MAGNETIC HYSTERESIS MODELING AND VISUALIZATION FOR SPICE BASED ENVIRONMENTS

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Today magnetic materials are employed in a truly wide range of applications, and have contributed materially to advances in electronics. On the other hand computer-based simulation tools are convenient for analyzing complex systems. Unfortunately there is insufficiency of models describing electrical behavior of such nonlinear devises. In order to simulate this devices with modern electronic design automation tools the implementation of SPICE oriented models, is imperative. In presented paper a survey of behavior modeling methods suited for visualization of hysteresis of various magnetic materials is given. In order to reduce the modeling time graphs for fitting the slope of the magnetization curve, histeresis' area and shape are obtained and present in the paper. The appended simulated results pointed to ability of the presented approach for modeling and visualization of different magnetic histeresises.

Keywords: Ferromagnetic Materials, Hysteresis Loop, Behavior Modeling, SPICE Simulation.

1. INTRODUCTION

Magnetism was probably the first natural force discovered by man but it has only been in the last century that any large usage of magnetic materials has been made. Much of the glamour of modern electronics has been centered on the semiconductor industry but many of the devices using these new concepts would not be practical without the accompanying magnetic components. The frequencies of application of magnetic materials range from DC to the highest ones at which any electronic device can function. The emergence of many new technologies driven by differing requirements, in turn, has led to a large variety of magnetic materials supplied in many different shapes and sizes.

The magnetic induction, B, of a ferromagnetic material is depicted in details as a function of the applied external magnetic field, H (i.e., B-H or hysteresis loop) [1, 7]. At high fields, the induction flattens out at a value called the saturation induction, B_s. If, after the material is saturated, the field is reduced to zero and then reversed in the opposite direction, the original magnetization curve is not reproduced but a hysteresis loop is obtained. The area included in the hysteresis loop is a measure of the magnetic losses incurred in the cyclic magnetization process. The value of the induction after saturation when the field is reduced to zero is called the remanent induction or retentivity, B_r. The values of the reverse field needed after saturation to reduce the induction to zero is called the coercive force or coercivity, H_c.

It is important to note that the magnetic permeability of ferromagnetic materials is not a constant physical quantity and depends on a particular region of the *B*-*H* diagram. The initial slope of the magnetization curve is called the initial magnetic permeability, and the maximum slope measured from the origin is called the maximum magnetic permeability, while the permeability measured for an applied alternating magnetic field is termed AC magnetic permeability. The differential permeability μ_d, is a more useful physical quantity and is obtained from [1]:

$$\mu_d = \frac{dB}{\mu_0 . dH}, \qquad (1)$$

where $\mu_0 = 2.\pi.10^{-7}$ = const is the magnetic permeability of a vacuum.

Up to date signal processing systems are usually composed of a variety of components, electrical as well as nonelectrical. For a long time there has been a search for a general model of magnetic material, i.e. a model capable of visualization of a hysteresis loop and defining the main magnetic parameters. Such a model could be easy incorporated in a power system analysis package based on SPICE simulators. The objective of this paper is to generalize the methods for modeling and visualization of *B*-*H* loop and to develop an approach for SPICE oriented simulation of magnetic hysteresis. In order to harmonize the proposed model with more of the SPICE simulators the use of equivalent circuit and analog behavior models (ABM) are suggested.

2. MAGNETIC CORE MODELS BUILD IN PSPICE LIBRARY

For simulation and visualization of hysteresis loop can be used build in PSpice library a nonlinear, magnetic core device. The magnetic core's *B*-*H* characteristics are analyzed using the Jiles-Atherton model. Some commercially available software environments [2] use this model to simulate the behaviour of magnetic devices.

Jiles and Atherton [2, 4] describe the nonlinear core based on physical properties of the magnetic material, using the current physical theories of magnetic domains in ferromagnetic materials. The Jiles-Atherton model requires the following input parameters: magnetization saturation, thermal energy parameter, domain flexing constant, domain anisotropy constant, interdomain coupling parameter. These are not the parameters that magnetic core manufacturers or producers of other magnets can provide. In fact they cannot even be determined directly through measurements. The various core hysteresis parameters required in this model are theoretical and can be calculated from experimental measurements of the coercivity, remanence, saturation flux density, initial anhysteretic susceptibility, initial normal susceptibility, and the maximum differential susceptibility. This is an iterative trial-and-error process [2, 5].

3. MAGNETIC HYSTERESIS ANALOGUE BEHAVIOR MODELING

The Analog Behavioral Modeling feature of SPICE can be used to make flexible descriptions of electronic components in terms of a transfer function or look-up table. In other words, a mathematical relationship is used to model a circuit segment, so the users do not need to design the segment component by component [6].

3.1 The equivalent circuit of the proposed model

Using the resources of National Instruments' Multisim and ABM parts [3, 5, 6], the model of magnetic core is developed and presented on fig. 1. As can be seen in order to compose the equivalent circuit of the model a number of passive components, ABM current and voltage sources are involved.

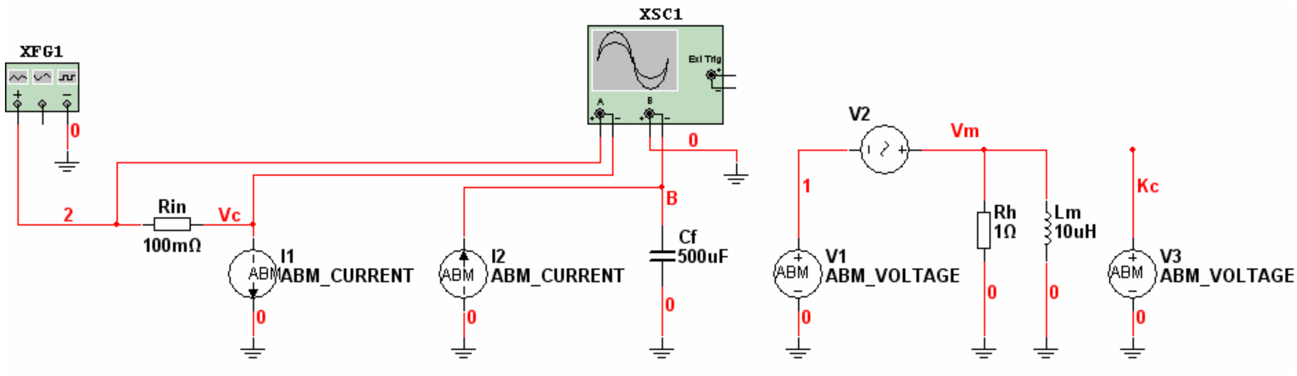

Fig. 1. The proposed model of magnetic core

The resistor R_{in} limits the current when the core is saturates and in addition is the magnetizing current measurement point for the hysteresis loop display. The value of the ABM current source I_1 is equal to $I(V_2)/V(\mathrm{Kc})$. The voltage source V_2 is the current reference for the behavioral current source I_1. V_2 is set to 0 V so that it does not affect the circuit. Of course current can be measured in a component, but it will cause errors, slow the simulation and may prevent convergence.

The inductor L_m models the magnetizing inductance and the resistor R_h represents the core losses. The core loss can be modeled with a more complex circuit, but this is a useful starting point and is sufficient for many applications. The flux B is modeled as the volt-seconds on the inductor L_m, scaled appropriately. Therefore the voltage of the ABM source V_1 is equal to $V(\mathrm{Vc})*V(\mathrm{Kc})$.

The voltage $V(\mathrm{Vm})$ is integrated with respect to time with the behavioral current source I_2. The current charges the capacitor C_f to a voltage $V(\mathrm{B})$. The value of C_f is the scaling factor to convert volt-seconds to flux. Volt-seconds, flux and flux density differ only by scale factors, so any of them may be easy modeled.

Core saturation is modeled as a coupling factor, *Kc*. The inductor value and current must remain static in saturation to conserve energy, and the flux B is asymptotic to the saturation flux B_s. For the current to remain static, the voltage $V(\mathrm{Vm})$ across the inductor L_m must go to zero, and this is done by reducing the coupling factor *Kc* to 0 as the flux B goes to B_s. There are many functions that can model this behavior, but the following was chosen for its simplicity and versatility:

$$Kc = 1 - \left(\frac{B}{B_s}\right)^{Exp}, \qquad (2)$$

where *Exp* is parameter of the proposed model. For any $Exp > 1$, *Kc* goes to 0 asymptotically, and the exponent controls the sharpness of the "knee". In the proposed model this is achieved by choosing the value of the voltage of the ABM source V_2 to be $1-\left(\frac{V(B)}{B_s}\right)^{Exp}$.

To model the hysteresis loop of a magnetic core using conventional units, scale factors that convert the input current to coercive force and volt-seconds to flux density can be used.

3.2 Curve fitting of the model

The first parameter to be adjusted is the "roundness" of the corners of the hysteresis. This is accomplished by varying the model parameter *Exp* in the expression (2) for *Kc* in the behavioral voltage source V_2, with reference to the SPICE model equivalent circuit above. As the exponent is increased, the corners get sharper. The saturation flux B_s is directly modeled in the same ABM part.

The next parameter for modeling is the magnetic permeability of ferromagnetic material. In this case is more convenient to use incremental permeability μ_Δ or the permeability about a specified operating point and applied *H*. The incremental permeability is expressed as the slope of the initial magnetization curve about the given operating point. Therefore using [1] and (1) μ_Δ can be derived as:

$$\mu_\Delta = \frac{\Delta B}{\Delta H} = a\frac{\Delta Y}{\Delta X}, \qquad (3)$$

where *a* is appropriate scale factor, ΔY and ΔX are small increments from the simulated magnetization curve.

On fig. 2 is presented relationship between the value of the inductance L_m and the calculated value of the relative parameter $\mu_{\Delta\ rel} = \mu_\Delta / a$. Using this graph and the measured or estimated value of μ_Δ it is easy to achieve good fitting of the slope of the *B*-*H* characteristic.

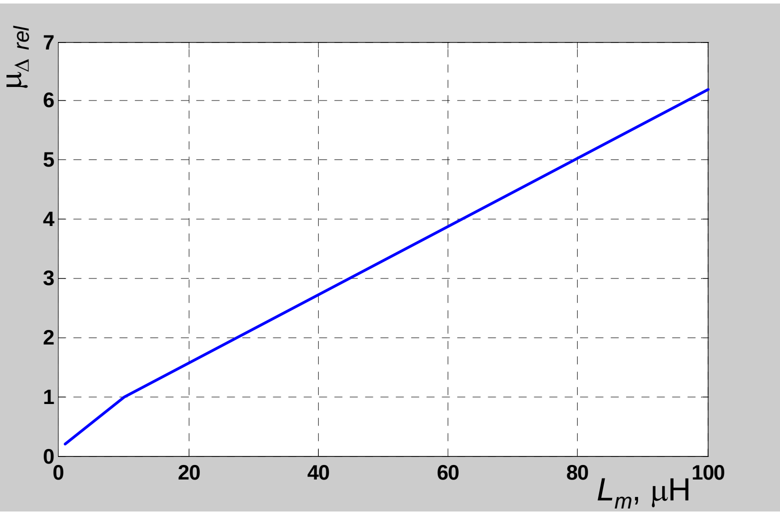

Fig. 2. Obtained $\mu_{\Delta\ rel}$ vs. L_m graph for fitting the slope of the magnetization curve

Next the core losses are modeled by varying the value of the resistor R_h and in this way changing the histeresis' area. As the value of resistor R_h is reduced, the hysteresis loop opens up. As the SPICE model can be refined, R_h will be replaced with a more complex function, but it will be resistive in nature and represents a loss whenever a voltage is applied and the core is not saturated. At least for ensure that the histeresis' shape enclosed is as close a match as possible is used the value of the capacitor C_f.

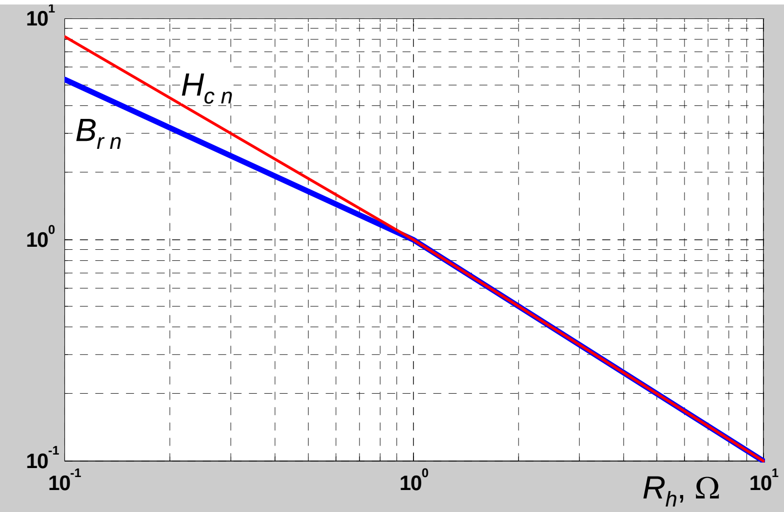

Fig. 3. Obtained $B_{r\,n}$ and $H_{c\,n}$ vs. R_h curves for fitting the histeresis' area

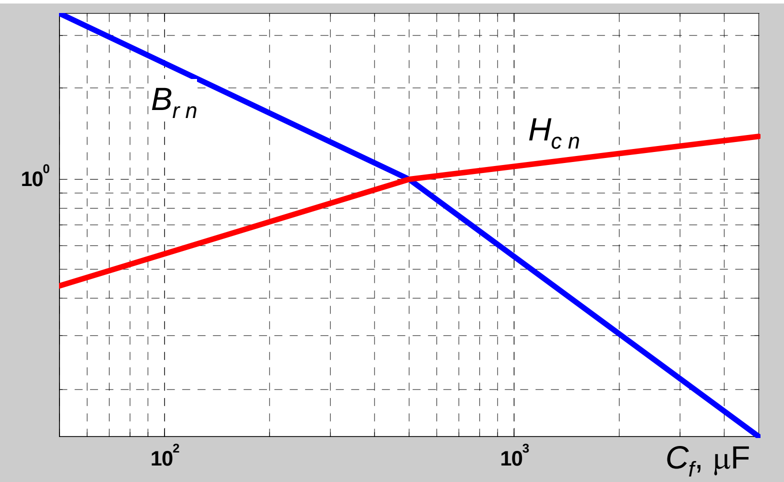

Fig. 4. Obtained $B_{r\,n}$ and $H_{c\,n}$ vs. C_f curves for fitting the histeresis' shape

The main parameters determining the area and the shape of the *B-H* loop are the remanent induction B_r and the coercive force H_c. Therefore more accurate curve fitting of the hysteresis can be achieved using the relations between B_r and H_c corresponding to the values of R_h and C_f.

The graphs on fig. 3 and fig. 4 show the change in $B_{r\,n}$ and $H_{c\,n}$ as the values of the resistance R_h and of the capacitance C_f changes. To increase the usage of these curves for creating models of various magnetic materials, the value of the parameters $B_{r\,n}$ and $H_{c\,n}$ are normalized. Therefore this approach can be easy adapted to every SPICE based simulator. The parameters (R_h and C_f) can then be tweaked to refine the match to be as close a fit as possible.

4. Visualization of the Hysteresis Loop

For the interactive simulation in Multisim can be use either a virtual instrument or run an analysis to display the simulation output [3]. The simulator also provides a convenient and realistic way to supply stimulus signals to a circuit. Therefore the hysteresis loop is very attractive to be investigated in the similar manner as the real *B-H* loop measurement. A voltage source is needed to operate the SPICE model, and a sinusoidal wave AC is preferred. This is performed by the functional generator set to a sinusoidal waveform for analysis and its frequency and amplitude can be controlled. The hysteresis loop is displayed using the dual-channel oscilloscope function. The voltage applied to the first channel is proportional to the input current, while to the second channel is applied voltage *V*(B) – see fig. 1. In this way the *X* axis of the oscilloscope represent the applied external magnetic field, *H*, and the *Y* axis is the flux or flux density *B*. The hysteresis loop may be copied to another program, where it may be cleaned up and scaled, if necessary, for presentation.

In fig. 5 are shown modeled and simulated *B-H* loops of different magnetic materials: nonretentive or soft magnetic material with narrow hysteresis loop, low coercive force, low magnetic core losses, and retentive or hard magnetic material with large hysteresis, high coercive force, and high core losses. As can be seen visualization and determination of the main hysteresis parameters using the oscilloscope's display are very convenient and attractive. In addition the proposed approach for modeling is suitable for various magnetic materials.

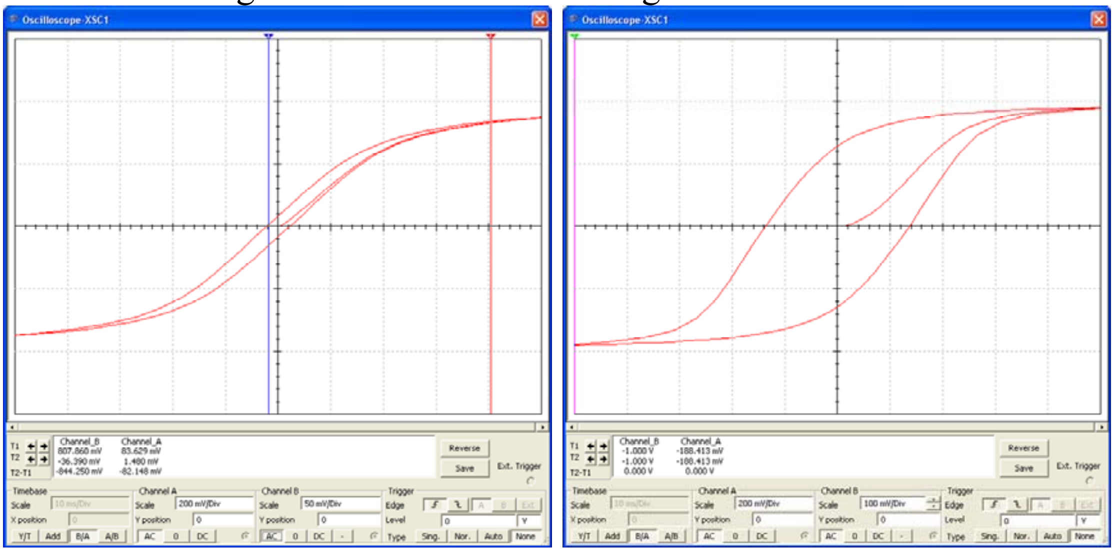

Fig. 5. Simulated and visualized magnetic hysreresises

5. CONCLUSION

The present study is devoted to the analogue behavior modeling of histeresis loop and the simulation of the nonlinear behavior of the magnetic materials. The main advantage of the proposed modeling approach is that it makes possible to represent any given magnetization curve. For close approximation of histeresis' area and shape, the model can be appropriate fitted by using derivates by simulation graphs together with the main magnetic parameters. The developed models are particularly suitable to be incorporated in any SPICE-like simulator. The proposed modeling and simulation approach is potentially a viable tool to study the behavior of various magnetic materials.

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