

Implementation of Energy based Hysteresis Model with Harmonic Balance method

Fabien Sixdenier¹, Riccardo Scorretti²

¹Universite Claude Bernard Lyon 1, INSA Lyon, ECLyon, CNRS, Ampère, F-69100, Villeurbanne, France

²University of Perugia, Via G. Duranti 96, 06125 Perugia, Italy

Circuit type simulation softwares (like SPICE) are routinely used in power electronics systems to analyze a large variety of topologies and parameter combinations (duty cycle, frequency, input/output voltages, ...). The magnetic components are usually considered linear in these simulations. This article discusses the feasibility of implementing the Energy Based Hysteresys Model (EBHM) into a harmonic balance simulation in order to obtain efficiently, the steady response of a power electronic topology including the saturation and hysteresis effect of the magnetic component.

Index Terms—magnetic hysteresis, saturation magnetization, Harmonic analysis

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 is critical for numerous applications, including power electronics. A number of commercial circuit-type simulation packages offer hysteresis model capabilities for simulation purposes. The Jiles Atherthon (JA) model [1] is implemented in PSPICE® for instance, and the Preisach model (PM) [2] in SABER®. The Energy-Based (EB) hysteresis model [3], on the other hand, has proven to be 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 software for transient simulations has been made successfully in [7].

However for fast predesign purposes this approach needs several simulations and each simulation needs to reach the steady state conditions. That's where the Harmonic-Balance technique is very interesting because it gives only the steady state answer even for complex problems such as a motor modeled with a 2DFE approach with motion and circuit coupling [8]. However including hysteresis is more complex, because one key difficulty arises from the inherently memory-dependent nature of hysteresis. Thus, while harmonic balance offers a powerful framework for analyzing periodic phenomena, the modeling of magnetic hysteresis within this paradigm continues to present unresolved theoretical and practical challenges. Some potential methodologies to overcome these challenges are for example to use smoothing functions before treating hysteresis [9] or to separate the H field into a reversible and an irreversible part [10]. However, in this abstract, only saturation effects, taken into account with the HB technique, of a coil into a typical power electronics applications will be presented.

II. METHODS

A. DC/DC "buck" converter output

Our approach will be tested on a classical DC/DC buck converter output composed of an LC filter and a load resistor presented in Fig.1. The whole circuit is supplied by $E(t)$ a voltage source of square waves $(+V_{max}, 0)$ where the frequency f , voltage level V_{max} and Duty cycle DT , can be changed. This allows to remove the active components of a full DC/DC converter to simplify the study.

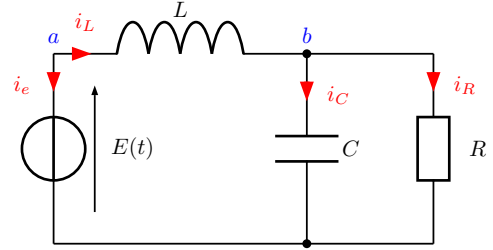


Fig. 1. Typical output of a DC/DC buck converter

B. HB Modeling

The temporal ordinary differential system of equation of the previous circuit is given by (1)

$$\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & C & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \frac{dv_a}{dt} \\ \frac{dv_b}{dt} \\ \frac{di_e}{dt} \\ \frac{d\psi}{dt} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 1 & -\frac{1}{L} \\ 0 & 1/R & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & -1 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} v_a \\ v_b \\ i_e \\ \psi \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ E(t) \\ 0 \end{bmatrix} \quad (1)$$

All the unknowns are put in a vector $\mathbf{X}(t)$ (2). The equation (1) is then rewritten as (3) with n_t , the number of time steps in one period T

$$\mathbf{X}(t) = \begin{bmatrix} v_a(t_1), \dots, v_a(t_{n_t}), v_b(t_1), \dots, v_b(t_{n_t}), \\ i_L(t_1), i_L(t_{n_t}), \psi(t_1), \dots, \psi(t_{n_t}) \end{bmatrix} \quad (2)$$

$$[\mathbf{C}_t] \cdot \left[\frac{d\mathbf{X}}{dt} \right] + [\mathbf{G}_t] \cdot [\mathbf{X}] = [\mathbf{U}(t)] \quad (3)$$

With $\mathbf{C}_t$ representing the action of differential variables and $\mathbf{G}_t$ representing links between unknowns (Kirchoff laws, flux vs current link,...). Both $\mathbf{C}_t$ and $\mathbf{G}_t$ are composed of block-diagonal submatrices of size n_t . $\mathbf{U}(t)$ is the source term vector. Then (3) is transformed into (4).

$$(\mathbf{\Omega} \cdot \mathbf{C}_f + \mathbf{G}_f) \cdot \mathbf{X}_f = \mathbf{U}_f \quad (4)$$

$\mathbf{\Omega}$ is a block diagonal matrix formed of several block diagonal submatrices representing the FFT of the differential operator $\mathbf{\Omega} = \text{diag}\{j\omega_0 [\dots, -2I, -I, 0, I, 2I, \dots]\}$ (ω_0 is the fundamental frequency). By introducing $\mathbf{\Gamma}$, the discrete Fourier operator and $\mathbf{\Gamma}^{-1}$ the inverse discrete Fourier operator, the temporal vectors and matrices are transformed into their equivalent in frequency domain such as (6).

$$\mathbf{X}_f = \mathbf{\Gamma} \cdot \mathbf{X}_t \quad (5)$$

$$\mathbf{G}_f = \mathbf{\Gamma} \cdot \mathbf{G}_t \cdot \mathbf{\Gamma}^{-1} \quad (6)$$

The matrix of the linear system of (4) is the Jacobian of the Harmonic Balance $\mathbf{J}_f$ system and has to be reevaluated in the case of non-linear simulations. To do so, inverse Fourier transforms are performed on $\mathbf{X}_f$ to obtain $\mathbf{X}_t$ and evaluate the temporal non linearities at each time step. $\mathbf{C}_t$ and $\mathbf{G}_t$ are then reevaluated and retransformed into $\mathbf{C}_f$ and $\mathbf{G}_f$ to update $\mathbf{J}_f$. This means that $L(t)$ is not constant during a period and has to be updated. To take into account the saturation we simulate the magnetization of the core with a simple Langevin function (7) with a saturation magnetization of $M_s = 310983$ A/m and $h_0 = 10.8903$ A/m, the shape parameter. These last parameters approximate the anhysteretic magnetization of a N30 ferrite material. Regarding the shape of the coil, the assumptions are that it is made of a toroidal core with a constant cross section A_e and magnetic path length ℓ_m and that there is no leakage flux.

$$M(H) = M_s \left(\coth\left(\frac{H}{h_0}\right) - \frac{h_0}{H} \right) \quad (7)$$

III. RESULTS

All results obtained by our approach were compared to LTspice simulations once the steady state has been reached (400 periods). The linear case was simulated with the conditions resumed in the table III. The non-linear case also, except that L was no more constant and the same model (Langevin function) has been used in LTspice and the HB technique.

V_{max} (V)	f (kHz)	DT	L (μ H)	C (μ F)	R (Ω)
10	10	0.5	557	100	10

Fig. 2, shows the voltages at points a and b and the current i_L versus time. First, The voltage at point b and the current i_L are very well retrieved for a limited number of harmonics. One can see the influence of this limited number of harmonics on the voltage waveform at point a for our approach. This last voltage can better match with SPICE measurements by increasing the number of harmonics n_h . In the non-linear case, the LTspice crashed systematically for this case because of the

too severe peak of current during the transient state. However the HB technique shows the right behaviour. Indeed because of the saturation of the core the current in the coil has a peak much higher than in the linear case. This current also induces a voltage ripple at point b higher than in the linear case. These very well known phenomena occur when the coil saturates and is well captured by the simulation.

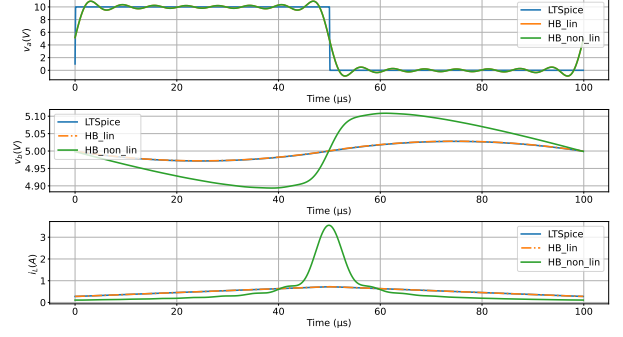


Fig. 2. voltage waveforms at the point a and b and current flowing into the inductor L for a number of harmonics $n_h = 16$

IV. CONCLUSION

In the extended version, more details about the algorithm will be given as well as how the hysteresis will be treated. Additionally, some metrics about the calculation cost and accuracy will be given especially regarding the number of harmonics.

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