EFFECTIVE NONLINEAR MAGNETIC SIMULATION USING RADSPICE[TM]

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ABSTRACT

SPICE has been used extensively by integrated circuit designers, but its use by the power electronics industry has been limited because of its lack of a nonlinear magnetics model. This paper describes the synthesis of such a model and its installation in RADSPICE (1). Methods for effective simulation techniques when using nonlinear magnetics are given. The model and methods are demonstrated through the accurate simulation of a closed-loop feed-back magnetic power oscilltor.

TECHNICAL DISCUSSION

The magnetics model implemented in RADSPICE is an improved version of the "Pheno" model (2). The model provides a clean way of representing the hysteresis B-H loop characteristics of toroidal magnetic cores by considering the rotation of magnetic dipoles into and out of the six directions of easy magnetization of the cubic structure of iron. The latching action of hysteresis is accomplished in the computer algorithm by keeping track of previous values of dipole orientations.

The main improvement of the original model involves the initialization procedure. Figure 1 illustrates the idea of the B-H curve found in transformer and choke data sheets from which the analyst abstracts data for computer input. In the orginal model implementation, the analyst has to input all eight of the B-H values shown in the figure. Since all eight values over-determines the model, the analyst frequently cannot get a consistent representation of the B-H curve he is trying to model. The problem is aggravated by the fact that the point identified as BM, HM, is quite ambiguous on many data sheet B-H curves. Since this point represents the situation where all magnetic dipoles have been rotated to the easy direction (parallel to one edge of the iron cubic lattice) but not yet elastically rotated to the direction of the applied magnetizing force (saturation) the correct determination of BM, HM is essential.

The new model circumvents this problem by calculating the proper values of BM, HM in the initializing phase of the model implementation. Also eliminated is the need to input BCR. Hence the analyst may just enter five values from the B-H curve (the values without parentheses in Figure 1). This initialization procedure in RADSPICE has proven to be trouble free despite the variety of B-H curve shapes encountered in the workaday application of RADSPICE. The use of TC (core time constant), AC (core area), LC (core length) and LG (gap length) is the same as in the original model.

The model is simply a way of generating a value of B given a value of H by keeping track of the history of B and H. However, the model had to be interfaced to the circuit analysis algorithms inherent in RADSPICE. Since the code already had a linear magnetics model based on using the inductance L of the coils involved, the new nonlinear magnetics model was interfaced to RADSPICE by providing a determination of L (u) from the value of u (the instantaneous permeability) using u = dB/dH (the instantaneous slope of the B-H curve). This relation is:

$$L = uN^2A/l$$

where A is identified with AC, l with LC, and N is the number of turns on the core. The mutual inductance effects between coupled windings on the transformer have to be taken into account in the numerical implementation of the model into SPICE. Mutual inductance tables have to be built which can be used to calculate mutual inductance and flux terms between all coupled windings. Since RADSPICE poses no upper limit on the number of windings which can be placed on a transformer, these tables are built "on the fly" during simulation to suit the specific transformer configuration that is being simulated. Extreme care has to exercised with the numerics in the incorporation of the model into RADSPICE. Since a SPICE style simulator uses a discrete linear approximation to linearize inductors and capacitors (thereby reducing a system of

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differential equations to a system of algebraic linear equations) there are several numerical pitfalls to avoid. The simulator time step controller has to be modified so that transformer characteristics do not change too much from one time point to another. If this were to happen, it would destroy the local linearity approximation that is implicit in the SPICE algorithm. It is usually difficult for any circuit simulator to obtain convergence on circuits that have positive feedback. This is true even for circuits that are relatively linear. Because we knew that one of the principal uses for a transformer model would be circuits such as switching power oscillators and converters, special care had to be exercised in the numerics to preserve convergence. We also found that magnetic circuits are best solved using GEAR integration.

We have used RADSPICE to effectively simulate various kinds of magnetic circuits, including the ROYER oscillator shown in Figure 2. As can be seen from the schematic diagram, the oscillator has full voltage feedback, and a nonlinear hysteresis core. The nonlinearity of the core is fundamental to the proper operation of the oscillator. Usually the simulation engineer has to break the loop in an oscillator of this type just to obtain stable DC convergence. Once the loop is broken, the engineer can perform a DC analysis and proceed to investigate the dynamic properties of the oscillator by driving the oscillator at some point and doing a transient analysis. To the best of our knowledge, no one has ever been able to simulate an oscillator of this type successfully in the closed loop configuration (as is, without breaking the loop or effectively breaking it) before. Care has to be exercised in the method used to start the oscillator in the simulation run. Using the wrong method to start oscillators of this type will result in a shift in the core operating point on the BH curve. The shift will inhibit proper oscillator operation. As can be seen in the RADSPICE circuit net-list, Figure 3, only a few magnetic model parameters were needed to model the transformer. RADSPICE has additional model parameters, such as LGAP (length of air gap) which allow greater flexibility in magnetic modeling. For example, setting LGAP to a suitable gap length will result in proper modelling of the effects of a gap on the BH curve. In addition to printing and plotting normal voltages, currents, power, etc., RADSPICE allows the user to plot magnetic state variables such as flux, B-field, H-field, dB/dT, d(flux)/dT, incremental inductance, etc.

We have used the new magnetic model in RADSPICE to simulate magnetic oscillators, driven converters (linear and nonlinear) and various other magnetic circuits. It has been used to simulate circuits that protect power converters from the effects of core saturation. The anti-saturation circuit in such a converter can be tested in the simulation run without destroying the switching transistors in an actual circuit. We have also used the new model to investigate nonlinear behaviour in power conditioning circuitry such as chokes in power supply filters.

A plot of collector voltage waveforms at nodes 3 and 4 is shown in Figure 3. Figures 4 and 5 show collector current waveforms. Note the current spikes that result from core saturation, as calculated by RADSPICE. Subsequent post-processing by an FFT program yields a spectrum which can be used to estimate RFI noise performance. Figures 6 and 7 are core "H" and "B" fields, respectively. Figure 8 is a parametric three dimensional plot of "B" field versus "H" field, with time as a Z-axis parameter. The nonlinear core model, in conjunction with a modern, efficient circuit simulator and high resolution graphics, allows one to study nonlinear magnetic circuits easily.

The new model, in conjunction with RADSPICE, has been tested on various configurations involving combinations of chokes and transformers and found to produce accurate simulations of commercial circuits not seen in codes using the older models.

REFERENCES

1. RADSPICE Users Guide, SAIC and Meta Software, 1985.
2. W. H. Dierking and C. T. Kleiner, "Phenomenological Magnetic Core Model for Circuit Analysis Programs", IEEE Transactions on Magnetics, September 1972.

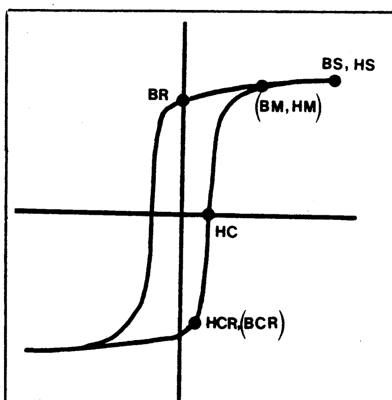

FIGURE 1. B-H CURVE

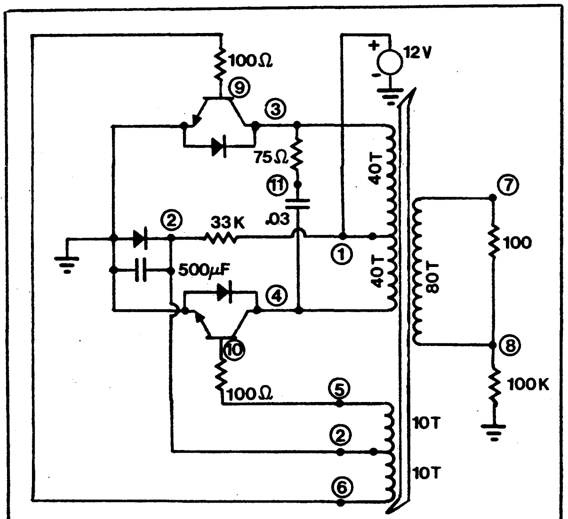

FIGURE 2. MAGNETIC OSCILLATOR

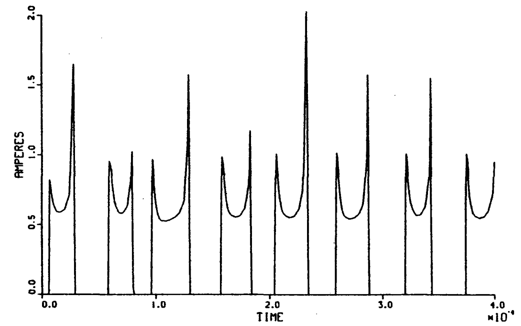

FIGURE 5. Q2 COLLECTOR CURRENT

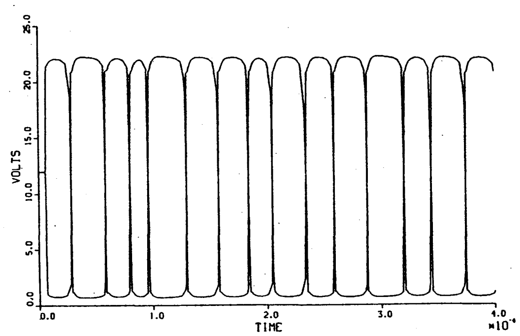

FIGURE 3. Q1 AND Q2 COLLECTOR VOLTAGE

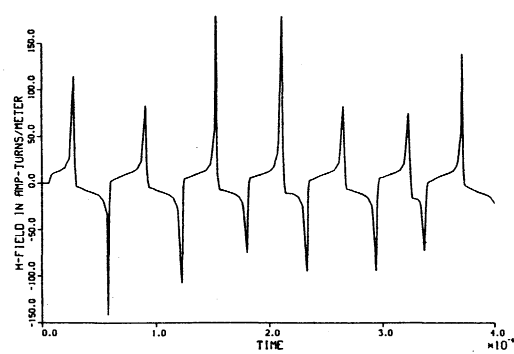

FIGURE 6. MAGNETIZING FORCE

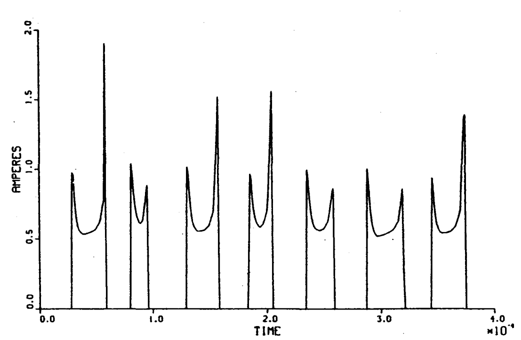

FIGURE 4.Q1 COLLECTOR CURRENT

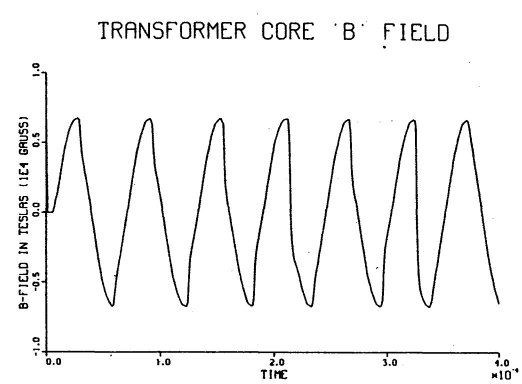

FIGURE 7. TRANSFORMER CORE 'B' FIELD

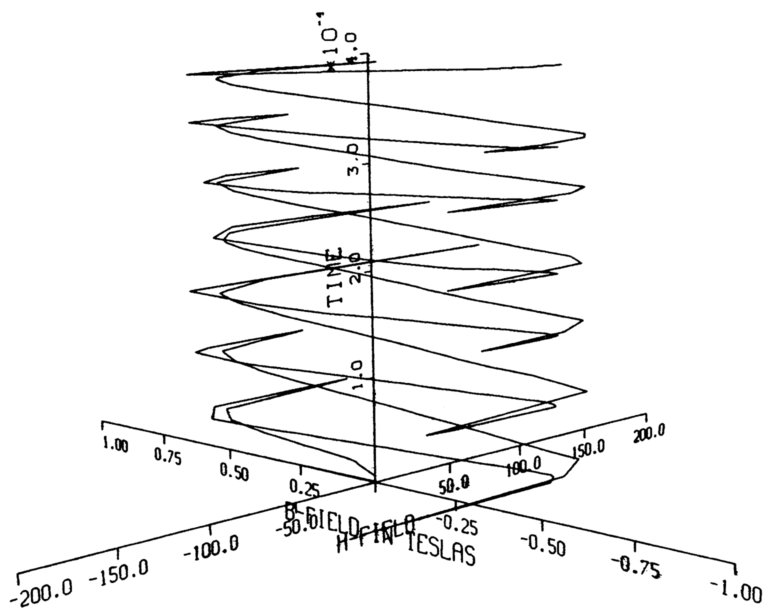

FIGURE 8. B AND H VERSUS TIME