Energy-based hysteresis model implementation in LTspice

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Circuit type simulation packages are routinely used to analyze a large variety of topologies and parameter combinations (duty cycle, frequency, input/output voltages, ...) in power electronics systems. The inductors present in the simulated systems usually contain magnetic cores, which are very often made of ferrite materials. As ferrite materials are soft magnetic materials exhibiting a significant hysteresis behaviour, scientists and engineers need accurate hysteresis models 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 simulate hysteresis phenomena in the magnetic cores of inductance components.

***Index Terms*—Magnetic hysteresis, Magnetic cores, ferrites, power electronics**

I. Introduction

Magnetic hysteresis is a complex phenomenon that significantly impacts the energy efficiency of electrical devices. This is particularly true in power electronics, where magnetic components containing ferrite materials are largely used at high operating frequencies. To model them, a number of commercial circuit-type simulation packages offer hysteresis model capabilities for simulation purposes. The Jiles Atherthon (JA) model [1] is proposed in PSPICE®for instance, and the Preisach model (PM) [2] is proposed in SABER®. The Energy-Based (EB) hysteresis model proposed by [3], on the other hand, has proven very accurate if the number of cells (parameters) is chosen large enough. Moreover robust identification protocols [4], [5] exist for that model that have proven their efficiency [6]. The implementation of the EB model into a circuit type simulation package is expected to enhance the modelling possibilities for power electronics circuits.

In this paper, we propose to implement the EB model into the software LTspice®. The next section briefly presents the EB model and explains how to implement it in LTspice using behavioural voltage sources. Preliminary results are then presented in Section III.

II. Methods

A. Energy-based hysteresis model

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

$$\mathbf{h} = \mathbf{h}_{re} + \mathbf{h}_{ir}. \tag{1}$$

. A better accuracy is obtained by subdividing $\mathbf{h}_{re}$ as a weighted sum of $\mathbf{h}_{re_k}$ contributions of a certain number of cells N:

$$\mathbf{h}_{re} = \sum_{k=1}^{N} \omega_k \mathbf{h}_{re_k}. \tag{2}$$

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In (2), $\omega_k \geq 0$ is the weight associated with the k cell and must verify $\sum_{k=1}^{N} \omega_k = 1$. The term $\mathbf{h}_{re_k}$ is the internal state of the cell k. It is updated such that:

$$\mathbf{h}_{re_k} = \begin{cases} \mathbf{h}_{re0_k} & \text{if } ||\mathbf{h} - \mathbf{h}_{re0_k}|| < \kappa_k \\ \mathbf{h} - \kappa_k \cdot \frac{\mathbf{h}-\mathbf{h}_{re0_k}}{||\mathbf{h}-\mathbf{h}_{re0_k}||} & \text{otherwise} \end{cases}, \tag{3}$$

where κ^k is the maximum pining field of the k cell. The magnetization $\mathbf{M}$ is calculated from $\mathbf{h}_{re}$:

$$\mathbf{M} = M_{an}(||\mathbf{h}_{re}||) \cdot \frac{\mathbf{h}_{re}}{||\mathbf{h}_{re}||}, \tag{4}$$

where $M_{an}(|||\mathbf{h}_{re}||)$ is a scalar anhysteretic function. Finally the flux density $\mathbf{b}$ is obtained through:

$$\mathbf{b} = \mu_0(\mathbf{M} + \mathbf{h}). \tag{5}$$

For the anhysteretic function, we use the Langevin function

$$M_{an}(h) = M_s \left[coth\left(\frac{h}{h_0}\right) - \frac{h_0}{h} \right]. \tag{6}$$

At each time step the state of each $\mathbf{h}_{re_k}$ has to be updated for the time step. The parameters to identify are (ω_k, κ_k). Note that the (ω, κ) distribution can be identified from unidirectional measurements. As the description of magnetic quantities in circuit type simulation software are 0D quantities, we no longer use vectorial notations in what follows.

Table I summarizes the parameter values that represent a 3C90 ferrite material [6] from ferroxcube®.

TABLE I
Identified parameter Values for the 3C90 ferrite

$M_s(A/m)$	3.4367e5		h_0	17	
ω_k	0.1818	0.2727	0.1818	0.2727	0.0909
$\kappa_k(A/m)$	0	0.2	6.95	25.99	42.26

B. Implementation in LTspice

1) Setting-up the EB model

The main idea of our approach is to assume that the induction field $\vec{B}$ and the magnetic field $\vec{H}$ are reasonably homogeneous across the magnetic core. This assumption is well-verified in practice. One can thus identify a pair of scalar field quantities B and H that represent the magnetic state of the ferrite core. These magnetic quantities are algebraically linked with the voltage u and the current i of an inductor. This will be explained in the extended paper.

We make use of several tools available in the LTspice software, in particular the behavioural voltage source (BV). It is a voltage source whose output can be entirely mathematically driven (computations mixing currents and voltages are possible). Figure 1 shows the behavioural sources used to solve (3), (2), (4), and (5).

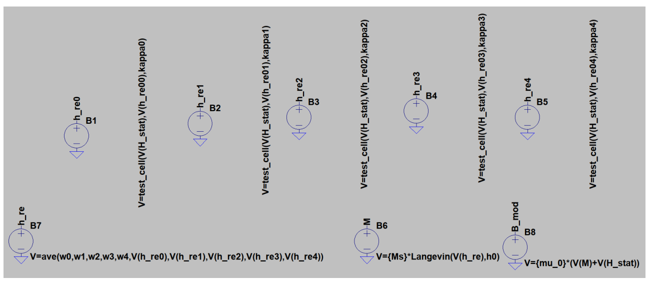

Fig. 1. Example of Behavioural Voltage (BV) sources.

2) Inverting the EB model

The EB model gives $B(H)$. For an inductor model, it is however necessary to have a $H(B)$ model rather than a $B(H)$ model. To do so, we use the technique mentioned in [7], and exploit the capabilities of spice-type solvers to invert the model numerically. In Fig. 2, B represents the flux density we want to impose to the material, whereas B_mod is the flux density calculated by the EB model. The value of H that produces $B - B\_mod(H) = 0$ is determined by solving the auxiliary circuit depicted on the right of Fig. 2. In this circuit H_stat is the node voltage (unknown H) that links $B14$ and the $R1$ resistor. $B14$ is a behavioural current source, where (7) is applied:

$$I = V(B) - V(B\_mod) + V(H\_stat)/R1. \tag{7}$$

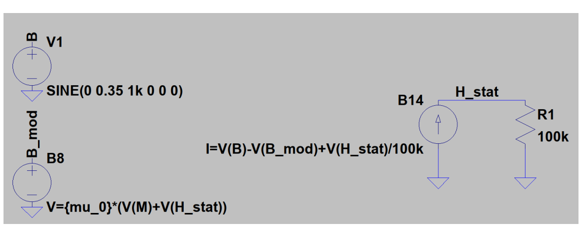

Fig. 2. Inversion of the EB model thanks to [7].

III. Results

Fig. 3 shows the results of the LTspice simulation, with the technique described above, in the following conditions: $\widehat{B} = 0.35$ T, f =1 kHz. The above plots represent the imposed sinusoidal B field and the corresponding H field. The effects of magnetic saturation and hysteresis are clearly seen. The signals $B(t)$ and $B\_mod(t)$ are also in very good agreement. The maximum difference is about 1.6μT, so that they are indistinguishable in the plot.

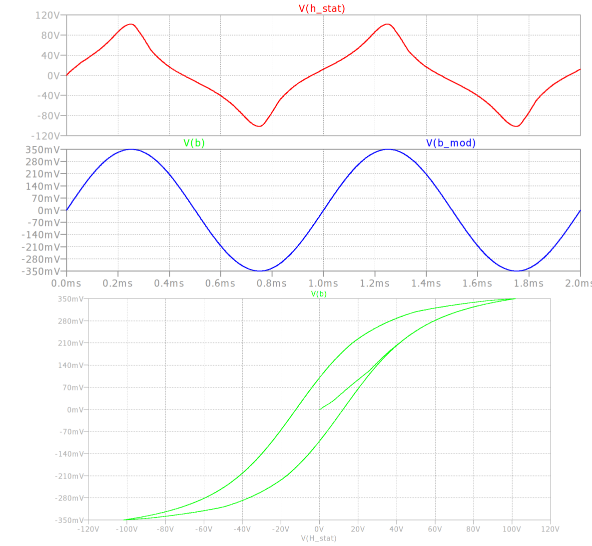

Fig. 3. Temporal waveforms (up) and corresponding BH loop (down) loop for $\widehat{B} = 0.35$ T, f =1 kHz. (units scale 1T=1V for $V(B)$; 1V=1 A/m for $V(H\_stat)$))

IV. Conclusion

In the extended paper, more details will be given on how to build a realistic inductor component including a magnetic core with hysteresis. A validation with a GetDP [8] finite element simulation where the ferrite material is also modeled with the EB hysteresis model will be provided. Finally, the extended paper will show that our model is able to predict hysteresis loops (with DC bias) of an inductor working in a DC-DC buck converter topology.

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