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Non-linear Transformer Modeling and Simulation

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Abstract--Transformers models for simulation with Pspice and Analogy's Saber are being developed using experimental B-H Loop and network analyzer measurements. The models are evaluated for accuracy and convergence using several test circuits. Results are presented which demonstrate the effects on circuit performance from magnetic core losses, eddy currents, and mechanical stress on the magnetic cores.

I. Introduction

Several transformers, of two different types, are in the process of being modeled for use in two different circuit simulators, PSpice and Saber. These simulators were selected because they are capable of simulating non-linear magnetics and hysteresis. The two types of components being modeled are: pulse transformers which have toroidal encapsulated cores and power transformers with pot ferrite unencapsulated cores. It should be noted that Sandia applications often require encapsulating the cores which is not standard industry practice. The encapsulating material, when cured, produces stress on the core.

For transformers with gapped cores, a linear model is usually sufficient when the cores are not driven into saturation, however, a non-linear model is required for encapsulated parts with gapped cores to simulate the actual permeability. The stresses on the core can change the gap and the intrinsic material permeability. The effect of stress on permeability is discussed in references 1 & 8. For encapsulated ungapped cores that are driven into saturation, a non-linear model is necessary for accuracy since the slope of the B-H Loop changes substantially.

The measured B-H Loops for unencapsulated transformers are generally sufficiently close to published and supplier data that one can use this information to extract core parameter values. Passive components are added to the circuit to simulate parasitic effects, (capacitive coupling, leakage inductance, and winding losses) at higher frequencies. The frequencies that require the parasitic components depend primarily on the transformer geometries. The primary and secondary coil proximity and geometry are very significant. The effects of core eddy currents depends on the core material characteristics, the conductivity of the core materials, and the core configuration, e.g. laminations.

II. B-H Loop Data

A. Measurement

We used an OS Walker Hysteresis system, AMH-400, to extract the B-H loop data. We measured the B-H Loops at frequencies from 60 Hz to 200 kHz using sine and square wave. All of the cores were ferrite materials. We had one encapsulated gapped core which had a linear characteristic with some hysteresis, one pot core with no gap which was unencapsulated, and one toroid that was encapsulated.

The most interesting effects are shown in Figure 1 for the pulse transformer with the toroidal core that was encapsulated. The B-H Loop for Magnetics Inc. core, R40603, which was encapsulated for this part, is quite different from the unencapsulated one. The basic shape of the B-H Loop for both parts has been modified, and each of the two parts have different saturation values. Since we only have data on two encapsulated parts, and no physical measurements were made on the cores before they were encapsulated, we can only speculate on the reasons for the different saturation values between the 2 samples. There should be no difference in the saturation

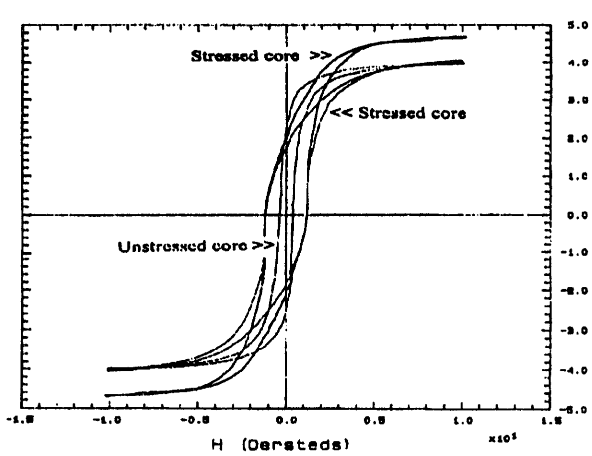

Figure 1. B-H loops for three different cores, 2 encapsulated (stressed) and one unencapsulated.

values. There could be variations in the core cross sectional areas which would make our plotted results look different, since we inputted this parameter into the hysteresis system..

For the unencapsulated power transformer core, Ferroxcube Core, Part No. 1811PL00-3B7, the B-H Loop data for a bare core and the actual part are almost identical as shown in Figure 2. The width of the B-H Loops, i.e., the apparent coercive force does increase for higher frequencies. Little difference was seen for square waves versus sine waves for driving the B-H Loops, Figure 3.

B. Parameter Extraction

Both simulators non-linear core models are based on the Jiles-Atherton model. Reference 3 goes into some

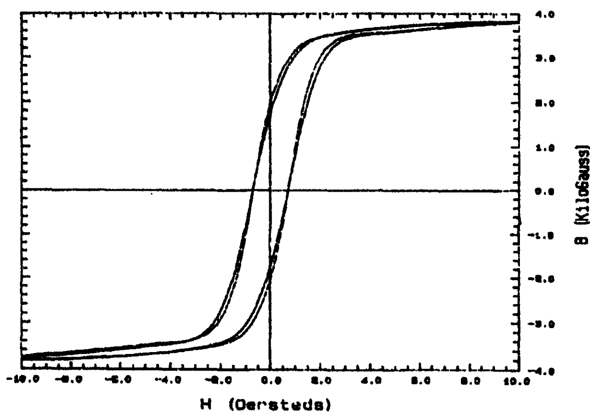

Figure 2. B-H loops for unencapsulated power transformer cores before and after winding.

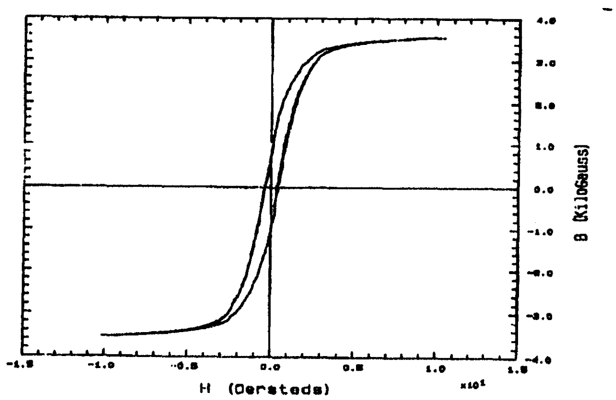

Figure 3. B-H loops measured with both sine square wave drive.

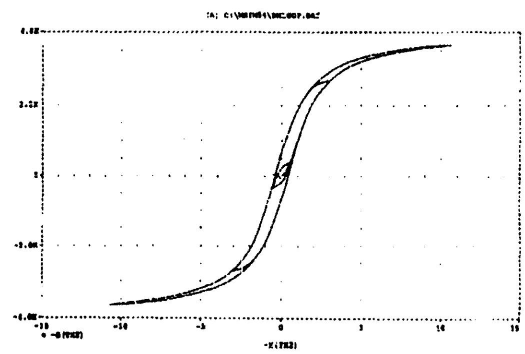

Figure 4. PSpice simulation of B-H loop.

detail on how to match measured data with the Jiles-Atherton model. The model can simulate many unencapsulated cores very well, however, the model cannot be adjusted to match actual B-H Loop for the encapsulated toroidal part that we have with the pulse transformer. A piece-wise linear approximation to the B-H Loop is possible with the SABER simulator, but has not been tried as of yet. For the power transformer a simulation of the B-H loop is shown in Figure 4.

PSpice uses an additional parameter, Gamma, to handle core loss, which increases the apparent coercive force. Use of the Gamma parameter will cause the loop to widen as frequency is increased.

III. Simulation

A. Accuracy

Figure 5 shows an oscillator circuit which has a center tapped transformer with two primaries and two secondaries. Figure 6 shows the operating region of the core B-H Loop for this circuit. Figure 7 shows the simulation results compared to actual data. The PSpice simulator gives reasonably accurate results.

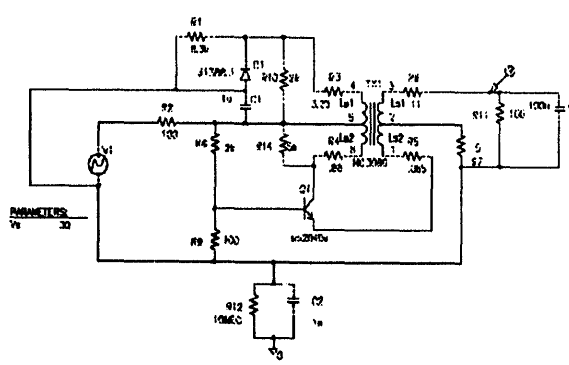

Figure 5. Blocking oscillator circuit for PSpice simulation.

However, one problem is apparent. There is a start up problem with the PSpice simulator. It does not allow the core to start from a residual value. Therefore, one must disregard the first pulse unless the core starts from a demagnetized state.

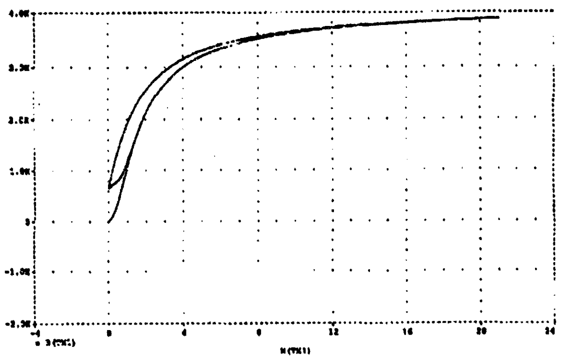

Figure 6. Simulation of the portion of the B-H loop over which the circuit of Figure 5 will operate.

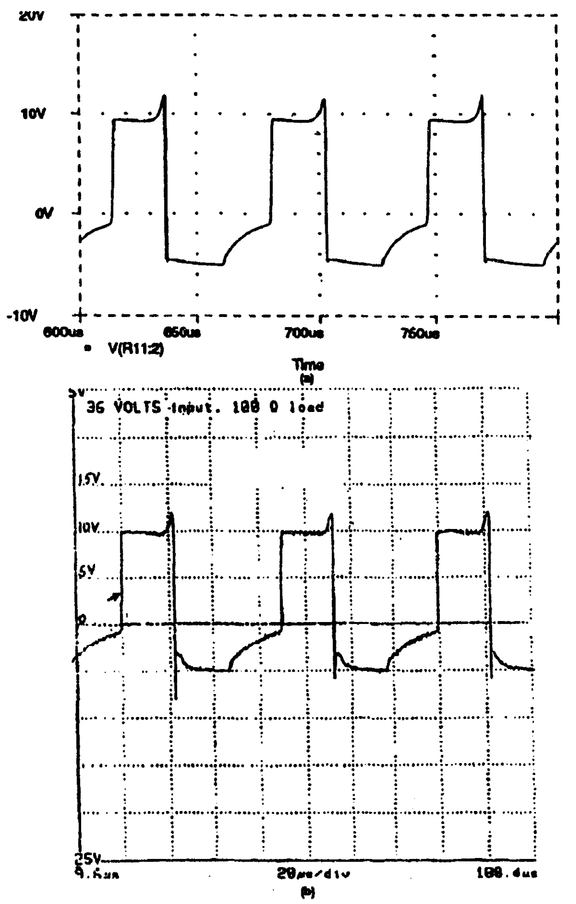

Figure 7. Comparison of simulated and measured output voltage for the circuit of Figure 5. (a) simulated (b) measured

Figure 8 shows the transformer from the circuit of Figure 5 with parasitic parameters, added. The parasitic parameters were measured with a HP4194 Impedance Analyzer. The coupling capacitances were measured at 10 kHz, which is close to the frequency of operation. Figure 9 shows a histogram which shows the effects of variations (manufacturing permutations like the spacing within and between the primary and secondary coils) in these parasitic parameters on the pulse amplitude. The parameters were allowed to have a 100% deviation in the Monte Carlo simulation. The simulator can also look at these effects on pulse height, frequency, rise time, etc. The effects of winding eddy currents, more commonly called "skin effect" and "proximity effect", are neglected since the circuit frequency is about 10 kHz, and small wire gauges are used. If the capacitive coupling became too large (approximately 2 orders of magnitude higher), then the circuit wave forms are like those shown in Figure 10. Estimates of the capacitive coupling can be calculated for new designs using formula given in references 5 and 6. The parameters that can be varied in the Monte Carlo simulation are limited in PSpice to resistors,

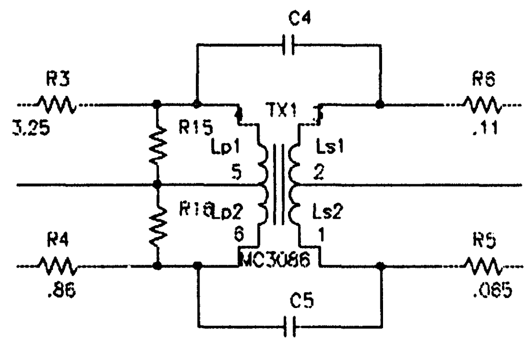

Figure 8. Transformer for the circuit of Figure 5 with parasitics added

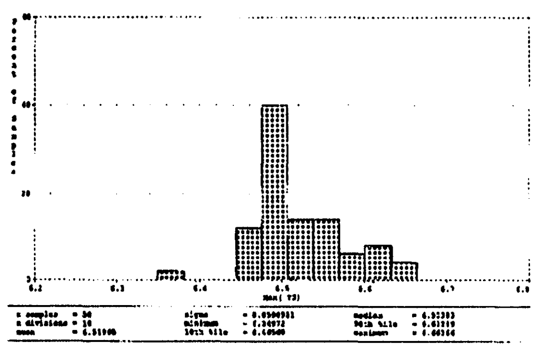

Figure 9. Histogram of oscillator output amplitude with variations in parasitic parameter values.

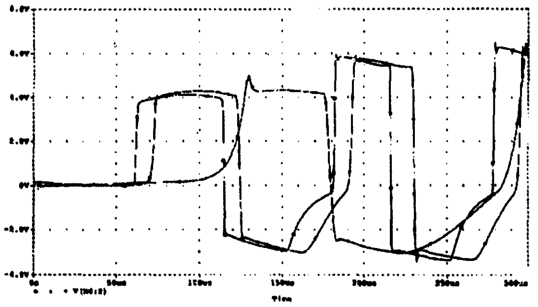

Figure 10. Oscillator output with varying coupling capacitance.

capacitors, inductors, etc. With SABER one can also look at the effects of B-H Loop variations. This is useful, since core properties can have fairly large variations in coercive force, permeabilities, etc.

Figure 11 shows the effect of the Gamma parameter, in PSpice, when the operating frequency is changed. A very simple test circuit, Figure 12, was used for this test. While the model is predicting a widening of the loop with frequency, the effect on the highest test frequency is not realistic. Exceedingly long run times were initially experienced, but these were drastically reduced by beginning with a non-zero current in the primary.

One drawback of the model in its present form, is the lack of temperature variation. Separate sets of parameter values must be used to simulate different temperatures.

B. Convergence

Convergence is a troublesome problem with PSpice for transformers with significant losses and highly non-linear B-H shapes. Saber is expected to improve convergence for these conditions.

The test circuits used for simulation comparisons required modification of convergence criteria

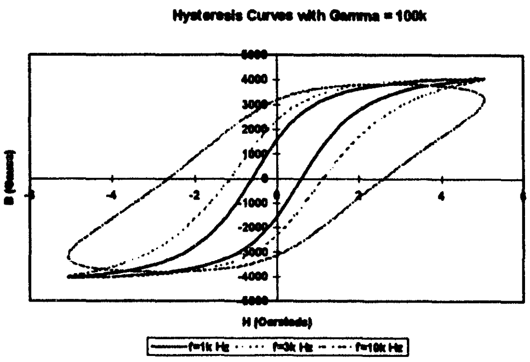

Figure 11. Change in simulated hysteresis curve with increasing frequency.

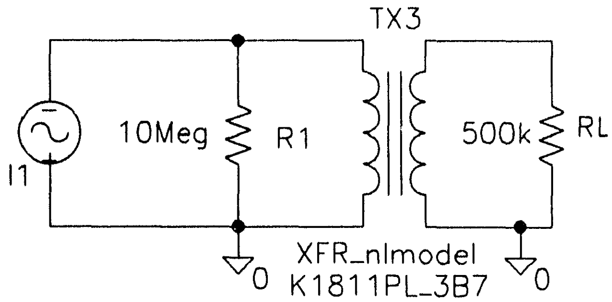

Figure 12. Circuit for simulating the curves of Figure 11.

(ABSTOL, VNTOL, & RELTOL) in order to obtain convergence. The first two should be set to approximately .1% of the maximum value expected during simulation, while RELTOL is set to .005 or higher. Also in PSpice, for transient solutions one can control the number of iterations at a given time interval, reference 7. For the power transformer circuit, a study was done to examine the effects of this parameter. Fifty Monte Carlo runs were made varying the parasitic parameters. Using the default number for iterations ITL4=10, 16 of the solutions did not converge. By increasing ITL4 to 40, only 6 did not converge. Increasing ITL4 to 400 provided convergence for all 50 Monte Carlo runs and did not increase the run time. It was also usually necessary to set a maximum time step size.

For the higher frequency simulation with the test circuits (50 - 200 kHz), Saber allows additional parameters to correct the B-H Loop for eddy currents and core losses. For example, this will show the effect of applying a single square wave pulse for a pulse transformer. The higher frequency components will produce eddy current effects in the core of the transformer. With PSpice, one has to select the frequency of operation and use the corresponding B-H Loop. A simple way to simulate core losses in PSpice is to add a resistor in parallel with the primary coil, as was done in the Monte Carlo simulations. Another way is to add the Gamma parameter; this increases the apparent hysteresis of the B-H Loop which can simulate eddy current losses. The Saber approach can improve the accuracy for simulation of circuit with higher frequency components because one does not need to select a single frequency.

IV. Conclusion

Nonlinear transformers models require measured core data for accurate simulation. The effects of stress can substantially change the B-H Loops for ferrite cores and encapsulated cores with gaps. These effects have to be built into the B-H Loop that is used by the circuit simulators. Accurate modeling of these stress effects is not always possible with the standard Jiles-Atherton

Model. The equations used for this model do not allow for accurate representation for stressed components. However, the errors introduced because of inaccurate B-H Loops are hard tc estimate without accurate simulation. Both simulators, PSpice and SABER, provide accurate results for the low frequency oscillator circuit that was modeled. However for higher frequency simulations, additional parasitic parameters must be added for accurate simulation with PSpice. The SABER simulator has built in modeling capability for core losses and eddy current effects, but one does need to add passive components to simulate coil coupling effects.

ACKNOWLEDGMENTS

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