Efficient Mixed-Domain Behavioural Modeling of Ferromagnetic Hysteresis Implemented in VHDL-AMS

Peter R. Wilson[1], J. Neil Ross[1], Andrew D. Brown[1], Tom Kazmierski[1] and Jerzy Baranowski[2]
[1]University of Southampton, UK, +44(0)23 5089 4162, prw@ecs.soton.ac.uk
[2] Warsaw University of Technology, 00-650 Warsaw, Nowowiejska 15/19, Poland, jbaranowski@ipe.pw.edu.pl

Abstract

In this paper a modified model of ferromagnetic hysteresis suitable for mixed-signal simulations in VHDL-AMS is presented. The aim of this paper is to demonstrate how a numerically stable and accurate implementation of the Jiles-Atherton model can be achieved using a 4th order Runga-Kutta integration of the derivative of magnetization with respect to the field strength (H). While most SPICE-like implementations require inconvenient integration in time to obtain the magnetization derivative, our approach is more general as it does not rely on the underlying differential equation solver for this purpose. The model addresses the non-physical situation of negative BH slopes and proposes an alternative implementation of the anhysteretic function using a polynomial approximation of the Langevin function for low signal levels and a new function with no discontinuities. Model efficiency is improved by monitoring the change in H and only activating the integration function when H changes by a specified amount.

1. Introduction

The Jiles-Atherton (JA) model of ferromagnetic hysteresis [1]-[3] has been used extensively for creating non-linear models of magnetic materials for use in circuit simulation. Despite the basic limitations of the original Jiles-Atherton approach, including poor minor loop modeling, minor loop relaxation and convergence difficulties, the JA model continues to be widely used in the simulation of magnetic and power applications. As a result of this usage, a number of incremental improvements to the model have taken place. Carpenter [4] and Jiles [5] have proposed methods for improving the modeling of minor loops, while Wilson and Ross [6] have shown how multiple loop optimization can lead to a useful characterization of the Jiles-Atherton model over a wide range of applications. Wilson, Ross and Brown [7]-[9] have added further enhancements to the model including improved loop modeling in saturation, dynamic thermal modeling and parameter optimization techniques.

This paper proposes an implementation of the Jiles-Atherton model in VHDL-AMS that specifically uses a different anhysteretic function and directly integrates the magnetization with respect to *H* (applied field strength) and not time. The issue of small time steps causing excessive simulation times is addressed by limiting the integration function to only operating when *H* has changed by a specified amount. Other modifications introduced in this paper are different forms of the Langevin function to improve the implementation of the model. It is important to note that existing SPICE-like simulators have great difficulty in carrying out integration with respect to variables other than time, whereas the approach presented in this paper allows the direct integration with respect to any variable, with accuracy and simulation performance able to be controlled to a significant extent within the model itself.

2. Modifications to the Jiles-Atherton Anhysteretic Function

The original Jiles-Atherton model uses a form of the Langevin function to describe the anhysteretic behaviour of the magnetic material. A simplified version of this has been developed and is shown in equation 1.

$$M_{an} = M_s \left(\frac{2}{\pi} \tan^{-1}\left(\frac{H}{a} \right) \right) \tag{1}$$

Where *H* is the applied field strength and *a* is a model parameter, M_s, the saturation magnetization The results of this are shown in figure 1.

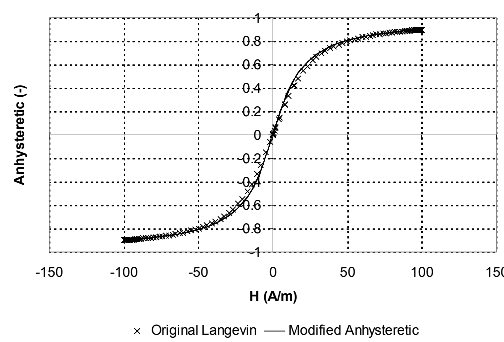

Figure 1: Original and Modified Anhysteretic Functions

3. Implementing the Original Jiles-Atherton model in VHDL-AMS

In order to make a comparison between the original Jiles-Atherton model [1]-[3] and the proposed new approach, a VHDL-AMS model was created using the original equations with a basic direct implementation

1530-1591/04 $20.00 (c) 2004 IEEE

commonly used with a resulting BH curve as shown in figure 2.

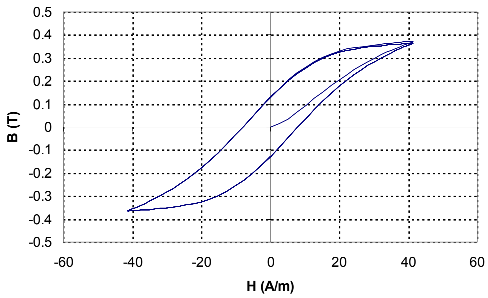

Figure 2: Simulation of Original Jiles-Atherton Model

Some aspects to note about this model are as follows. The way the model implements the integration of the magnetization slope with respect to *H* is to first multiply by the rate of change of *H* and then integrate with respect to time (using the VHDL-AMS '**INTEG** operator). One aspect of the Jiles-Atherton model that has been mentioned previously [1-3] is the non-physical negative slope of dM/dh, and in this model this feature has been checked for and the slope limited to non-negative values only. This removes the anomalous situation in the model where increasing field strength (*H*) can apparently cause a decreasing flux density (*B*).

4. Implementing the modified Model in VHDL-AMS

A Runga-Kutta integration approach can be used to calculate the flux directly without the need for multiplication by the derivative of H with respect to time and then integration of dM/dt with respect to time. This approach is generally not possible in SPICE-like simulators. Simulating the model with a sinusoidal applied field strength (*H*) as before gives the BH curve as shown in figure 3 below. Note that with the different anhysteretic function, for the same model parameters the BH curve exhibits some differences with the two models, including the amplitude of the basic function.

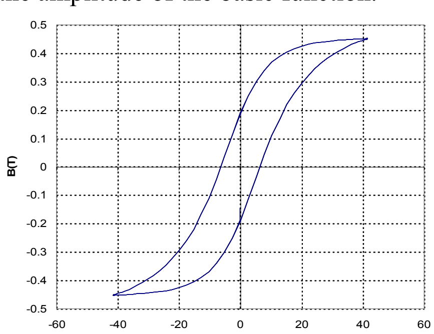

Figure 3: Modified JA Model BH Curve

5. Conclusions

This paper describes a modified Jiles-Atherton model of ferromagnetic hysteresis that is implemented in VHDL-AMS. The modifications address the anhysteretic function and the integration of the derivative of magnetization (*M*) with respect to the applied field strength (*H*). A continuous anhysteretic function is presented that provides a simpler implementation than the commonly used Langevin function, with broadly similar results. The second major modification is the implementation of a direct integration of the magnetization derivative with respect to *H*. This shifts the dependence of the integral of dM/dH from time to H, with a granularity defined by the model user. This has potentially significant benefits from a simulation (convergence) point of view with accuracy controlled on a model rather than a global basis. This approach is a direct result of the ability of VHDL-AMS to run separate process effectively in parallel with the analog solver mechanism and is generally not possible in SPICE-like simulators.

6. References

[1] D.C. Jiles & D.L. Atherton, "Theory of Ferromagnetic Hysteresis (invited)", *Journal of Applied Physics*, Vol. 55 , No 6, Mar 1984, 2115-2120

[2] D.C. Jiles & D.L.Atherton, "Theory of Ferromagnetic Hysteresis", *Journal of Magnetism and Magnetic Materials*, 61, 1986, 48-60

[3] D.C. Jiles & D.L. Atherton, "Ferromagnetic Hysteresis", *IEEE Transactions on Magnetics*, Vol 19, No. 5, Sep 1983, pp2183-2185

[4] K.H. Carpenter, "A differential equation approach to minor loops in the Jiles-Atherton hysteresis model", *IEEE Transactions on Magnetics*, Vol. 27, No. 6, Nov 1991, pp4404-4406

[5] D.C. Jiles, "A self consistent generalized model for the calculation of minor loop excursions in the theory of hysteresis", *IEEE Transactions on Magnetics*, Vol. 28, No.5, Sep 1992, pp2602-2604

[6] P.R. Wilson & J.N. Ross, "Definition and Application of Magnetic Material Metrics in Modeling and Optimization", *IEEE Transactions on Magnetics*, Vol. 37, No. 5, Sep 2001, pp3774-3780

[7] P.R. Wilson, J.N. Ross & A.D. Brown, "Optimizing the Jiles-Atherton model of hysteresis using a Genetic Algorithm", *IEEE Transactions on Magnetics*, Vol. 37, No. 2, March 2001, pp989-993

[8] P. R. Wilson, J. N. Ross & A. D. Brown, "Simulation of Magnetic Component Models in Electric Circuits including Dynamic Thermal Effects", *IEEE Transactions on Power Electronics*, Vol. 17, No. 1, Jan. 2002, pp55-65

[9] P.R. Wilson, J.N. Ross & A.D. Brown, "Magnetic Material Model Characterization and Optimization Software", *IEEE Transactions on Magnetics*, Vol. 38, No. 2, Part 1, Mar. 2002, pp1049-1052