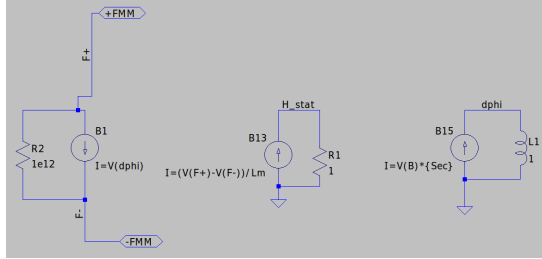


Fig. 1. Illustration of how to implement a non-linear charge capacitance depending on the voltage for the core of an inductor with behavioural sources.

III. RESULTS

The model retrieves quite well the current and voltage in the coil even for saturated cases (Fig. 2). The main advantage of the model is that it is able to predict how the magnetic material will "work" (local $B(H)$ loop) for a large range of working conditions like duty cycle, input voltage level or frequency value (Fig. 3).

IV. CONCLUSION

The extended version will show more details about the implementation and more comparisons versus the experimental measurements.

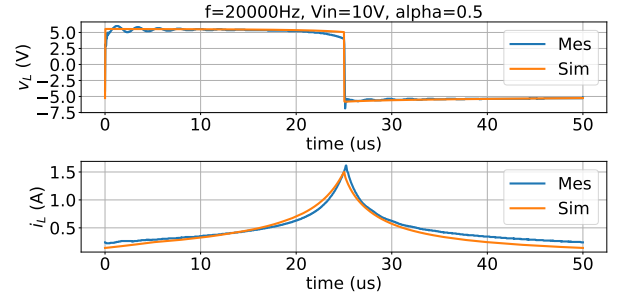


Fig. 2. Simulated and measured voltage (top), current (bottom) versus time

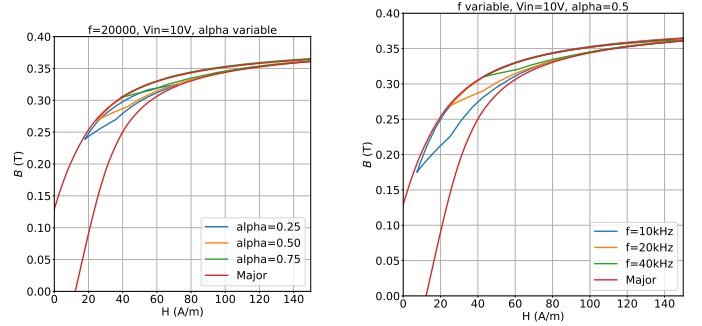


Fig. 3. Simulated loops at constant frequency $f = 20$ kHz and input voltage $V_{in} = 10$ V but different duty cycle values (left) and at constant input voltage $V_{in} = 10$ V and duty cycle $\alpha = 0.5$ but for different frequencies (right)

REFERENCES

- [1] D. Jiles and D. Atherton, "Ferromagnetic hysteresis," *IEEE Transactions on Magnetics*, vol. 19, no. 5, pp. 2183–2185, 1983.
- [2] F. Preisach, "Über die magnetische nachwirkung," *Zeitschrift für Physik*, vol. 94, no. 1, pp. 277–302, 1935.
- [3] F. Henrotte, A. Nicolet, and K. Hameyer, "An energy-based vector hysteresis model for ferromagnetic materials," *COMPEL*, vol. 25, no. 1, pp. 71–80, 2006.
- [4] F. Sixdenier and R. Scorretti, "Numerical model of static hysteresis taking into account temperature," *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields*, pp. e2221–n/a, 2017, e2221 jnm.2221. [Online]. Available: <http://dx.doi.org/10.1002/jnm.2221>
- [5] K. Jacques, S. Steentjes, F. Henrotte, C. Geuzaine, and K. Hameyer, "Representation of microstructural features and magnetic anisotropy of electrical steels in an energy-based vector hysteresis model," *AIP Advances*, vol. 8, no. 4, p. 047602, 2018.
- [6] R. Scorretti and F. Sixdenier, "An analytical formula to identify the parameters of the energy-based hysteresis model," *Journal of Magnetism and Magnetic Materials*, p. 168748, 2021.
- [7] M.-R. Longhitano, F. Sixdenier, R. Scorretti, C. Geuzaine, F. Henrotte, and L. Krähenbühl, "Comparison of identification protocols of a static hysteresis model," in *2019 22nd International Conference on the Computation of Electromagnetic Fields (COMPUMAG)*, 2019, pp. 1–4.
- [8] F. Sixdenier, R. Scorretti, N. Davister, C. Geuzaine, and F. Henrotte, "Energetic based hysteresis model implementation in LTspice," in *Compumag 2022*, Cancun, Mexico, Jan. 2022. [Online]. Available: <https://hal.science/hal-03540757>
- [9] D. Karnopp, D. Margolis, and R. Rosenberg, *System Dynamics: A Unified Approach*. Wiley, 1990. [Online]. Available: <https://books.google.fr/books?id=EHZRAAAAMAAJ>
- [10] D. Hamill, "Lumped equivalent circuits of magnetic components: the gyrator-capacitor approach," *IEEE Transactions on Power Electronics*, vol. 8, no. 2, pp. 97–103, 1993.
- [11] H. Zhang, M. Tian, H. Li, L. Dong, and L. Sun, "Improved gyrator-capacitor model considering eddy current and excess losses based on loss separation method," *AIP Advances*, vol. 10, no. 3, p. 035309, 2020. [Online]. Available: <https://doi.org/10.1063/1.5143172>