DEVELOPMENT OF HIGH FREQUENCY SPICE MODELS FOR
FERRITE CORE INDUCTORS AND TRANSFORMERS

by

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ABSTRACT

In this work high frequency SPICE models were developed to simulate the actual behavior of ferrite core inductors and transformers. The models include the nonlinear, multi-valued B-H characteristic of the core material, leakage flux, stray capacitances, and core losses. The saturation effects were modeled using two diode clamping arrangements in conjunction with nonlinear dependent sources. Two possible controlling schemes were developed for the saturation switch. One of the arrangements used the current flowing through a series RC branch to control the switch, while the other used a NAND gate. The NAND gate implementation of the switch proved to be simpler and the parameters associated with it were easier to determine from the measurements and the B-H characteristics of the material. Lumped parameters were used to simulate the parasitic effects. Techniques for measuring these parasitics are described. The models were verified using manganese-zinc ferrite-type toroidal cores and they have general applicability to all circuit analysis codes provided that they contain nonlinear sources or equivalent function blocks such as multipliers, adders, and logic components.

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CHAPTER I

INTRODUCTION

SPICE is an acronym for "Simulation Program with Integrated Circuit Emphasis" and is a circuit analysis program that contains the basic ideal models for resistors, inductors, capacitors, dependent sources, transistors, diodes, and other circuit elements. In order to obtain a realistic model that characterizes the actual behavior of a component, the existing elements must be combined or model parameters must be added to those components which have a built-in library, such as the transistor and diode models, to create a higher order model, or both. Such modeling is essential in order to predict accurately the performance of the circuit before it is built. Thus, it is important to understand how the models work, their limitations, and their accuracy.

The objective of this work was to develop higher order circuit models for inductors and transformers, which characterize the actual behavior of these components in a frequency range between 100 kHz and 10 MHz, as well as techniques for calculating and measuring the corresponding model parameters. Such a model must account for the nonlinear, multi-valued B-H characteristic of the core material; leakage flux; stray capacitances; and core losses. Manganese-zinc (MnZn) ferrite-type cores were used to verify the models because these cores are generally used in this frequency range for power applications, such as switching power supplies. The advantages of using ferrite cores, in general, are their low cost compared to magnetic metals; high electrical resistivity, which results in low eddy current losses over a wide range of frequencies; high permeability; and a high Curie temperature.

A literature survey was carried out to determine what modeling techniques have been employed using SPICE to model the nonlinear behavior of inductors and transformers and what the mechanisms are that control these nonlinearities. Three SPICE models were found in the literature. The first is described in Rumsey's paper [1], and represents a saturating transformer; it uses a variable resistor as a function of saturation in parallel with a linear inductor (figure 1). The value of the nonlinear resistor, $R(I_L)$, depends on the ratio of residual inductor current, I_L , to its saturation value, having a large value out of saturation and a small value at saturation. The model for a general N turn winding saturating transformer with its control function circuitry is depicted in figure 2. The controlling network has 14 elements which must be specified in order to determine the switching conditions of the variable resistor. Thus, it is a rather involved procedure to calculate the parameter values of the model. The second model, by Pei and Lauritzen [2], uses two first-order nonlinear current sources in parallel with a linear inductor (figure 3). One of the sources simulates the saturation effect, the other, the hysteresis characteristic. The coefficients used in the polynomial sources must be determined numerically from the magnetic core characteristic curves. The drawback of this model is that the coefficients are not provided by every manufacturer for its cores, and for frequencies greater than 50 kHz there are no data available, rendering the model unusable at high frequencies. The last model, which is discussed in Meares' paper [3], uses simple dependent sources to simulate the core characteristics and losses (figure 4). It is interesting to note that the model does not include a linear inductor. However, when it was tested, convergence problems were encountered and the performance of the model could not be evaluated unless several modifications were made.

Figure 1. Rumsey's saturating transformer model.

Figure 2. Saturating transformer model with its control function circuitry.

Figure 3. Pei's and Lauritzen's inductor model.

Figure 4. Meares' saturable reactor model.

The basic concepts of electromagnetic theory used in the development of the inductor and transformer models can be found in any textbook of electromagnetic field theory. The book used in this work was the one written by Kraus [4]. A detailed treatment of the mechanism that governs the saturation phenomena and a general piecewise-linear model to illustrate such effects are discussed in Watson's book [5]. This book provides many examples and discussions about the nonlinear behavior of inductors, but it does not provide any details for modeling the saturation switch used in the circuits. The essential physics and magnetic properties of ferrites used for inductors and transformers are thoroughly discussed by Snelling and Giles [6,7]. Among the topics discussed are the magnetization processes caused by wall movement and rotation, magnetic losses such as hysteresis loss, eddy current loss, and dimensional resonance loss, and examples of inductor and transformer designs.

The SPICE models described in this work do not account for all possible scenarios of nonlinear behavior of ferrite core inductors and transformers. The models assume negligible eddy current losses and dimensional resonance losses and were developed for small toroidal cores and low power applications; they simulate the hysteresis and saturation effects of the core. The implementation of these effects were made as simple as possible in order to obtain reasonable execution times and to avoid overloading the computer memory. Because of these constraints, the models have several limitations. The core losses, which are dependent on frequency, are simulated with a single resistor of fixed value in parallel with a linear inductor. This approach is acceptable in most cases where a quick approximate estimate of the performance of the core at a particular frequency is needed. The dependence of the permeability of the core with respect to frequency and temperature has not been incorporated in the

models and the models have been validated only using sinusoidal excitations at different frequencies and amplitudes.

CHAPTER II

THEORY

The theory behind the development of the inductor and the transformer models are the basic concepts of electromagnetic field theory. Faraday's law, which relates the induced voltage across a coil to the instantaneous change in flux linking the coil, is given by

$$v(t) = - N \frac{d\phi}{dt} \quad (1)$$

where N is the number of turns of the coil and $\frac{d\phi}{dt}$ is the rate of change of the flux linked by the coil. Equation 1 can be solved for the flux such that

$$\phi(t) = \frac{1}{N} \int_0^t v(t) dt + \phi_{\text{initial}} \quad (2)$$

The total flux through a surface is defined as

$$\phi(t) = \iint_S \mathbf{B} \cdot d\mathbf{s} \quad (3)$$

If the flux distribution is assumed to be uniform over the cross-sectional area of the core and perpendicular to it, Equation 3 becomes

$$\phi(t) = B(t) \cdot A \quad (4)$$

or

$$\phi_{\text{max}} = B_{\text{max}} \cdot A \quad (5)$$

$$B_{\text{max}} = \frac{\phi_{\text{max}}}{A} \quad (6)$$

The maximum flux density in the core can be estimated from Equations 2 and 6. The relation between the electric current, I , flowing through the coil and the corresponding magnetic field intensity, H , is determined by Ampere's law:

$$\oint \mathbf{H} \cdot d\mathbf{l} = I + \iint_S \frac{\partial \mathbf{D}}{\partial t} \cdot d\mathbf{s} \quad (7)$$

Assuming that the flux is effectively restricted to the core and negligible displacement current, Equation 7 becomes

$$H = \frac{N \cdot I}{l_m} \quad (8)$$

where l_m is the mean length of the magnetic flux path.

2.1 Core Losses

2.1.1 Eddy Current Loss

Core losses are related to the inherent properties of ferromagnetic materials. A time-varying flux induces small current loops (eddy currents) in the core material, which are independent of the load current; the resulting power loss (volume) density, P_e , is

$$P_e = K_e f^2 B_{p-p}^2 \left[\frac{W}{m^3} \right], \quad (9)$$

where $K_e = \frac{\pi A_e}{16\rho}$ is a constant depending on the resistivity, ρ , and the effective cross-sectional area, A_e , of the core material, f is the operating frequency in Hz and B_{p-p} is the peak-to-peak flux density (Tesla) in the core. Thus, the eddy current losses are inversely proportional to the resistivity of the core material. These losses can be minimized either by lamination of the core or by the use of magnetic materials of high resistivity, such as some ferrites, which have resistivities of up to $10^6 \Omega \cdot \text{cm}$ at room temperatures. The MnZn cores used in this work have resistivities less than $100 \Omega \cdot \text{cm}$, so that the eddy current losses cannot be neglected.

2.1.2 Dimensional Resonance Loss

The dimensions of the ferrite cores must be carefully selected to avoid ferromagnetic resonance dispersion. The dimensional resonance causes standing waves within the core that can cause high magnetic and dielectric losses and can hamper the performance of the inductor or transformer [6]. Standing waves

occur when the smallest cross-sectional dimension of the core perpendicular to the magnetic field is one-half wavelength. For a typical manganese-zinc ferrite, the relative magnetic permeability, μ_r , is approximately 10^3 and the relative dielectric permittivity, ϵ_r , is around 10^5 . The velocity of propagation of the electromagnetic wave in this medium is given by

$$v = \frac{1}{\sqrt{\mu \cdot \epsilon}}. \quad (10)$$

where $\mu = \mu_0 \cdot \mu_r$ and $\epsilon = \epsilon_0 \cdot \epsilon_r$, and μ_0 and ϵ_0 are the permeability and permittivity, respectively, of free space. The wavelength depends on the operating frequency, f , and is

$$\lambda = \frac{v}{f}. \quad (11)$$

At $f = 100$ kHz, the wavelength is around 30 cm, and at $f = 1$ MHz, around 3 cm. Thus, the effects of dimensional resonance losses can be neglected between 100 kHz and 1 MHz if manganese-zinc ferrite cores of dimensions less than 1.5 cm are used in this range of frequencies.

2.1.3 Hysteresis Loss

If an alternating magnetomotive force is applied to a ferromagnetic material, driving it into and out of saturation, a magnetization curve (or hysteresis loop) is obtained when B versus H is plotted (figure 5). Initially, the core material is assumed to be unmagnetized. As the magnetizing force, H , is increased, the magnetic domains begin to align themselves in the direction of the field and the magnetic flux density, B , begins to increase from zero, following the path indicated by the arrows in the figure. If H continues to increase, ultimately all the domains will be aligned parallel to the field, and any further increase in H will result in a very small change in the magnetic flux density; a flat magnetization curve results, and the core is said to be saturated.

Figure 5. Hysteresis loop (or B-H curve).

If H is then reduced to zero, the path followed by the curve differs from the initial magnetization curve, as depicted in the figure. There will be a residual flux density (or remanence), B_r , when H is equal to zero; to reduce this flux density to zero, a negative magnetizing force must be applied. The magnetizing force required to reduce the flux density to zero is known as the coercive force, H_c . If H is further increased in the negative direction, the magnetic domains will again become completely aligned in the direction of the field, opposite to their original direction. This corresponds to saturation in the negative direction. Reducing H to zero again produces a negative residual flux density. A positive coercive force is now needed to reduce B to zero. Increasing H beyond this value forces the curve to follow the path shown in the figure until it reaches saturation in the positive direction. The entire cycle is then repeated. The magnetic flux density lags behind the magnetic field intensity because of this characteristic of ferromagnetic materials, and the energy loss per cycle will be proportional to the area of the hysteresis loop. This energy is used in aligning the magnetic domains in the core and is manifested as heat. The hysteresis loss (volume) density, P_h , is calculated from

$$P_h = K_h \cdot f^m \cdot B_{p-p}^n \left[\frac{W}{m^3} \right], \quad (12)$$

where K_h is a constant depending on the core material, f is the operating frequency in Hz, B_{p-p} is the peak-to-peak flux density (Tesla), m is greater or equal to 1, and n lies between 1.5 and 3.0, depending on the material that is used. For MnZn ferrite cores such as the P41005TC material n is 2.461 and m is 1.757; and for the YF41003TC material, n is 2.569 and m is 1.621.

The theory discussed in the previous sections is the basis of the models derived in this work. Information about the B-H curve of the core material, the input impedance characteristic of the coil, and values of the parameters of Equations 2, 6, and 8 are required to establish the parameters of the model.

CHAPTER III

DEVELOPMENT OF THE INDUCTOR MODEL

3.1 Input Impedance Measurement

Two sets of toroidal shaped MnZn ferrite cores, with different thicknesses, were tested; both sets were made by the same manufacturer (Magnetics). One set of cores was made from P41005TC material, with an outer diameter of 9.53 mm, an inner diameter of 4.75 mm, and a height of 4.78 mm. The other set was made from YF41003TC material, with the same outer and inner diameters, but with a height of 3.18 mm. Both sets were wound in two configurations in such a way that they could be used as inductors or as transformers. The first arrangement consisted of 10 turns of uniformly interwound AWG 30 wires around the core. The second configuration used the same wire and number of turns, except that the wires were on opposing sides of the toroid, instead of being interwound. The configurations are shown in figure 6. The input impedance (magnitude and phase) of each coil was measured over a range of frequencies (e.g., 100 kHz to 10 MHz) using an HP-4192A LF impedance analyzer (frequency range: 5 Hz to 13 MHz) or an HP-4815A rf vector impedance meter (frequency range: 0.5 to 108 MHz) (figure 7). These instruments are used for measuring complex impedance of circuits and components. The internal rf oscillator of the HP-4192A meter supplies a test signal of 12.6 μA on the 10 Ω scale range and 4 μA on all other ranges to the unknown impedance. The test signal is small enough that it does not saturate the core material. The measurements were performed with the secondary terminals open-circuited and the leads were kept short to reduce the parasitics. The magnitude and phase were then plotted versus frequency using an XY recorder or by inputting the data points into a spreadsheet program such as LOTUS. The two interwound

a) Bifilar Configuration.

b) Opposing sides Configuration.

Figure 6. The two winding configurations.

Figure 7. Impedance measurement.

cores (P41005TC and YF41003TC) were examined first. The impedance looking into each port (primary side and secondary side) of each coil was measured (Appendix A), and the magnitude and phase were plotted versus frequency, as shown in figures 8 through 15. (The magnitude and the phase of the primary and secondary impedances of each coil were compared to detect any variation between them.) As shown in figures 16 through 19, the difference between values for the primary and the secondary sides is negligible. In the second arrangement, three cases were examined in order to determine if the way of winding the coils had a significant effect on the input impedance. The first two cases consisted in using a single wire in two different topologies. One of the topologies was a uniformly wound 10 turns of wire around the core and the other was 10 turns on one side of the core only. In neither case was there a significant change in the input impedance. In the third arrangement, in which two wires were wound on opposite sides of the core, the impedance looking into one side was different from the impedance looking into the other terminal, as shown in figures 20 and 21. This difference between the impedance of one set of terminals and the other one occurred because the configuration arrangement of the wires is slightly different on each side changing the impedance of the coils. For this reason the opposite wire configuration was not used in this work.

3.2 Synthesis of the Inductor Model

The measurements on the interwound cores indicate that the magnitude of the impedance behaves in a linear fashion up to a particular frequency. For the P41005TC core, it is around 1 MHz, and for the YF41003TC core, around 550 kHz. The phase plot has a zero crossing at 6.25 MHz for the P41005TC core and at 7 MHz for the YF41003TC core. This zero crossing indicates that there

Figure 8. Primary impedance magnitude (P41005TC).

Figure 9. Primary phase (P41005TC).

Figure 10. Primary impedance magnitude (YF41003TC).

Figure 11. Primary phase (YF41003TC).

Figure 12. Secondary impedance magnitude (P41005TC).

Figure 13. Secondary phase (P41005TC).

Figure 14. Secondary impedance magnitude (YF41003TC).

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Figure 16. Comparison between the primary and secondary impedance magnitudes (P41005TC).

Figure 17 . Comparison between the primary and secondary impedance phase angles (P41005TC).

Figure 18. Comparison between the primary and secondary impedance magnitudes (YF41003TC).

Figure 19. Comparison between the primary and secondary impedance phase angles (YF41003TC).

Figure 20. Comparison between the primary and secondary impedance magnitudes (opposing windings).

Figure 21. Comparison between the primary and secondary phase angles (opposing windings).

is a resonant frequency at which the inductor becomes purely resistive. If the frequency is increased beyond resonance, the phase goes negative and the inductor behaves like a capacitor. A small-signal model of the inductor can be synthesized from these linear data; this is illustrated in figure 22. The input impedance of the inductor model, which is a parallel combination of a resistor, an inductor, and a capacitor, is calculated below.

$$Y(s) = \frac{1}{R} + \frac{1}{sL} + sC \quad (13)$$

$$Z(s) = \frac{1}{Y(s)} \quad (14)$$

$$Z(s) = \frac{s}{C(s^2 + s \frac{1}{RC} + \frac{1}{LC})} \quad (15)$$

If $\omega_0^2 = \frac{1}{LC}$ and $\omega_1 = \frac{1}{RC}$

$$Z(j\omega) = \frac{1}{C} \frac{j\omega}{((\omega_0^2 - \omega^2) + j\omega\omega_1)} \quad (16)$$

The magnitude of the impedance is given by

$$|Z(j\omega)| = \frac{1}{C} \frac{\omega}{\sqrt{(\omega_0^2 - \omega^2)^2 + (\omega\omega_1)^2}} \quad (17)$$

Three cases were considered in order to determine the values of the components to be used in a SPICE program.

Case 1:

For $\omega = \omega_0$ (at resonance)

$$|Z(j\omega)| = \frac{1}{C} \frac{1}{\omega_1} = R. \quad (18)$$

Figure 22. Small signal inductor model.

Case 2:

For $w \ll w_0, w_1$ (linear region)

$$|Z(jw)| = \frac{1}{C} \frac{w}{w_0^2} = wL. \quad (19)$$

Case 3:

For $w \gg w_0, w_1$

$$|Z(jw)| = \frac{1}{wC}. \quad (20)$$

The frequency at which the maximum impedance is obtained is the resonant frequency, w_0 ; at this frequency, $|Z(jw_0)|$ is equal to R , which represents the core resistance. The inductance L , which accounts for the magnetizing current, corresponds to the slope of $|Z(jw)|$ for $w \ll w_0$ (Case 2). The value of C , which is the lumped capacitance of the capacitances between the turns of the coil, is computed from

$$C = \frac{1}{w_0^2 L}. \quad (21)$$

If these expressions are used with the information obtained from the measurements, the values of the components of the equivalent circuit can be obtained. For example, using the data for the P41005TC core (Appendix A), the maximum value of $|Z|$ is 2.288 k Ω at a frequency of 6.25 MHz, the resonant frequency. This value is assigned to the resistor R in the model. The value for the inductor L is selected by estimating the maximum frequency to which $|Z|$ in figure 3 increases linearly. For this data, it was estimated that the frequency is around 1 MHz, at which the value of $|Z|$ is 1.4 k Ω . The calculated value for L (Case 2) is then 222.8 μ H, from Equation 21, the value of C is 2.91 pF. A small resistor, which can be considered as the winding resistance of the inductor, is added in series with the inductor in the SPICE model in order

to provide a DC path to ground in the DC analysis. Appendix B contains listings of the programs and their corresponding outputs.

An AC analysis with a 1 V source was performed with SPICE program to obtain the magnitude and phase of the current flowing into the inductor. The reciprocal of this current corresponds to the input impedance. The results obtained from the SPICE simulation and the measurements are compared in figures 23 through 26. The SPICE predictions were within 6% of the measured values for material P41005TC, and within 16% for material YF41003TC. The SPICE simulations predicted a more conservative behavior, having a lower quality factor and greater bandwidth, than the actual measurements. A better correlation can be obtained by adjusting the capacitor by a few picofarads and the inductor by a few microhenries. The model can be understood better if the values of stray capacitance are varied by a few picofarads while holding the values of the other components constant. Figures 27 and 28 show the effect of increasing the capacitance; the resonant frequency is reduced and the magnitude of the impedance above resonant is decreased. Increasing the values of inductances while holding the other component values constant, as seen in figures 29 and 30, simply increases the slope of the impedance in the linear region, as expected.

3.3 Inductor Model with an RC Switch

Two models were developed to include the hysteresis losses in the small-signal inductor model. The first consists of a flux controlling circuit and an RC switch in combination with the small-signal model, as shown in figure 31. This is a modification of the model described by Meares [3]; Meares' model could not be successfully applied. The saturation switch, which was modeled by a current-controlled current source and its reference branch current, was replaced by a current-controlled voltage source

Figure 23. Comparison between measured values and values calculated by SPICE (magnitudes, P41005TC).

Figure 24. Comparison between measured values and values calculated by SPICE (phases, P41005TC).

Figure 25. Comparison between measured values and values calculated by SPICE (magnitudes,YF41003TC).

Figure 26. Comparison between measured values and values calculated by SPICE (phase,YF41003TC).

Figure 27. Dependence of impedance magnitude on the capacitor value.

Figure 28. Dependence of phase on the capacitor value.

$|Z|$ vs f

Figure 29. Dependence of impedance magnitude on inductor value.

Phase vs f

Figure 30. Dependence of phase on inductor value.

Figure 31. Higher order inductor model using an RC switch.

controlled by the current flowing through the series combination of RSE and CBH. The magnetic flux in the core is determined by integrating the applied voltage (Equation 2), which is analogous to integrating the current flowing through a capacitor to obtain the voltage across it. The integration can be implemented by using a voltage-controlled current source, GF, the controlling voltage of which is the input voltage, in parallel with a capacitor, CF. The voltage across the capacitor, which is proportional to the magnetic flux in the core and corresponds to the voltage at node 4, is then

$$V_4(t) = \frac{1}{C_F} \int_0^t i(t) dt + v_c(0). \quad (22)$$

For $v_c(0) = 0$ V and $i(t) = I_m \sin(\omega t)$,

$$V_4(t) = V_{inpeak} * \text{Gain of GF} * \left(-\frac{1}{\omega C_F} \cos(\omega t) \right) \Big|_0^t \quad (23)$$

or

$$V_4(t) = V_{inpeak} * \text{Gain of GF} * \frac{1}{\omega C_F} (1 - \cos(\omega t)). \quad (24)$$

The gain of GF is selected such that the voltage across CF reaches its maximum allowable value at the same instant as the core saturates.

An initial negative current is specified on the inductor in order to force the current negative and to obtain a symmetrical hysteresis loop and a starting point on the loop. The time required to reach saturation is determined by equating the area under the input voltage (for either polarity) to the peak-to-peak saturation flux linkages, Λ_{satp-p} , which is the maximum allowable change of Λ ,

$$\Lambda_{\text{satp-p}} = \int_0^{t_{\text{sat}}} V_{\text{in}}(t) dt. \quad (25)$$

To simulate the saturation effect, two sets of clipping diodes with their respective voltage sources are added in parallel across CF. One set controls the positive cycle of the flux, the other, the negative cycle. The clamping voltage is set one diode voltage drop less than the desired saturation flux voltage, which is proportional to the product of B_{sat} (from B-H curve) and the cross-sectional area of the core, so that the voltage at node 4 will be clamped precisely at this value.

The switch consists of a current-controlled voltage source, HBH, the controlling current of which depends on the current flowing through the RC branch of the components RSE and CBH. A current will flow in this branch as long as the voltage across it, which is proportional to the voltage at node 4, is varying with respect to time. As soon as this voltage reaches the saturation value, it is clamped, forcing the current in this branch to go to zero and to flow through the resistor RK. A small resistor is added in series with the dependent source HBH to ensure that no inductor-source loop is encountered in the SPICE simulations. The current flowing through the RC branch, and the current, $I(\text{VS1})$, which flows through the current limiting resistor, RS1, just before the device goes into saturation, must be known before the gain of HBH can be set. The following procedure was used to obtain the current values.

The voltage across CBH is calculated from

$$V_4(t) = R_{\text{SE}} I_{\text{RSE}}(t) + V_{\text{CBH}}(t), \quad (26)$$

$$\text{where } I_{\text{RSE}}(t) = I_{\text{CBH}}(t) = C_{\text{BH}} \frac{d V_{\text{CBH}}(t)}{dt}.$$

Substituting $I_{RSE}(t)$ in Equation (26) and solving the differential equation with zero initial conditions,

$$V_{CBH}(t) = \frac{e^{-at}}{R_{SE}C_{BH}} \int_0^t V_4(t) e^{at} dt, \quad (27)$$

where $a = \frac{1}{R_{SE}C_{BH}}$.

Substituting $V_4(t)$ from Equation (24) into Equation (27),

$$V_{CBH}(t) = \frac{A}{R_{SE}C_{BH}} e^{-at} \left[\int_0^t e^{at} dt - \int_0^t \cos(wt) e^{at} dt \right] \quad (28)$$

where $A = V_{in_{peak}} * \text{Gain of GF} * \frac{1}{wC_F}$.

But

$$\int e^{ax} \cos(bx) dx = \frac{e^{ax}}{a^2 + b^2} [a \cos(bx) + b \sin(bx)], \quad (29)$$

so that

$$V_{CBH}(t) = A(1 - e^{-at}) - \frac{A}{R_{SE}C_{BH}} e^{-at} \left[\frac{e^{at}}{a^2 + w^2} (a \cos(wt) + w \sin(wt)) \right] \Big|_0^t \quad (30)$$

and

$$V_{CBH}(t) = A(1 - e^{-at}) + \frac{A}{R_{SE}C_{BH}} \left[\frac{a(e^{-at} - \cos(wt)) - w \sin(wt)}{a^2 + w^2} \right]. \quad (31)$$

The current flowing through the RC branch is

$$I_{CBH}(t) = C_{BH} \frac{dV_{CBH}(t)}{dt} \quad (32)$$

$$I_{CBH}(t) = \frac{A}{R_{SE}} e^{-at} + \frac{A}{R_{SE}^2 C_{BH}} \frac{1}{(w^2 + a^2)} * \\ [-a e^{-at} + w \sin(wt) - w^2 R_{SE} C_{BH} \cos(wt)]. \quad (33)$$

If $at \gg 1$, e^{-at} is close to zero, and if $a \gg w$, the only terms remaining are the sine and the cosine terms.

$$I_{CBH}(t) = wAC_{BH} [\sin(wt) - w R_{SE} C_{BH} \cos(wt)]. \quad (34)$$

If $wR_{SE}C_{BH} \ll 1$,

$$I_{CBH}(t) = wAC_{BH} \sin(wt). \quad (35)$$

Note that, if $V_4(t)$ is constant, then $V_{CBH}(t)$ is also constant. In this case, $\frac{dV_{CBH}(t)}{dt}$ is equal to zero, and $I_{CBH}(t) = 0$. A numerical value for I_{CBH} can be obtained by replacing t by the saturation time t_{sat} . The voltage required across the source HBH at $t=t_{sat}$ is

$$V_{HBH}(t_{sat}) = V_{in}(t_{sat}) - (R_{S1} + R_{BH}) I(VS1) \quad (36)$$

where $I(VS1)$ is the value of the current flowing in the inductor just before it saturates. Finally, the gain of HBH is the ratio of V_{HBH} to I_{CBH} . In order to facilitate these calculations, a series of programs, listed in Appendix C, were written for a programmable calculator, such as the HP-41C.

3.4 Inductor Model with a NAND Gate Switch

The second model is similar to the previous one in that it employs the flux controlling circuit and the small-signal inductor model; however, a NAND gate is used to control the switch (figure 32), that is the positive and negative portions of the saturation cycle. Its output goes low (less than 0.7 V) when both of its controlling inputs go high (greater than 0.7 V); otherwise, its output remains high (equal to the supply voltage, 10 V). One of the inputs to the NAND gate is related to the flux in the core and the value of the saturation flux, which is determined from the B-H curve and the cross-sectional area of the core; when the flux exceeds this value, the input goes high. A two-dimensional voltage-controlled voltage source, the controlling voltage of which is the difference between these two fluxes, is used to achieve this level change in the SPICE implementation; the saturation flux being represented by a separate circuit which consists of a voltage source, the nominal value of which is the value of the saturation flux, in parallel with a 1 Ω resistor.

The other input to the NAND gate is related to the current flowing into the inductor model and the magnetic field strength at saturation, H_{sat} , which is expressed in terms of a current and represented as a current source in parallel with a 1 Ω resistor. Again, a two-dimensional current-controlled voltage source, the controlling current of which is the difference between the square of these two currents, is used. The output of this nonlinear dependent source must go high whenever the input current exceeds the current equivalent of H_{sat} . An input voltage is considered to be high if it is greater than 0.7 V; therefore, the values of the polynomial coefficients of the respective dependent sources must scale their controlling quantities accordingly. The SPICE manual contains details of specifying the different coefficients.

Switch: EWP 2 16 POLY(2) 1 0 13 0 0 0 0 0.8

NAND gate: EFP 7 0 POLY(2) 30 0 20 0 0 1 -1.67MEG
HCP 8 0 POLY(2) VSE1 VSE2 0 2MEG -20

Figure 32. Inductor model with a NAND gate switch.

The switch in this model was modified because the output of the NAND gate is either 0.7 V or 10 V, instead of varying with respect to time as in the previous model. To implement the switch in the model, the output of the NAND gate is scaled down to unity (1 V) when it is high by using a voltage-controlled voltage source, which has a gain equal to the reciprocal of the supplied voltage used in the NAND gate, in parallel with a 1 Ω resistor. The voltage across the switch is controlled by another two-dimensional voltage-controlled voltage source, the controlling voltage of which is the product of the input voltage to the model and the scaled output of the NAND gate, which is either unity or close to zero. When the core is not in saturation, the applied voltage appears across the switch. However, when the two conditions for saturation are satisfied, approximately zero volts appear across the switch. A small resistor is added in series with the dependent sources to avoid an inductor-voltage source loop error in the SPICE simulation.

CHAPTER IV

DEVELOPMENT OF THE TRANSFORMER MODEL

4.1 Impedance Measurements

The small-signal transformer model is derived from the inductor model, which includes core resistance, winding resistance, and stray capacitance. However, the transformer model should include leakage inductance and the capacitance between the primary and the secondary windings. In order to measure the capacitance between the windings, the inputs of both coils were separately shorted and connected to an impedance analyzer (figure 33). The results are provided in Appendix A; the magnitude and phase of the impedances of each device are shown in figures 34 and 35. (The measurements indicate, in fact, a capacitive impedance.) This measurement was also performed with the core grounded and no significant change was observed in the input impedance. The leakage inductance was measured (figure 36) by shorting one set of terminals and measuring the input impedance, which corresponds to the winding resistance and the leakage inductance, at the other terminals. The leakage inductance was only a few tenths of a microhenry, which is small compared to the unsaturated total inductance of the coil, and could be neglected; however, it should be included in the model for complete accuracy.

4.2 Transformer Model

The transformer model is shown in figure 37. The ideal transformer (figure 38) was implemented by using dependent sources to perform the ratio transformation of voltage and current.

Figure 33. Interwinding capacitance measurement

Figure 34. Magnitude of the impedance between the windings.

Figure 35. Interwinding phase shift.

Figure 36. Leakage inductance measurement.

Figure 37. Transformer model.

Figure 38. Ideal transformer model.

A SPICE program, using the measured values as the model component values, was written for the transformer model and the input impedance was computed for two different resistive load conditions, 1 k Ω and a 10 k Ω . The measured data for each case are listed in Appendix F and the SPICE simulation in Appendix G. The input impedances are compared in figures 39 through 46; the computed values are within 10% of the measured values. The difference between them increases as the load is increased; the limiting value of the difference approaches the open circuit condition, which is the inductor case. As a final step, the saturable inductor model using the NAND gate switch is incorporated in the transformer model (figure 47) and the SPICE program is listed in Appendix H. The measurements and results are discussed in the next chapter.

Figure 39. Transformer impedance magnitude ($R_L=1$ k Ω , P41005TC).

Figure 40. Transformer phase ($R_L=1$ k Ω , P41005TC).

Figure 41. Transformer impedance magnitude ($R_L=10\text{ k}\Omega$, P41005TC).

Figure 42. Transformer phase ($R_L=10\text{ k}\Omega$, P41005TC).

Figure 43. Transformer impedance magnitude ($R_L=1\text{ k}\Omega$, YF41003TC).

Figure 44. Transformer phase ($R_L=1\text{ k}\Omega$, YF41003TC).

Figure 45. Transformer impedance magnitude ($R_L=10\text{ k}\Omega$, YF41003TC).

Figure 46. Transformer phase ($R_L=10\text{ k}\Omega$, YF41003TC).

Figure 47. Transformer model with saturable inductor model.

CHAPTER V

MEASUREMENTS AND RESULTS

5.1 Measurement of B-H Curves

The experimental arrangement of figure 48 was used to obtain the B-H characteristic of the cores. The B-H characteristic appears on the CRT when the coil input current and the voltage across C_T are fed to the horizontal and vertical inputs, respectively, of the oscilloscope. The applied magnetizing force, H , is related to the current, I , by Equation (8) and assuming negligible displacement current.

$$H = \frac{NI}{l_m}, \quad (8)$$

where l_m is the mean length of the magnetic path of the core and N is the number of turns. The voltage induced in the secondary, which has the same number of turns as the primary, is determined by Faraday's law. If $R_T \gg \frac{1}{\omega C_T}$, the current flowing is essentially the ratio of the induced voltage to R_T . Integrating this current, and making appropriate substitutions, the voltage across C_T is

$$V_{C_T} = \frac{NA_m B}{R_T C_T}, \quad (37)$$

where A_m is the mean cross-sectional area of the core and B , the magnetic flux density. The voltage across C_T is then proportional to the magnetic flux density. R_T was set equal to 1 k Ω and C_T , to 0.025 μ F, in the experimental arrangement of figure 48, and a sinusoidal input was used to drive the test core into saturation. The input current, the voltage across the inductor and the voltage across C_T were the measured quantities. Measurements were

Figure 48. Experimental arrangement for measuring B-H curves.

made on both types of cores and similar results were obtained for each; therefore, only the results for the YF41003TC core are discussed in detail. The measured waveforms for this core are shown in figures 49 through 52; and the following information was extracted. With an applied peak voltage of 22 V at a frequency of 100 kHz, the current just before saturation was about 400 mA; the peak current during saturation, 2.6 A; and the time to reach saturation, approximately 2 μ s. The peak voltage across the capacitor was 1.2 V and the saturation flux, calculated from Equation (38), 3 μ Wb. The values of the components for the model incorporating the RC switch were computed using the programs in Appendix C; the SPICE output listing is given in Appendix D. The results obtained from this simulation are plotted in figures 53 through 56. For the model employing the NAND gate, the relevant quantities are the saturation flux and the current just before saturation. The SPICE output listing is in Appendix E and the results are depicted in figures 57 through 60. The measured saturation times are 2 μ s for the negative portion of the cycle and 0.8 μ s for the positive one, whereas the results of the simulation are saturation times of 2 μ s for each cycle. This difference is the result of the assumptions used in obtaining the model, that is, symmetric B-H characteristics and equal saturation times for each portion of the cycles were assumed. The voltages V1 and V2 in the clamping diode arrangement of the flux circuit must be changed to obtain unequal saturation times in the simulation. The plots of flux versus current for both models predict a flat saturation response whereas the measurement shows the residual flux is not equal to the saturation flux. A linear inductor must be added in parallel with the small resistor in the saturation switch; varying the values of this parallel combination as shown in figures 61 through 64 predicts the required residual flux voltage. When the models were modified, the predictions simulated very closely the actual behavior of an inductor. The

Figure 49. Measured voltage across the inductor.

Figure 50. Measured input current.

Figure 51. Measured voltage across C_T .

Figure 52. V_{C_T} versus input current.

Figure 53. Voltage across the inductor (RC switch).

Figure 54. Input current (RC switch).

Figure 55. Flux voltage (RC switch).

Figure 56. Flux voltage versus input current (RC switch).

Figure 57. Voltage across the inductor (NAND gate switch).

Figure 58. Input current (NAND gate switch).

Figure 59. Flux voltage (NAND gate switch).

Figure 60. Flux voltage versus input current (NAND gate switch).

Figure 61. B-H characteristic with $RWP = 0.1 \, \Omega$ and no LWP.

Figure 62. B-H characteristic with RWP = 10 Ω and no LWP.

Figure 63. B-H characteristic with $RWP = 10 \Omega$ and $LWP = 100 \mu H$.

Figure 64. B-H characteristic with $RWP = 10 \Omega$ and $LWP = 50 \mu H$.

transformer model shown in figure 47 was verified under three different resistive load conditions (500 Ω , 1 k Ω , and 10 k Ω). The measured load voltage and current for each case are shown in figures 65 through 67. The results of the SPICE simulations are shown in figures 68 and 69. The simulated waveforms agree with the measured data.

5.2 Effects on Hysteresis Losses with Changes in Applied Voltage and Frequency

The effects on the hysteresis losses of three different operating conditions were examined, and both types of material were tested in order to compare the losses between them. The first case consisted of varying the applied sinusoidal voltage from 10 V_{p-p} to 60 V_{p-p} for the P41005TC material and from 10 V_{p-p} to 40 V_{p-p} for the YF41003TC material, in steps of 10 V_{p-p} , at a fixed frequency. The arrangement in figure 48 with $R_T = 1$ k Ω and $C_T = 0.056$ μ F was used to obtain the B-H characteristics for both cores, which are shown in figures 70 and 71. The smaller loop corresponds to an applied voltage of 10 V_{p-p} ; the size of the loops increasing as the input voltage was increased. The energy lost per cycle in a unit volume of the material [J/(m³ cycle)] is then equal to the hysteresis loop area. This area was determined by plotting the B-H loop on graph paper and counting the number of squares enclosed by the loop. After the energy was calculated, the hysteresis power loss was obtained by multiplying this energy by the volume of the core and the operating frequency. The results for $f = 100$ kHz are shown in Table 1, and the power loss is plotted versus the applied voltage in figure 72. The second case consisted of varying the frequency and keeping the applied voltage at a constant value. The frequencies used were 100 kHz, 200 kHz, 300 kHz, 400 kHz, 500 kHz and 1 MHz. The input voltage was maintained constant at 10 V_{p-p} , 20 V_{p-p} , 30 V_{p-p} , 40 V_{p-p} , and

Figure 65. Measured load voltage and current (smaller curve) for $R_L = 500\Omega$. The voltage and current scales are 10 V and 50 mA, respectively, per large division. The horizontal scale is 5 μ s per large division.

Figure 66. Measured load voltage and current (smaller curve) for $R_L = 1 \text{ k}\Omega$. The voltage and current scales are 10 V and 50 mA, respectively, per large division. The horizontal scale is 5 μs per large division.

Figure 67. Measured load voltage and current (smaller curve) for $R_L = 10 \text{ k}\Omega$. The voltage and current scales are 10 V and 50 mA, respectively, per large division. The horizontal scale is 5 μs per large division.

Figure 68. Load voltage for $R_L = 500\ \Omega$, $1\ \text{k}\Omega$, and $10\ \text{k}\Omega$.

Figure 69. Load current for $R_L = 500\ \Omega$, $1\ \text{k}\Omega$, and $10\ \text{k}\Omega$.

Figure 70. B-H characteristics obtained for the P41005TC material by varying the applied voltage from 10 V_{p-p} to 60 V_{p-p} in steps of 10 V_{p-p} at a fixed frequency of 100 kHz. The inner loop corresponds to 10 V_{p-p} and the outer one, to 60 V_{p-p} . The vertical scale is 200 mV per large division and the horizontal scale is 50 mA per large division.

Figure 71. B-H characteristics obtained for the YF41003TC material by varying the applied voltage from 10 V_{p-p} to 40 V_{p-p} in steps of 10 V_{p-p} at a fixed frequency of 100 kHz. The inner loop corresponds to 10 V_{p-p} and the outer one, to 40 V_{p-p}. The vertical scale is 200 mV per large division and the horizontal scale is 50 mA per large division.

Table 1: Measured power loss obtained by varying the applied voltage in steps of 10 V_{p-p} at a fixed frequency of 100 kHz.

		P41005TC	
Applied Voltage	# of Squares	Energy Loss	Power Loss
[Vp-p]		J/(m**3 cycle)	[mW]
10	9	0.61	14
20	39.5	2.7	61.5
30	123	8.39	191.4
40	255.5	17.44	397.6
50	463	31.58	720.1
		YF41003TC	
10	12	1.23	18.6
20	110.75	11.39	171.9
30	203.75	20.95	316.3
40	341.25	35.08	529.7
50	- - -	- - -	- - -

Figure 72. Measured power loss obtained by varying the applied voltage at a fixed frequency of 100 kHz.

50 V_{p-p}. The results for the P41005TC material are shown in figures 73 through 77, and for the YF41003TC material, in figures 78 through 81. Table 2 shows the losses for different cases of applied voltage; the power loss variations under these conditions are shown in figure 82. The third case consisted of varying the frequency and the applied voltage so that the flux density level in the core remained at a constant level. The B-H characteristics in figures 83 and 84 are for the P41005TC material for a peak flux density level of 101.8 mT and 127.3 mT, respectively. The frequency was varied in steps of 100 kHz, starting from 100 kHz, while the input voltage was adjusted so that the same peak flux density was obtained. This same approach was used to acquire the B-H characteristics for the YF41003TC material, shown in figures 85 and 86. The peak flux densities in this case were 153.4 mT and 198.2 mT, respectively. Table 3 shows the power losses for the P41005TC material for $B_{\text{peak}} = 127.3 \text{ mT}$ and for the YF41003TC material for $B_{\text{peak}} = 198.2 \text{ mT}$. Figures 87 and 88 show the power losses as a function of frequency and applied voltage, respectively, while holding the flux density level constant.

The three measurement schemes permit the following conclusions to be drawn. The hysteresis losses increased as the amplitude of the applied voltage at a fixed frequency was increased. This occurs because an increase in the magnitude of the applied voltage corresponds to an increase in the magnitude of the flux density level. The same effect was observed when the frequency was increased while maintaining a constant flux level in the core. However, the losses decrease when the frequency is increased and the amplitude of the applied voltage is held constant. This happens because the magnitude of the flux density level in the core is inversely proportional to the frequency. Table 4 summarizes these results. The total power loss is equal to the sum of the eddy current and the hysteresis losses, and is given by

$$P_{\text{Total}} = V_e (P_e + P_h) \quad [\text{W}] \quad (38)$$

Figure 73. B-H characteristics obtained for the P41005TC material by varying the frequency of the applied voltage, while keeping its amplitude fixed at $10\text{ V}_{\text{p-p}}$. The inner loop corresponds to a frequency of 1 MHz and the outer one, to 100 kHz. The vertical scale is 50 mV per large division and the horizontal scale is 10 mA per large division.

Figure 74. B-H characteristics obtained for the P41005TC material by varying the frequency of the applied voltage, while keeping its amplitude fixed at 20 V_{p-p}. The inner loop corresponds to a frequency of 1 MHz and the outer one, to 100 kHz. The vertical scale is 200 mV per large division and the horizontal scale is 50 mA per large division.

Figure 75. B-H characteristics obtained for the P41005TC material by varying the frequency of the applied voltage, while keeping its amplitude fixed at 30 V_{p-p}. The inner loop corresponds to a frequency of 1 MHz and the outer one, to 100 kHz. The vertical scale is 200 mV per large division and the horizontal scale is 50 mA per large division.

Figure 76. B-H characteristics obtained for the P41005TC material by varying the frequency of the applied voltage, while keeping its amplitude fixed at 40 V_{p-p}. The inner loop corresponds to a frequency of 1 MHz and the outer one, to 100 kHz. The vertical scale is 200 mV per large division and the horizontal scale is 50 mA per large division.

Figure 77. B-H characteristics obtained for the P41005TC material by varying the frequency of the applied voltage, while keeping its amplitude fixed at 50 V_{p-p}. The inner loop corresponds to a frequency of 1 MHz and the outer one, to 100 kHz. The vertical scale is 200 mV per large division and the horizontal scale is 50 mA per large division.

Figure 78. B-H characteristics obtained for the YF41003TC material by varying the frequency of the applied voltage, while keeping its amplitude fixed at 10 V_{p-p}. The inner loop corresponds to a frequency of 1 MHz and the outer one, to 100 kHz. The vertical scale is 200 mV per large division and the horizontal scale is 50 mA per large division.

Figure 79. B-H characteristics obtained for the YF41003TC material by varying the frequency of the applied voltage, while keeping its amplitude fixed at 20 V_{p-p}. The inner loop corresponds to a frequency of 1 MHz and the outer one, to 100 kHz. The vertical scale is 200 mV per large division and the horizontal scale is 50 mA per large division.

Figure 80. B-H characteristics obtained for the YF41003TC material by varying the frequency of the applied voltage, while keeping its amplitude fixed at 30 V_{p-p}. The inner loop corresponds to a frequency of 1 MHz and the outer one, to 100 kHz. The vertical scale is 200 mV per large division and the horizontal scale is 50 mA per large division.

Figure 81. B-H characteristics obtained for the YF41003TC material by varying the frequency of the applied voltage, while keeping its amplitude fixed at 40 V_{p-p}. The inner loop corresponds to a frequency of 1 MHz and the outer one, to 100 kHz. The vertical scale is 200 mV per large division and the horizontal scale is 50 mA per large division.

Table 2: Measured power loss obtained by varying the operating frequency of a fixed applied voltage.

		P41005TC	Vin p-p = 50V
f	# of Squares	Energy Loss	Power Loss
[kHz]		[J/m**3 cycle]	[mW]
100	444.25	30.32	691.3
200	165.5	11.3	515.1
300	85.5	5.84	399.1
400	62	4.23	385.9
500	47.25	3.23	367.6
1000	22	1.5	342.3
			Vin p-p = 30V
100	139.5	9.53	217.2
200	41.5	2.83	129.25
300	26	1.78	121.5
400	18	1.23	112.1
500	14	0.96	109
1000	6.5	0.44	101.2
		YF41003TC	Vin p-p = 30V
100	239.75	24.66	372.3
200	89.75	9.23	278.7
300	47.25	4.86	220.1
400	35	3.6	217.4
500	24.5	2.52	190.2
1000	11	1.13	170.8

Figure 82. Measured power loss obtained by varying the frequency of the applied voltage while keeping its magnitude fixed at a constant value.

Figure 83. B-H characteristics obtained for the P41005TC material by varying the frequency (in steps of 100 kHz) and the applied voltage to obtain a constant peak flux density level in the core of 101.8 mT. The inner loop corresponds to a frequency of 100 kHz and the outer one, to 400 kHz. The vertical scale is 100 mV per large division and the horizontal scale is 50 mA per large division.

Figure 84. B-H characteristics obtained for the P41005TC material by varying the frequency (in steps of 100 kHz) and the applied voltage to obtain a constant peak flux density level in the core of 127.3 mT. The inner loop corresponds to a frequency of 100 kHz and the outer one, to 300 kHz. The vertical scale is 100 mV per large division and the horizontal scale is 50 mA per large division.

Figure 85. B-H characteristics obtained for the YF41003TC material by varying the frequency (in steps of 100 kHz) and the applied voltage to obtain a constant peak flux density level in the core of 153.4 mT. The inner loop corresponds to a frequency of 100 kHz and the outer one, to 400 kHz. The vertical scale is 100 mV per large division and the horizontal scale is 50 mA per large division.

Figure 86. B-H characteristics obtained for the YF41003TC material by varying the frequency (in steps of 100 kHz) and the applied voltage to obtain a constant peak flux density level in the core of 191.8 mT. The inner loop corresponds to a frequency of 100 kHz and the outer one, to 300 kHz. The vertical scale is 100 mV per large division and the horizontal scale is 50 mA per large division.

Table 3: Measured power loss for the P41005TC material for $B_{\text{peak}} = 127.3 \text{ mT}$ and for the YF41003TC material for $B_{\text{peak}} = 198.2 \text{ mT}$.

		P41005TC		
f	Applied Voltage	# of Squares	Energy Loss	Power Loss
[kHz]	[Vp-p]		J/(m**3 cycle)	[mW]
100	18	98.5	3.36	76.6
200	36	142.75	4.87	222.1
300	50	220.75	7.53	515.3
		YF41003TC		
100	18	167.5	8.61	130.1
200	36	244.5	12.57	379.7
300	52	333.25	17.14	776.3

Figure 87. Measured power loss as a function of frequency, while keeping a constant flux density level and varying the amplitude of the applied voltage.

Figure 88. Measured power losses as a function of applied voltage, while keeping the flux density level constant and varying the frequency.

Table 4: Effects on hysteresis losses and flux density levels with changes in frequency and amplitude of the applied voltage.

$V_{in\ p-p}$	f	B_{peak}	P_h
↑	constant	↑	↑
constant	↑	↓	↓
↑	↑	constant	↑

or

$$P_{\text{Total}} = V_e (K_e f^2 B_{p-p}^2 + K_h f^m B_{p-p}^n) \quad [\text{W}] \quad (39)$$

where V_e is the effective volume of the core in m^3 .

A least-squares fit was used to determine the constant coefficients, K_e and K_h , in Equation (39) from the measured data.

The algorithm used for the least-squares fit was

$$S = \sum_{i=1}^n (P_i - K_e X_i - K_h Y_i)^2 \quad (40)$$

where

S = the sum of the square of the individual errors;

i = i th data point;

n = total number of measured points;

P_i = the measured power at a certain frequency, f_i , and flux density level $B_{p-p\ i}$;

$X_i = f_i^2 B_{p-p\ i}^2 V_e$;

$Y_i = f_i^m B_{p-p\ i}^n V_e$;

K_e = eddy current loss coefficient; and

K_h = hysteresis loss coefficient.

To find the values for K_e and K_h such that S is a minimum, Equation (40) is differentiated with respect to K_e and K_h and the respective derivatives are set equal to zero. Using this approach, the following equations are obtained:

$$K_e \sum_{i=1}^n (X_i)^2 + K_h \sum_{i=1}^n X_i Y_i = \sum_{i=1}^n P_i X_i \quad (41)$$

and

$$K_e \sum_{i=1}^n X_i Y_i + K_h \sum_{i=1}^n (Y_i)^2 = \sum_{i=1}^n P_i Y_i. \quad (42)$$

These two equations are solved simultaneously for K_e and K_h to obtain the following expressions:

$$K_e = \frac{\left(\sum_{i=1}^n P_i X_i \right) \left(\sum_{i=1}^n (Y_i)^2 \right) - \left(\sum_{i=1}^n P_i Y_i \right) \left(\sum_{i=1}^n X_i Y_i \right)}{\Delta} \quad (43)$$

and

$$K_h = \frac{\left(\sum_{i=1}^n P_i Y_i \right) \left(\sum_{i=1}^n (X_i)^2 \right) - \left(\sum_{i=1}^n P_i X_i \right) \left(\sum_{i=1}^n X_i Y_i \right)}{\Delta}, \quad (44)$$

$$\text{where } \Delta = \left(\sum_{i=1}^n (X_i)^2 \right) \left(\sum_{i=1}^n (Y_i)^2 \right) - 2 \left(\sum_{i=1}^n X_i Y_i \right). \quad (45)$$

Using these equations and the measured data in Tables 1, 2, and 3, the values for K_e and K_h were calculated. For the P41005TC material, K_e is approximately 1.48543×10^{-4} and K_h is 8.99413×10^{-3} ; for the YF41003TC material, K_e is around 3.11627×10^{-4} and K_h is 1.747292×10^{-2} . The hysteresis losses, the eddy current losses, and the total power losses were calculated from Equations (9), (12), and (39), respectively, for each of the cases tested. These results, as well as a comparison between measured power loss and calculated power loss for each case, are shown in figures 89 through 102. As it can be seen from the comparison of the total power losses, the losses estimated by Equation (39) provide a good prediction of the actual losses. However, the eddy current losses were not negligible and in some cases exceeded the hysteresis losses.

5.3 Experimental Problems

Several experimental problems affected the measurements above 500 kHz. The dynamic range of the power amplifier decreased as the operating frequency was increased, causing distortions in the input waveform, and hence, the cores could not be completely driven into saturation. The B-H characteristics of

Figure 89. Measured and estimated power loss obtained by varying the applied voltage ($f = 100\text{ kHz}$, P41005TC).

Figure 90. Eddy current and hysteresis losses obtained by varying the applied voltage ($f = 100\text{ kHz}$, P41005TC).

Figure 91. Measured and estimated power loss obtained by varying the frequency ($V_{p-p} = 50$ V, P41005TC).

Figure 92. Eddy current and hysteresis losses obtained by varying frequency ($V_{p-p} = 50$ V, P41005TC).

Figure 93. Measured and estimated power loss obtained by varying the frequency ($V_{p-p} = 30\text{ V}$, P41005TC).

Figure 94. Eddy current and hysteresis losses obtained by varying frequency ($V_{p-p} = 30\text{ V}$, P41005TC).

Figure 95. Measured and estimated power losses obtained at a constant peak flux density level of 127.3 mT (P41005TC).

Figure 96. Eddy current and hysteresis losses obtained a constant peak flux density level of 127.3 mT (P41005TC).

Figure 97. Measured and estimated power loss obtained by varying the applied voltage ($f = 100$ kHz, YF41003TC).

Figure 98. Eddy current and hysteresis losses obtained by varying the applied voltage ($f = 100$ kHz, YF41003TC).

Figure 99. Measured and estimated power loss obtained by varying the frequency ($V_{p-p} = 30$ V, YF41003TC).

Figure 100. Eddy current and hysteresis losses obtained by varying frequency ($V_{p-p} = 30$ V, YF41003TC).

Figure 101. Measured and estimated power losses obtained at a constant peak flux density level of 191.8 mT (YF41003TC).

Figure 102. Eddy current and hysteresis losses obtained a constant peak flux density level of 191.8 mT (YF41003TC).

the cores were generated by displaying the voltage across the capacitor C_T versus the input current with the XY display mode of the oscilloscope. It was later observed that when identical signals at a frequency of 100 kHz or higher were applied to the amplifiers in the XY mode, an elongated slanted ellipse, instead of a straight line at 45 degrees, was displayed. This effect became more apparent as the frequency was increased. It was concluded that there was an inherent phase shift in the XY mode of all oscilloscope amplifiers (the effect was verified with a digital oscilloscope).

CHAPTER VI

CONCLUSIONS

This work shows the potential of SPICE to simulate the behavior of magnetic components by using the proper combination of circuit elements and nonlinear dependent sources. The two inductor models require the input impedance of the inductor over a selected frequency range, the B-H characteristic of the core, and the time to core saturation for a particular input excitation. Both models provided similar predictions, the principal difference between the models being the implementation of the saturation switch. The model using the RC switch requires more involved calculations and information about the type of excitation being used, in order to determine the component values and the gains in the dependent sources. On the other hand, the model using the NAND gate switch is easier to implement because the two controlling quantities, the saturation flux and the current just before saturation, can easily be obtained from the measurements. The models have been verified only up to 500 kHz because the dynamic range of the power amplifier decreased as the operating frequency was increased, producing a distorted signal above this frequency.

The transformer model, which is an extension of the inductor model with the parasitic components added to it, has been tested for the input impedance for two load conditions (1 k Ω and 10 k Ω) and for the primary and secondary voltages and currents. The results from the SPICE simulations are in satisfactory agreement with the measured data.

The models were made as general as possible so that different components can be represented by changing the values of the parameters. The models are complex enough to provide a

realistic representation of the behavior of inductors and transformers, yet simple enough to be implemented in any other circuit analysis codes and have reasonable execution times. The models can be improved if the effect of the core losses are simulated by incorporating a frequency dependent resistor model and by including an inductor model that depends on the frequency and temperature dependence of the permeability of the material. However, increasing the complexity of the models can cause long execution times and can exceed the computer memory capabilities.

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APPENDIX A
MEASURED DATA

Impedance Measurement

File : Graph 123 measurements
 Core : P41005TC
 #Turns : 10:10
 O.D. : 9.53 mm
 I. D. : 4.75 mm
 Height : 4.78 mm
 Weight : 1.2 gms
 l_e : 2.072cm
 A_e : 0.110 cm²
 V_e : 0.228 cm³

Note : The impedance values were read from Graph I, II, and III.

<u>Primary Side</u> (Graph I)			<u>Secondary Side</u> (Graph II)		<u>Shorted Ends</u> (Graph III)	
f	Z	ϕ	Z	ϕ	Z	ϕ
[MHz]	[K Ω]	[deg]	[K Ω]	[deg]	[K Ω]	[deg]
0.1	0.150	88.0	0.150	90.0		-
90						
0.2	0.275	88.0	0.275	90.0		-90
0.3	0.42	87.5	0.425	88.5		-90
0.4	0.575	86.0	0.575	86.0		-90
0.5	0.750	82.5	0.750	82.5		-90
0.6	0.900	78.0	0.900	77.0		-90
0.7	1.025	73.5	1.025	72.0		-90
0.8	1.163	69.0	1.175	67.5		-90
0.9	1.300	64.5	1.300	63.0		-90
1.0	1.400	60.0	1.420	59.0		-90
1.1	1.500	57.0	1.512	55.5		-90
1.2	1.575	52.5	1.600	51.0		-90
1.3	1.650	48.0	1.660	47.0		-90
1.4	1.700	45.0	1.725	43.5		-90
1.5	1.750	42.0	1.770	42.0		-90
1.6	1.775	39.0	1.800	39.0		-90

1.7	1.800	36.0	1.825	36.0		-90
1.8	1.825	34.5	1.850	34.5	12.0	-90
1.9	1.850	32.0	1.870	33.0	11.5	-90
2.0	1.875	30.0	1.882	31.0	11.0	-90
2.5	1.950	24.0	1.950	25.0	8.8	-90
3.0	2.000	19.5	2.012	20.0	7.4	-90
3.5	2.075	16.5	2.075	17.0	6.4	-90
4.0	2.125	13.0	2.140	14.0	5.6	-90
4.5	2.200	10.5	2.200	11.0	5.0	-90
5.0	2.237	7.5	2.237	8.0	4.5	-90
5.5	2.263	4.5	2.270	5.0	4.1	-90
6.0	2.275	1.5	2.287	2.0	3.8	-90
6.25	2.288	0.0	2.287	1.0	3.65	-90
6.5	2.288	-1.5	2.287	0.0	3.5	-90
7.0	2.275	-4.5	2.287	-3.0	3.3	-90
7.5	2.263	-6.0	2.270	-6.0	3.1	-90
8.0	2.238	-9.0	2.250	-8.0	2.9	-90
8.5	2.200	-11.0	2.225	-10.0	2.7	-90
9.0	2.175	-12.5	2.185	-12.0	2.6	-90
9.5	2.132	-14.0	2.150	-13.5	2.45	-90
10.0	2.113	-16.0	2.125	-15.0	2.35	-90

Impedance Measurement

File : Graph 789 measurements
 Core : YF41003TC
 #Turns : 10:10
 O.D. : 9.53 mm
 I. D. : 4.75 mm
 Height : 3.18 mm
 Weight : 0.82 gms
 l_e : 2.072 cm
 A_e : 0.073 cm²
 V_e : 0.151 cm³

Note : Measurements were taken at LMSC.
 The impedance values were read from Graph VII, VIII,
 and IX.

<u>Primary Side</u> (Graph VII)			<u>Secondary Side</u> (Graph VIII)		<u>Shorted Ends</u> (Graph IX)	
f	Z	ϕ	Z	ϕ	Z	ϕ
[MHz]	[K Ω]	[deg]	[K Ω]	[deg]	[K Ω]	[deg]
0.1	0.120	86.0	0.113	86.0		-90
0.2	0.225	84.0	0.213	84.0		-90
0.3	0.325	81.0	0.300	81.0		-90
0.4	0.425	76.5	0.425	76.5		-90
0.5	0.525	72.0	0.525	72.0		-90
0.6	0.613	67.5	0.613	67.5		-90
0.7	0.700	63.0	0.687	63.0		-90
0.8	0.763	58.5	0.763	58.5		-90
0.9	0.825	55.5	0.825	55.5		-90
1.0	0.875	52.0	0.875	52.0		-90
1.1	0.913	49.5	0.913	49.5		-90
1.2	0.950	46.5	0.950	46.5		-90
1.3	0.975	45.0	0.975	45.0		-90
1.4	1.000	42.0	1.000	42.0		-90
1.5	1.025	41.0	1.025	41.0		-90
1.6	1.050	39.0	1.050	39.0		-90
1.7	1.075	38.0	1.075	38.0		-90
1.8	1.100	37.5	1.113	37.5		-90

1.9	1.125	36.0	1.125	36.0		-90
2.0	1.150	35.0	1.150	35.0	12.0	-90
2.5	1.250	31.5	1.250	31.5	9.7	-90
3.0	1.350	27.0	1.350	27.0	8.1	-90
3.5	1.425	24.0	1.437	24.0	7.0	-90
4.0	1.513	20.0	1.513	20.0	6.1	-90
4.5	1.575	16.5	1.575	16.5	5.5	-90
5.0	1.613	13.0	1.625	13.0	4.9	-90
5.5	1.625	9.0	1.650	9.0	4.5	-90
6.0	1.650	6.0	1.663	6.0	4.1	-90
6.25	1.663	4.5	1.675	4.5	4.0	-90
6.5	1.650	3.0	1.675	3.0	3.8	-90
7.0	1.650	0.7	1.660	0.7	3.6	-90
7.5	1.637	-0.7	1.650	-1.5	3.3	-90
8.0	1.625	-4.5	1.637	-4.5	3.1	-90
8.5	1.600	-6.0	1.620	-6.0	3.0	-90
9.0	1.575	-8.0	1.600	-8.0	2.8	-90
9.5	1.550	-9.0	1.575	-9.0	2.7	-90
10.0	1.538	-11.5	1.550	-10.5	2.5	-90

Impedance Measurement

File : P1010OP

Core : P41005TC

#Turns : 10:10 (opposite sides, blue wire AWG=30)

Note : Measurements were taken at TTU.

Date : 3-29-88

<u>Primary Side</u>			<u>Secondary Side</u>		<u>Shorted Ends</u>	
f	Z	∅	Z	∅	Z	∅
[MHz]	[KΩ]	[deg]	[KΩ]	[deg]	[KΩ]	
	[deg]					
0.5	0.700	86.0	0.700	86.0	46.0	-90
0.6	0.880	82.0	0.880	82.0	38.0	-90
0.7	1.050	77.0	1.050	77.0	36.0	-90
0.8	1.200	72.0	1.200	72.0	30.0	-90
0.9	1.325	67.0	1.325	66.0		
1.0	1.450	63.0	1.460	61.0	28.0	-90
1.1	1.600	58.0	1.575	56.0		
1.2	1.700	53.0	1.700	52.0		
1.3	1.800	49.0	1.800	48.0		
1.4	1.900	44.0	1.860	43.0		
1.5	1.940	40.0	1.925	40.0	18.5	-90
1.6	1.960	37.0	1.975	36.0		
1.7	2.000	34.0	2.000	33.0		
1.8	2.025	31.0	2.050	30.0		
2.0	2.040	27.0	2.090	26.0	14.0	-90
2.5	2.060	18.0	2.100	18.0	11.0	-90
3.0	2.075	13.0	2.150	12.0	9.2	-90
3.5	2.100	9.0	2.200	7.0	7.9	-90
4.0	2.150	4.0	2.200	1.0	6.9	-90
4.5	2.175	0.0	2.250	-4.0	6.1	-90
5.0	2.175	-3.0	2.250	-8.0	5.6	-90

6.0	2.160	-10.0	2.160	-16.0	4.7	-90
6.5	2.140	-14.0	2.125	-20.0	4.2	-90
7.0	2.100	-17.0	2.050	-24.0	4.0	-90
8.0	2.000	-23.0	1.940	-30.0	3.5	-90
9.0	1.900	-28.0	1.800	-34.0	3.0	-90
10.0	1.800	-31.0	1.700	-37.0	2.7	-90

APPENDIX B
SPICE LISTINGS AND OUTPUTS

```
*File: SPICE PC41005TC 10 10 LMSC
*CORE: P41005TC N1=N2=10 FROM LMSC GRAPH I.
*PRIMARY SIDE DATA |Z|=1400 AT F=1MEGHZ
VIN 1 0 AC 1V
VSE 1 2 0V
R1 2 0 2.288K
L1 2 3 222.8UH
RW 3 0 0.1
C1 2 0 2.91PF
.WIDTH IN=72 OUT=72
.AC LIN 100 100KHZ 10MEGHZ
.PRINT AC I(VSE) IP(VSE)
.END
```

*** 7-APR-88 *** SPICE 2G.6 3/15/83***09:24:10*****

*INDUCTOR MODEL.

**** AC ANALYSIS TEMPERATURE = 27.000 DEG C

FREQ	I(VSE)	IP(VSE)
1.000E+05	7.155E-03	-8.646E+01
2.000E+05	3.595E-03	-8.300E+01
3.000E+05	2.416E-03	-7.956E+01
4.000E+05	1.832E-03	-7.618E+01
5.000E+05	1.485E-03	-7.288E+01
6.000E+05	1.258E-03	-6.966E+01
7.000E+05	1.098E-03	-6.655E+01
8.000E+05	9.811E-04	-6.354E+01
9.000E+05	8.917E-04	-6.065E+01
1.000E+06	8.219E-04	-5.787E+01
1.100E+06	7.662E-04	-5.522E+01
1.200E+06	7.210E-04	-5.268E+01
1.300E+06	6.837E-04	-5.026E+01
1.400E+06	6.526E-04	-4.795E+01
1.500E+06	6.265E-04	-4.576E+01
1.600E+06	6.042E-04	-4.367E+01
1.700E+06	5.852E-04	-4.168E+01
1.800E+06	5.688E-04	-3.978E+01
1.900E+06	5.545E-04	-3.798E+01
2.000E+06	5.421E-04	-3.626E+01
2.100E+06	5.311E-04	-3.462E+01
2.200E+06	5.215E-04	-3.306E+01
2.300E+06	5.130E-04	-3.157E+01
2.400E+06	5.054E-04	-3.014E+01
2.500E+06	4.986E-04	-2.877E+01
2.600E+06	4.926E-04	-2.747E+01
2.700E+06	4.872E-04	-2.621E+01
2.800E+06	4.823E-04	-2.501E+01
2.900E+06	4.779E-04	-2.386E+01

FREQ	I(VSE)	IP(VSE)
3.000E+06	4.739E-04	-2.275E+01
3.100E+06	4.703E-04	-2.168E+01
3.200E+06	4.671E-04	-2.065E+01
3.300E+06	4.641E-04	-1.966E+01
3.400E+06	4.614E-04	-1.870E+01
3.500E+06	4.590E-04	-1.777E+01
3.600E+06	4.567E-04	-1.688E+01
3.700E+06	4.547E-04	-1.601E+01
3.800E+06	4.528E-04	-1.517E+01
3.900E+06	4.512E-04	-1.436E+01
4.000E+06	4.496E-04	-1.356E+01
4.100E+06	4.482E-04	-1.280E+01
4.200E+06	4.469E-04	-1.205E+01
4.300E+06	4.457E-04	-1.132E+01
4.400E+06	4.447E-04	-1.061E+01
4.500E+06	4.437E-04	-9.923E+00
4.600E+06	4.428E-04	-9.251E+00
4.700E+06	4.420E-04	-8.594E+00
4.800E+06	4.413E-04	-7.953E+00
4.900E+06	4.407E-04	-7.326E+00
5.000E+06	4.401E-04	-6.713E+00
5.100E+06	4.396E-04	-6.114E+00
5.200E+06	4.391E-04	-5.527E+00
5.300E+06	4.387E-04	-4.953E+00
5.400E+06	4.384E-04	-4.390E+00
5.500E+06	4.380E-04	-3.838E+00
5.600E+06	4.378E-04	-3.296E+00
5.700E+06	4.376E-04	-2.764E+00
5.800E+06	4.374E-04	-2.242E+00
5.900E+06	4.373E-04	-1.730E+00
6.000E+06	4.372E-04	-1.226E+00
6.100E+06	4.371E-04	-7.304E-01
6.200E+06	4.371E-04	-2.432E-01

FREQ	I(VSE)	IP(VSE)
6.300E+06	4.371E-04	2.363E-01
6.400E+06	4.371E-04	7.082E-01
6.500E+06	4.372E-04	1.173E+00
6.600E+06	4.372E-04	1.631E+00
6.700E+06	4.374E-04	2.082E+00
6.800E+06	4.375E-04	2.526E+00
6.900E+06	4.376E-04	2.964E+00
7.000E+06	4.378E-04	3.397E+00
7.100E+06	4.380E-04	3.823E+00
7.200E+06	4.383E-04	4.244E+00
7.300E+06	4.385E-04	4.659E+00
7.400E+06	4.388E-04	5.069E+00
7.500E+06	4.391E-04	5.474E+00
7.600E+06	4.394E-04	5.874E+00
7.700E+06	4.397E-04	6.269E+00
7.800E+06	4.400E-04	6.660E+00
7.900E+06	4.404E-04	7.046E+00
8.000E+06	4.408E-04	7.428E+00
8.100E+06	4.412E-04	7.805E+00
8.200E+06	4.416E-04	8.179E+00
8.300E+06	4.420E-04	8.548E+00
8.400E+06	4.424E-04	8.913E+00
8.500E+06	4.429E-04	9.275E+00
8.600E+06	4.433E-04	9.633E+00
8.700E+06	4.438E-04	9.987E+00
8.800E+06	4.443E-04	1.034E+01
8.900E+06	4.448E-04	1.068E+01
9.000E+06	4.453E-04	1.103E+01
9.100E+06	4.458E-04	1.137E+01
9.200E+06	4.463E-04	1.171E+01
9.300E+06	4.469E-04	1.204E+01
9.400E+06	4.475E-04	1.237E+01
9.500E+06	4.480E-04	1.270E+01

FREQ	I(VSE)	IP(VSE)
9.600E+06	4.486E-04	1.303E+01
9.700E+06	4.492E-04	1.335E+01
9.800E+06	4.498E-04	1.367E+01
9.900E+06	4.504E-04	1.399E+01
1.000E+07	4.510E-04	1.430E+01

```
*FILE: SPICE YF INDUCTOR MODEL
*CORE: YF41003TC N1=N2=10 FROM LMSC GRAPH
*VII.
*PRIMARY SIDE DATA |Z|=0.525 AT F=0.5MEGHZ
VIN 1 0 AC 1V
VSE 1 2 0V
R1 2 0 1.6625K
L1 2 3 167.1UH
RW 3 0 0.1
C1 2 0 3.88PF
.WIDTH IN=72 OUT=72
.AC LIN 100 100KHZ 10MEGHZ
.PRINT AC I(VSE) IP(VSE)
.END
```

*** 7-APR-88 ** SPICE 2G.6 3/15/83 ** 09:25:10

*INDUCTOR MODEL.

* AC ANALYSIS TEMPERATURE = 27.000 DEG C

FREQ	I(VSE)	IP(VSE)
1.000E+05	9.542E-03	-8.633E+01
2.000E+05	4.796E-03	-8.277E+01
3.000E+05	3.224E-03	-7.923E+01
4.000E+05	2.447E-03	-7.575E+01
5.000E+05	1.986E-03	-7.236E+01
6.000E+05	1.684E-03	-6.906E+01
7.000E+05	1.472E-03	-6.588E+01
8.000E+05	1.317E-03	-6.281E+01
9.000E+05	1.198E-03	-5.986E+01
1.000E+06	1.106E-03	-5.705E+01
1.100E+06	1.032E-03	-5.436E+01
1.200E+06	9.728E-04	-5.180E+01
1.300E+06	9.237E-04	-4.936E+01
1.400E+06	8.829E-04	-4.705E+01
1.500E+06	8.485E-04	-4.485E+01
1.600E+06	8.193E-04	-4.276E+01
1.700E+06	7.944E-04	-4.078E+01
1.800E+06	7.729E-04	-3.889E+01
1.900E+06	7.542E-04	-3.710E+01
2.000E+06	7.379E-04	-3.540E+01
2.100E+06	7.237E-04	-3.378E+01
2.200E+06	7.111E-04	-3.223E+01
2.300E+06	7.000E-04	-3.076E+01
2.400E+06	6.901E-04	-2.936E+01
2.500E+06	6.814E-04	-2.801E+01
2.600E+06	6.735E-04	-2.673E+01
2.700E+06	6.664E-04	-2.550E+01
2.800E+06	6.601E-04	-2.432E+01
2.900E+06	6.544E-04	-2.319E+01

FREQ	I(VSE)	IP(VSE)
3.000E+06	6.492E-04	-2.211E+01
3.100E+06	6.446E-04	-2.106E+01
3.200E+06	6.404E-04	-2.006E+01
3.300E+06	6.365E-04	-1.909E+01
3.400E+06	6.330E-04	-1.816E+01
3.500E+06	6.299E-04	-1.725E+01
3.600E+06	6.270E-04	-1.638E+01
3.700E+06	6.243E-04	-1.554E+01
3.800E+06	6.219E-04	-1.472E+01
3.900E+06	6.197E-04	-1.393E+01
4.000E+06	6.177E-04	-1.316E+01
4.100E+06	6.159E-04	-1.241E+01
4.200E+06	6.142E-04	-1.168E+01
4.300E+06	6.127E-04	-1.098E+01
4.400E+06	6.113E-04	-1.029E+01
4.500E+06	6.101E-04	-9.620E+00
4.600E+06	6.090E-04	-8.967E+00
4.700E+06	6.079E-04	-8.330E+00
4.800E+06	6.070E-04	-7.708E+00
4.900E+06	6.062E-04	-7.100E+00
5.000E+06	6.054E-04	-6.506E+00
5.100E+06	6.047E-04	-5.925E+00
5.200E+06	6.041E-04	-5.356E+00
5.300E+06	6.036E-04	-4.799E+00
5.400E+06	6.032E-04	-4.253E+00
5.500E+06	6.028E-04	-3.718E+00
5.600E+06	6.024E-04	-3.193E+00
5.700E+06	6.022E-04	-2.678E+00
5.800E+06	6.019E-04	-2.173E+00
5.900E+06	6.018E-04	-1.676E+00
6.000E+06	6.016E-04	-1.188E+00
6.100E+06	6.016E-04	-7.076E-01
6.200E+06	6.015E-04	-2.356E-01

FREQ	I(VSE)	IP(VSE)
6.300E+06	6.015E-04	2.289E-01
6.400E+06	6.015E-04	6.861E-01
6.500E+06	6.016E-04	1.136E+00
6.600E+06	6.017E-04	1.580E+00
6.700E+06	6.019E-04	2.017E+00
6.800E+06	6.021E-04	2.447E+00
6.900E+06	6.023E-04	2.872E+00
7.000E+06	6.025E-04	3.291E+00
7.100E+06	6.028E-04	3.704E+00
7.200E+06	6.031E-04	4.112E+00
7.300E+06	6.034E-04	4.514E+00
7.400E+06	6.037E-04	4.912E+00
7.500E+06	6.041E-04	5.304E+00
7.600E+06	6.045E-04	5.692E+00
7.700E+06	6.049E-04	6.075E+00
7.800E+06	6.053E-04	6.454E+00
7.900E+06	6.058E-04	6.828E+00
8.000E+06	6.063E-04	7.199E+00
8.100E+06	6.068E-04	7.565E+00
8.200E+06	6.073E-04	7.927E+00
8.300E+06	6.078E-04	8.285E+00
8.400E+06	6.084E-04	8.640E+00
8.500E+06	6.090E-04	8.990E+00
8.600E+06	6.096E-04	9.338E+00
8.700E+06	6.102E-04	9.682E+00
8.800E+06	6.108E-04	1.002E+01
8.900E+06	6.115E-04	1.036E+01
9.000E+06	6.121E-04	1.069E+01
9.100E+06	6.128E-04	1.102E+01
9.200E+06	6.135E-04	1.135E+01
9.300E+06	6.142E-04	1.168E+01
9.400E+06	6.149E-04	1.200E+01
9.500E+06	6.157E-04	1.232E+01

FREQ	I(VSE)	IP(VSE)
9.600E+06	6.164E-04	1.263E+01
9.700E+06	6.172E-04	1.295E+01
9.800E+06	6.180E-04	1.326E+01
9.900E+06	6.188E-04	1.357E+01
1.000E+07	6.196E-04	1.387E+01

APPENDIX C
HP-41C CALCULATOR PROGRAMS

HP Calculator Programs

- RTD : Converts radians to degrees.
- DTR : Converts degrees to radians.
- INPUT : Calculates the value of CBH needed for a certain I(VS1).
- HBH : Calculates the gain needed for HBH.
- V4 : Calculates the value of V4 at a certain time.
- G1 : Calculates the gain of G1 needed for a certain V4.

INPUT PROGRAM

Note : Run V4 Program first and get the value for A.

Inputs : Frequency in Hz: [F?]
 Peak amplitude in volts: [AMPLITUDE?]
 Time to saturation in seconds: [TIME?]

Outputs:

wt=
 $V_{in}(t)=$

Current controlling resistor: [RS1?]
 Resistor in HBH source: [RHB?]
 Desired current in amps: [DESIRED I(VS1)?]

Voltage at
 HBH=
 V2=

Gain of HBH: [GAIN HBH?]

I(VBH)=

Amplitude of $V_4(t)$: [A OF V4?]

CBH=

Program Listing:

```
01 LBL INPUT
02 F?
03 XEQ PROMPT
04 STO 00
05 AMPLITUDE?
06 XEQ PROMPT
```

```

07 STO 01
08 TIME?
09 XEQ PROMPT
10 STO 02
11 RCL 00
12 2
13 *
14 PI
15 *
16 STO 04..... Stores value of w [radians/seconds]
17 RCL 02
18 *
19 STO 03..... Stores value of wt [radians]
20 W*T=
21 XEQ PROMPT
22 VIEW . X
23 STOP
24 XEQ RAD
25 SIN
26 STO 05..... Stores value of Sin(wt)
27 RCL 01
28 *
29 VIN=.....  $V_{in}(at\ t) = V_m \sin(wt)$ 
30 XEQ PROMPT
31 VIEW . X
32 STOP
33 RS1?
34 XEQ PROMPT
35 RHB?
36 XEQ PROMPT
37 STO 06..... Stores value of RHB
38 +
39 DESIRE I(VS1)?
40 XEQ PROMPT
41 STO 07..... Stores value of I(VS1)
42 *
43 -
44 STO 08..... Stores value of HBH
45 HBH=.....  $HBH = V_{in}(at\ t) - (R_{S1} + R_{HB})I(VS1)$ 
46 XEQ PROMPT
47 VIEW . X
48 STOP
49 RCL 06
50 RCL 07
51 *
52 +

```

```

53 V2=.....  $V_2 = HBH + R_{HB} I(VS1)$ 
54 XEQ PROMPT
55 VIEW . X
56 STOP
57 RCL 08
58 GAIN HBH?
59 XEQ PROMPT
60 /
61 I(VBH)=.....  $I(VBH) = \frac{HBH}{GAIN HBH}$ 
62 XEQ PROMPT
63 VIEW . X
64 STOP
65 RCL 04
66 /
67 RCL 05
68 /
69 A OF V4?.....  $A = \frac{V_{in peak} * Gain of G1}{wC_F}$ 
70 XEQ PROMPT
71 /
72 CBH=.....  $C_{BH} = \frac{I(VBH)}{wASin(wt)}$ 
73 XEQ PROMPT
74 VIEW . X
75 XEQ DEG
76 END

```

HBH PROGRAM:

Note : Run V4 program and get the value for A.

This program is similar to the input program above up to line 57.

Inputs : Frequency in Hz: [F?]
 Amplitude in volts: [AMPLITUDE?]
 Time to saturaion in seconds: [TIME?]

Outputs:
 $w * T =$
 $V_{in}(t) =$

Current controlling resistor: [RS1?]
 Resistor in HBH source: [RHB?]
 Desired current in amps: [DESIRED I(VS1)?]

Voltage at
HBH=
V2=

Amplitude of $V_4(t)$: [A OF V4?]
Capacitor value of CBH in Farads: [CBH?]

I(VBH)=
GAIN
HBH=

Program Listing:

From line 01 to line 57 the program is the as the input program.

```

58 RCL 04..... w
59 RCL 05..... Sin(wt)
60 *
61 A OF V4?
62 PROMPT
63 *
64 CBH?
65 PROMPT
66 *
67 I(VBH)=.....  $I(VBH) = wAC_{BH} \sin(wt)$ 
68 PROMPT
69 VIEW X
70 STOP
71 /
72 GAIN HBH=.....  $\text{Gain of HBH} = \frac{HBH}{I(VBH)}$ 
73 PROMPT
74 VIEW X
75 DEG
76 END

```

V4 PROGRAM

Inputs : Peak voltage (V_m) of sine wave: [VPEAK?]
Gain of G1 source: [GAIN G1?]
Frequency in Hz: [F?]
Capacitor value for C_F in farads: [CF?]

Outputs:
A=

Time in seconds: [TIME?]

V4=

Program Listing:

```

01 LBL V4
02 VPEAK?
03 PROMPT
04 GAIN G1?
05 PROMPT
06 *
07 2
08 PI
09 *
10 F?
11 PROMPT
12 *
13 STO 01..... Stores value of w
14 /
15 CF?
16 PROMPT
17 /

18 A=.....  $A = \frac{V_{in\ peak} * Gain\ of\ G1}{w\ C_F}$ 

19 PROMPT
20 VIEW X
21 STO 02..... Stores value of A
22 STOP
23 1
24 RAD
25 RCL 01
26 TIME?
27 PROMPT
28 *
29 STO 03..... Stores value of wt
30 COS
31 -
32 *
33 V4.....  $V_4(t) = A ( 1 - Cos(wt))$ 
34 PROMPT
35 VIEW X
36 DEG
37 END

```

G1 PROGRAM

Inputs : Frequency in Hz: [F?]
 Capacitor value for C_F : [CF?]

Desired voltage at node 4: [DESIRED V4?]
 Peak voltage of input source: [VIN PEAK]
 Time to saturation: [TIME?]

Output:
 Gain
 needed=
 (in G1
 source)

Program Listing:

```

01 LBL G1
02 F?
03 PROMPT
04 2
05 *
06 PI
07 *
08 STO 00..... Stores value of w
09 CF?
10 PROMPT
11 *
12 DESIRED V4?
13 PROMPT
14 *
15 VIN PEAK?
16 PROMPT
17 /
18 TIME?
19 PROMPT
20 RCL 00
21 *
22 RAD
23 COS
24 CHS
25 1
26 +
27 /
28 GAIN NEEDED=
29 PROMPT
30 VIEW X
31 DEG
32 END

```

APPENDIX D
SPICE OUTPUT LISTING FOR THE INDUCTOR
MODEL USING AN RC SWITCH

```

*FILE: YFRMLS.OUT
*CORE : YF41003TC N1:N2=10:10
VIN 1 0 SIN(0 22V 100KHZ)
VS1 1 18 0V
RS1 18 2 9
*****
* SWITCH T SAT = 2US      *
*****
HBH 2 16 VBH 3MEG
RHB 16 0 0.1
*****
* INDUCTOR MODEL          *
*****
R1 2 0 1.6625K
L1 2 3 180UH IC=-194.5MA
RW2 3 0 0.1
C1 2 0 4PF
*****
* FLUX CIRCUIT            *
*****
GF 0 4 1 0 0.25U
CF 4 0 1PF
D1 4 5 DIO
V1 5 0 5.5V
D2 6 4 DIO
V2 0 6 5.5V
*****
* B-H CURVE MODEL         *
*****
EBH 22 0 4 0 1
RK 22 0 1MEG
RSE 22 23 100
VBH 23 24 0V
CBH 24 0 1.1013743PF
*****
.MODEL DIO D
.WIDTH IN=72 OUT=72
.TRAN 0.1US 40US 0 0.01US UIC
.PRINT TRAN V(2) I(VS1) V(4)
.OPTION LIMPTS=1K ITL5=20K
.END

```


APPENDIX E
SPICE OUTPUT LISTING FOR THE INDUCTOR
MODEL USING A NAND GATE SWITCH

```

*FILE : YFN.OUT
*CORE : YF41003TC N1:N2=10:10
VIN 1 0 SIN(0 22V 100KHZ)
VS1 1 18 0V
RS1 18 2 9
*****
* SWITCH *
*****
EWP 2 16 POLY(2) 1 0 13 0 0 0 0 0 0.8
RWP 16 0 0.1
*LWP 16 0 100UH
*****
* INDUCTOR MODEL *
*****
R1 2 0 1.6625K
L1 2 3 180UH IC=-194.5MA
RW2 3 0 1
C1 2 0 4PF
*****
* FLUX CIRCUIT *
*****
GF 0 4 2 0 0.3U
CF 4 0 1PF
D1 4 5 DIO
V1 5 0 5.5V
D2 6 4 DIO
V2 0 6 5.5V
*****
* NAND GATE (POSITIVE)*
*****
EFP 7 0 POLY(2) 30 0 20 0 0 1 -1.67MEG
HCP 8 0 POLY(2) VSE1 VSE2 0 2.1MEG -20
DP1 9 7 DIO
DP2 9 8 DIO
DP3 9 10 DIO
RP1 12 9 10K
RP2 12 11 1K
Q1 11 10 0 TR
VCP 12 0 10V
ERP 13 0 11 0 0.1
RRP 13 0 1
*****
* REFERENCE(B-H CURVE) *
* VRMS=4.44*F*N*A*B *
*****
VF 20 0 3UV
RF 20 0 1

```

```
*****
* SQUARE OF THE CURRENT *
*****
```

```
IC 0 21 0.16A
VSE2 21 22 0V
RC 22 0 1
```

```
*****
* SQUARING SOURCES      *
*****
```

```
ESQ 30 0 4 0 0 0 0.16666667
RSQ 30 0 1
FSQ 0 40 VS1 0 0 1
VSE1 40 41 0V
RSC 41 0 1
```

```
*****
```

```
.MODEL DIO D
.MODEL TR NPN CJC=0.1PF CJE=0.1PF
.WIDTH IN=72 OUT=72
.TRAN 100NS 40US UIC
.PRINT TRAN V(2) I(VS1) V(4) V(11)
.OPTION METHOD=GEAR
.OPTION LIMPTS=1K ITL5=20K
.END
```

APPENDIX F
INPUT IMPEDANCE MEASUREMENT
OF THE TRANSFORMER

Transformer Configuration

File : XFORM P 101

Core : P41005TC

N1:N2: 10:10

Load : 1K Ω & 10K Ω

f	<u>RL=1KΩ</u>		<u>RL=10KΩ</u>	
	Z	$\emptyset$	Z	$\emptyset$
[MHz]	[K Ω]	[deg]	[K Ω]	[deg]
0.1	0.150	80.0	0.150	87.0
0.2	0.270	72.0	0.280	85.5
0.3	0.375	66.0	0.420	84.0
0.4	0.475	57.0	0.550	81.0
0.5	0.560	48.0	0.720	76.0
0.6	0.600	41.5	0.870	70.5
0.7	0.630	36.0	1.000	66.0
0.8	0.645	31.5	1.105	61.0
0.9	0.660	27.5	1.200	56.0
1.0	0.670	23.0	1.300	52.0
1.1	0.675	22.0	1.380	48.0
1.2	0.680	19.5	1.440	44.5
1.3	0.682	18.0	1.480	40.5
1.4	0.683	16.5	1.520	37.5
1.5	0.683	15.0	1.560	34.5
1.6	0.683	13.5	1.580	32.5
1.7	0.683	12.5	1.600	30.0
1.8	0.680	12.0	1.620	28.5
1.9	0.680	11.0	1.625	26.5
2.0	0.679	10.5	1.630	25.5
2.5	0.678	8.0	1.660	19.5
3.0	0.680	6.0	1.680	16.0
3.5	0.685	5.0	1.725	13.0
4.0	0.688	4.5	1.760	10.5

f	<u>RL=1KΩ</u>		<u>RL=10KΩ</u>	
	Z	$\varnothing$	Z	$\varnothing$
[MHz]	[K Ω]	[deg]	[K Ω]	[deg]
4.5	0.690	3.0	1.800	7.5
5.0	0.695	2.0	1.830	5.0
5.5	0.697	1.5	1.840	3.0
6.0	0.700	0.5	1.860	0.5
6.5	0.700	-0.5	1.860	-2.0
7.0	0.700	-1.5	1.860	-4.5
7.5	0.697	-2.0	1.845	-6.0
8.0	0.695	-3.0	1.840	-8.0
8.5	0.694	-3.5	1.820	-10.0
9.0	0.693	-4.0	1.800	-11.0
9.5	0.690	-4.5	1.780	-13.0
10.0	0.687	-5.0	1.750	-14.0

Transformer Configuration

File : XFORM Y 101

Core : YF41003TC

N1:N2: 10:10

Load : 1K Ω & 10K Ω

f	<u>RL=1KΩ</u>		<u>RL=10KΩ</u>	
	Z	$\emptyset$	Z	$\emptyset$
[MHz]	[K Ω]	[deg]	[K Ω]	[deg]
0.1	0.090	79.5	0.100	85.5
0.2	0.200	72.0	0.200	82.5
0.3	0.300	64.0	0.300	79.0
0.4	0.375	55.5	0.400	73.5
0.5	0.420	48.0	0.500	68.0
0.6	0.460	42.0	0.600	64.0
0.7	0.480	38.0	0.660	60.0
0.8	0.500	34.0	0.725	55.5
0.9	0.515	30.5	0.780	51.0
1.0	0.525	28.0	0.820	48.0
1.1	0.530	25.5	0.850	45.5
1.2	0.535	24.0	0.880	43.5
1.3	0.540	22.5	0.910	41.0
1.4	0.543	21.0	0.940	40.0
1.5	0.545	20.0	0.960	38.0
1.6	0.550	19.5	0.980	37.0
1.7	0.555	19.0	1.000	35.0
1.8	0.560	17.5	1.020	34.5
1.9	0.563	17.0	1.040	33.0
2.0	0.565	16.5	1.050	32.0
2.5	0.580	13.5	1.140	28.0
3.0	0.600	12.0	1.220	24.0
3.5	0.610	10.0	1.300	20.0
4.0	0.620	7.5	1.340	16.5

f	<u>RL=1KΩ</u>		<u>RL=10KΩ</u>	
	Z	$\varnothing$	Z	$\varnothing$
[MHz]	[K Ω]	[deg]	[K Ω]	[deg]
4.5	0.625	6.0	1.380	13.5
5.0	0.630	4.5	1.420	10.0
5.5	0.635	3.0	1.440	6.0
6.0	0.640	2.0	1.440	4.0
6.5	0.640	1.5	1.440	1.5
7.0	0.640	0.0	1.430	-1.5
7.5	0.640	-1.5	1.420	-4.0
8.0	0.635	-2.0	1.410	-6.0
8.5	0.630	-2.5	1.380	-7.5
9.0	0.625	-3.0	1.375	-9.0
9.5	0.620	-4.0	1.350	-10.0
10.0	0.615	-4.5	1.340	-11.0

APPENDIX G
SPICE LISTINGS AND OUTPUTS FOR
THE TRANSFORMER MODEL

```

*FILE: XP1K.OUT.
*CORE: P41005TC N1=N2=10.
*PRIMARY SIDE DATA |Z|=1400 AT F=1MEGHZ FROM
*GRAPH I.
*SHORTED ENDS GRAPH III |Z|=3.8K AT F=6MHZ
*LOAD = 1K
VIN 1 0 AC 1V
VSE 1 2 0V
R1 2 0 2.288K
L1 2 3 222.8UH
RW 3 0 0.1
C1 2 0 2.91PF
C2 6 0 2.91PF
*****
* IDEAL TRANSFORMER *
*****
E1 5 0 1 0 1
VTO 5 6 0V
F1 2 0 VTO 1
*****
* LOAD *
*****
RL 6 0 1K
*****
* C SHORTED ENDS *
*****
CSH 2 5 7PF
*****
.WIDTH IN=72 OUT=72
.AC LIN 100 100KHZ 10MEGHZ
.PRINT AC I(VSE) IP(VSE)
.END

```

18-APR-88 *** SPICE 2G.6 3/15/8316:03:00***

*TRANSFORMER MODEL.

**** AC ANALYSIS TEMPERATURE = 27.000 DEG

FREQ	I(VSE)	IP(VSE)
1.000E+05	7.286E-03	-7.858E+01
2.000E+05	3.847E-03	-6.804E+01
3.000E+05	2.777E-03	-5.882E+01
4.000E+05	2.287E-03	-5.106E+01
5.000E+05	2.020E-03	-4.464E+01
6.000E+05	1.859E-03	-3.938E+01
7.000E+05	1.755E-03	-3.504E+01
8.000E+05	1.684E-03	-3.143E+01
9.000E+05	1.634E-03	-2.841E+01
1.000E+06	1.597E-03	-2.584E+01
1.100E+06	1.569E-03	-2.365E+01
1.200E+06	1.547E-03	-2.175E+01
1.300E+06	1.530E-03	-2.009E+01
1.400E+06	1.517E-03	-1.864E+01
1.500E+06	1.506E-03	-1.734E+01
1.600E+06	1.496E-03	-1.619E+01
1.700E+06	1.489E-03	-1.515E+01
1.800E+06	1.482E-03	-1.421E+01
1.900E+06	1.477E-03	-1.336E+01
2.000E+06	1.472E-03	-1.258E+01
2.100E+06	1.468E-03	-1.186E+01
2.200E+06	1.465E-03	-1.120E+01
2.300E+06	1.462E-03	-1.058E+01
2.400E+06	1.459E-03	-1.001E+01
2.500E+06	1.457E-03	-9.482E+00
2.600E+06	1.455E-03	-8.984E+00
2.700E+06	1.453E-03	-8.517E+00
2.800E+06	1.451E-03	-8.077E+00

FREQ	I(VSE)	IP(VSE)
2.900E+06	1.450E-03	-7.661E+00
3.000E+06	1.449E-03	-7.267E+00
3.100E+06	1.448E-03	-6.894E+00
3.200E+06	1.446E-03	-6.539E+00
3.300E+06	1.446E-03	-6.201E+00
3.400E+06	1.445E-03	-5.877E+00
3.500E+06	1.444E-03	-5.568E+00
3.600E+06	1.443E-03	-5.272E+00
3.700E+06	1.443E-03	-4.988E+00
3.800E+06	1.442E-03	-4.714E+00
3.900E+06	1.441E-03	-4.451E+00
4.000E+06	1.441E-03	-4.197E+00
4.100E+06	1.440E-03	-3.951E+00
4.200E+06	1.440E-03	-3.714E+00
4.300E+06	1.440E-03	-3.484E+00
4.400E+06	1.439E-03	-3.262E+00
4.500E+06	1.439E-03	-3.046E+00
4.600E+06	1.439E-03	-2.836E+00
4.700E+06	1.439E-03	-2.632E+00
4.800E+06	1.438E-03	-2.433E+00
4.900E+06	1.438E-03	-2.239E+00
5.000E+06	1.438E-03	-2.050E+00
5.100E+06	1.438E-03	-1.866E+00
5.200E+06	1.438E-03	-1.686E+00
5.300E+06	1.438E-03	-1.510E+00
5.400E+06	1.437E-03	-1.337E+00
5.500E+06	1.437E-03	-1.169E+00
5.600E+06	1.437E-03	-1.003E+00
5.700E+06	1.437E-03	-8.413E-01
5.800E+06	1.437E-03	-6.823E-01
5.900E+06	1.437E-03	-5.262E-01
6.000E+06	1.437E-03	-3.729E-01
6.100E+06	1.437E-03	-2.222E-01

FREQ	I(VSE)	IP(VSE)
6.200E+06	1.437E-03	-7.395E-02
6.300E+06	1.437E-03	7.186E-02
6.400E+06	1.437E-03	2.154E-01
6.500E+06	1.437E-03	3.568E-01
6.600E+06	1.437E-03	4.960E-01
6.700E+06	1.437E-03	6.333E-01
6.800E+06	1.437E-03	7.687E-01
6.900E+06	1.437E-03	9.023E-01
7.000E+06	1.437E-03	1.034E+00
7.100E+06	1.437E-03	1.164E+00
7.200E+06	1.437E-03	1.293E+00
7.300E+06	1.438E-03	1.420E+00
7.400E+06	1.438E-03	1.545E+00
7.500E+06	1.438E-03	1.669E+00
7.600E+06	1.438E-03	1.792E+00
7.700E+06	1.438E-03	1.914E+00
7.800E+06	1.438E-03	2.034E+00
7.900E+06	1.438E-03	2.153E+00
8.000E+06	1.438E-03	2.271E+00
8.100E+06	1.438E-03	2.387E+00
8.200E+06	1.438E-03	2.503E+00
8.300E+06	1.439E-03	2.617E+00
8.400E+06	1.439E-03	2.731E+00
8.500E+06	1.439E-03	2.843E+00
8.600E+06	1.439E-03	2.955E+00
8.700E+06	1.439E-03	3.066E+00
8.800E+06	1.439E-03	3.175E+00
8.900E+06	1.439E-03	3.284E+00
9.000E+06	1.440E-03	3.392E+00
9.100E+06	1.440E-03	3.500E+00
9.200E+06	1.440E-03	3.606E+00
9.300E+06	1.440E-03	3.712E+00
9.400E+06	1.440E-03	3.817E+00

FREQ	I(VSE)	IP(VSE)
9.500E+06	1.440E-03	3.921E+00
9.600E+06	1.441E-03	4.025E+00
9.700E+06	1.441E-03	4.128E+00
9.800E+06	1.441E-03	4.230E+00
9.900E+06	1.441E-03	4.332E+00
1.000E+07	1.441E-03	4.433E+00

```

*FILE: XP.OUT.
*CORE: P41005TC N1=N2=10.
*PRIMARY SIDE DATA |Z|=1400 AT F=1MEGHZ FROM
*GRAPH I.
*SHORTED ENDS GRAPH III |Z|=3.8K AT F=6MHZ
*LOAD = 10K
VIN 1 0 AC 1V
VSE 1 2 0V
R1 2 0 2.288K
L1 2 3 222.8UH
RW 3 0 0.1
C1 2 0 2.91PF
C2 6 0 2.91PF
*****
* IDEAL TRANSFORMER *
*****
E1 5 0 1 0 1
VTO 5 6 0V
F1 2 0 VTO 1
*****
* LOAD *
*****
RL 6 0 10K
*****
* C SHORTED ENDS *
*****
CSH 2 5 7PF
*****
.WIDTH IN=72 OUT=72
.AC LIN 100 100KHZ 10MEGHZ
.PRINT AC I(VSE) IP(VSE)
.END

```

18-APR-88 SPICE2G.63/15/83 *****15:57:29*****

*TRANSFORMER MODEL.

**** AC ANALYSIS TEMPERATURE = 27.000 DEG C

FREQ	I(VSE)	IP(VSE)
1.000E+05	7.162E-03	-8.566E+01
2.000E+05	3.608E-03	-8.142E+01
3.000E+05	2.436E-03	-7.725E+01
4.000E+05	1.858E-03	-7.319E+01
5.000E+05	1.518E-03	-6.927E+01
6.000E+05	1.296E-03	-6.551E+01
7.000E+05	1.142E-03	-6.194E+01
8.000E+05	1.030E-03	-5.855E+01
9.000E+05	9.448E-04	-5.535E+01
1.000E+06	8.792E-04	-5.234E+01
1.100E+06	8.273E-04	-4.952E+01
1.200E+06	7.856E-04	-4.687E+01
1.300E+06	7.516E-04	-4.439E+01
1.400E+06	7.234E-04	-4.206E+01
1.500E+06	6.999E-04	-3.988E+01
1.600E+06	6.801E-04	-3.784E+01
1.700E+06	6.632E-04	-3.592E+01
1.800E+06	6.488E-04	-3.412E+01
1.900E+06	6.363E-04	-3.243E+01
2.000E+06	6.255E-04	-3.083E+01
2.100E+06	6.160E-04	-2.933E+01
2.200E+06	6.078E-04	-2.791E+01
2.300E+06	6.005E-04	-2.656E+01
2.400E+06	5.940E-04	-2.529E+01
2.500E+06	5.883E-04	-2.408E+01
2.600E+06	5.832E-04	-2.293E+01
2.700E+06	5.786E-04	-2.184E+01
2.800E+06	5.745E-04	-2.079E+01
2.900E+06	5.708E-04	-1.979E+01
3.000E+06	5.675E-04	-1.884E+01

FREQ	I(VSE)	IP(VSE)
3.100E+06	5.645E-04	-1.793E+01
3.200E+06	5.618E-04	-1.705E+01
3.300E+06	5.593E-04	-1.621E+01
3.400E+06	5.571E-04	-1.540E+01
3.500E+06	5.550E-04	-1.462E+01
3.600E+06	5.532E-04	-1.387E+01
3.700E+06	5.515E-04	-1.314E+01
3.800E+06	5.500E-04	-1.244E+01
3.900E+06	5.486E-04	-1.176E+01
4.000E+06	5.473E-04	-1.111E+01
4.100E+06	5.462E-04	-1.047E+01
4.200E+06	5.451E-04	-9.854E+00
4.300E+06	5.441E-04	-9.254E+00
4.400E+06	5.433E-04	-8.671E+00
4.500E+06	5.425E-04	-8.103E+00
4.600E+06	5.418E-04	-7.550E+00
4.700E+06	5.411E-04	-7.011E+00
4.800E+06	5.405E-04	-6.486E+00
4.900E+06	5.400E-04	-5.973E+00
5.000E+06	5.395E-04	-5.472E+00
5.100E+06	5.391E-04	-4.982E+00
5.200E+06	5.387E-04	-4.503E+00
5.300E+06	5.384E-04	-4.034E+00
5.400E+06	5.381E-04	-3.575E+00
5.500E+06	5.379E-04	-3.125E+00
5.600E+06	5.377E-04	-2.683E+00
5.700E+06	5.375E-04	-2.250E+00
5.800E+06	5.373E-04	-1.825E+00
5.900E+06	5.372E-04	-1.408E+00
6.000E+06	5.371E-04	-9.976E-01
6.100E+06	5.371E-04	-5.944E-01
6.200E+06	5.371E-04	-1.979E-01
6.300E+06	5.371E-04	1.923E-01
6.400E+06	5.371E-04	5.763E-01

FREQ	I(VSE)	IP(VSE)
6.500E+06	5.371E-04	9.545E-01
6.600E+06	5.372E-04	1.327E+00
6.700E+06	5.373E-04	1.694E+00
6.800E+06	5.374E-04	2.056E+00
6.900E+06	5.375E-04	2.413E+00
7.000E+06	5.377E-04	2.765E+00
7.100E+06	5.379E-04	3.113E+00
7.200E+06	5.380E-04	3.456E+00
7.300E+06	5.382E-04	3.794E+00
7.400E+06	5.385E-04	4.129E+00
7.500E+06	5.387E-04	4.459E+00
7.600E+06	5.389E-04	4.786E+00
7.700E+06	5.392E-04	5.109E+00
7.800E+06	5.395E-04	5.428E+00
7.900E+06	5.398E-04	5.744E+00
8.000E+06	5.401E-04	6.056E+00
8.100E+06	5.404E-04	6.365E+00
8.200E+06	5.407E-04	6.671E+00
8.300E+06	5.411E-04	6.974E+00
8.400E+06	5.414E-04	7.273E+00
8.500E+06	5.418E-04	7.570E+00
8.600E+06	5.422E-04	7.864E+00
8.700E+06	5.426E-04	8.155E+00
8.800E+06	5.429E-04	8.444E+00
8.900E+06	5.434E-04	8.730E+00
9.000E+06	5.438E-04	9.013E+00
9.100E+06	5.442E-04	9.294E+00
9.200E+06	5.446E-04	9.572E+00
9.300E+06	5.451E-04	9.848E+00
9.400E+06	5.456E-04	1.012E+01
9.500E+06	5.460E-04	1.039E+01
9.600E+06	5.465E-04	1.066E+01
9.700E+06	5.470E-04	1.093E+01
9.800E+06	5.475E-04	1.119E+01

FREQ	I(VSE)	IP(VSE)
9.900E+06	5.480E-04	1.146E+01
1.000E+07	5.485E-04	1.172E+01

```

*FILE: XY1K.OUT
*TRANSFORMER MODEL.
*CORE: YF41003TC N1=N2=10 FROM LMSC GRAPH VII.
*PRIMARY SIDE DATA |Z|=0.525 AT F=0.5MEGHZ
*SHORTED ENDS GRAPH IX
*LOAD = 1K
VIN 1 0 AC 1V
VSE 1 2 0V
R1 2 0 1.6625K
L1 2 3 167.1UH
RW 3 0 0.1
C1 2 0 3.88PF
C2 6 0 3.88PF
*****
* IDEAL TRANSFORMER *
*****
E1 5 0 1 0 1
VTO 5 6 0V
F1 2 0 VTO 1
*****
* LOAD *
*****
RL 6 0 1K
*****
CSH 2 5 6.47PF
*****
.WIDTH IN=72 OUT=72
.AC LIN 100 100KHZ 10MEGHZ
.PRINT AC I(VSE) IP(VSE)
.END

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19-APR-88 *** SPICE 2G.6 3/15/83* 09:11:40*****

**** AC ANALYSIS TEMPERATURE = 27.000 DEG C

FREQ	I(VSE)	IP(VSE)
1.000E+05	9.657E-03	-8.040E+01
2.000E+05	5.020E-03	-7.137E+01
3.000E+05	3.550E-03	-6.316E+01
4.000E+05	2.862E-03	-5.596E+01
5.000E+05	2.480E-03	-4.976E+01
6.000E+05	2.245E-03	-4.448E+01
7.000E+05	2.091E-03	-3.999E+01
8.000E+05	1.984E-03	-3.617E+01
9.000E+05	1.908E-03	-3.291E+01
1.000E+06	1.851E-03	-3.009E+01
1.100E+06	1.808E-03	-2.765E+01
1.200E+06	1.775E-03	-2.552E+01
1.300E+06	1.748E-03	-2.364E+01
1.400E+06	1.727E-03	-2.197E+01
1.500E+06	1.710E-03	-2.049E+01
1.600E+06	1.695E-03	-1.915E+01
1.700E+06	1.683E-03	-1.795E+01
1.800E+06	1.673E-03	-1.686E+01
1.900E+06	1.665E-03	-1.586E+01
2.000E+06	1.658E-03	-1.494E+01
2.100E+06	1.651E-03	-1.410E+01
2.200E+06	1.646E-03	-1.332E+01
2.300E+06	1.641E-03	-1.260E+01
2.400E+06	1.637E-03	-1.193E+01
2.500E+06	1.633E-03	-1.130E+01
2.600E+06	1.630E-03	-1.071E+01
2.700E+06	1.627E-03	-1.016E+01
2.800E+06	1.624E-03	-9.636E+00
2.900E+06	1.622E-03	-9.142E+00

FREQ	I(VSE)	IP(VSE)
3.000E+06	1.620E-03	-8.675E+00
3.100E+06	1.618E-03	-8.231E+00
3.200E+06	1.617E-03	-7.809E+00
3.300E+06	1.615E-03	-7.406E+00
3.400E+06	1.614E-03	-7.021E+00
3.500E+06	1.612E-03	-6.653E+00
3.600E+06	1.611E-03	-6.300E+00
3.700E+06	1.610E-03	-5.961E+00
3.800E+06	1.609E-03	-5.635E+00
3.900E+06	1.608E-03	-5.320E+00
4.000E+06	1.608E-03	-5.017E+00
4.100E+06	1.607E-03	-4.724E+00
4.200E+06	1.606E-03	-4.441E+00
4.300E+06	1.606E-03	-4.167E+00
4.400E+06	1.605E-03	-3.901E+00
4.500E+06	1.605E-03	-3.643E+00
4.600E+06	1.604E-03	-3.392E+00
4.700E+06	1.604E-03	-3.148E+00
4.800E+06	1.604E-03	-2.910E+00
4.900E+06	1.603E-03	-2.678E+00
5.000E+06	1.603E-03	-2.453E+00
5.100E+06	1.603E-03	-2.232E+00
5.200E+06	1.602E-03	-2.017E+00
5.300E+06	1.602E-03	-1.806E+00
5.400E+06	1.602E-03	-1.600E+00
5.500E+06	1.602E-03	-1.398E+00
5.600E+06	1.602E-03	-1.200E+00
5.700E+06	1.602E-03	-1.007E+00
5.800E+06	1.602E-03	-8.163E-01
5.900E+06	1.602E-03	-6.296E-01
6.000E+06	1.602E-03	-4.461E-01
6.100E+06	1.602E-03	-2.658E-01
6.200E+06	1.602E-03	-8.848E-02

FREQ	I(VSE)	IP(VSE)
6.300E+06	1.602E-03	8.597E-02
6.400E+06	1.602E-03	2.577E-01
6.500E+06	1.602E-03	4.268E-01
6.600E+06	1.602E-03	5.935E-01
6.700E+06	1.602E-03	7.577E-01
6.800E+06	1.602E-03	9.197E-01
6.900E+06	1.602E-03	1.079E+00
7.000E+06	1.602E-03	1.237E+00
7.100E+06	1.602E-03	1.393E+00
7.200E+06	1.602E-03	1.547E+00
7.300E+06	1.602E-03	1.699E+00
7.400E+06	1.602E-03	1.849E+00
7.500E+06	1.602E-03	1.997E+00
7.600E+06	1.603E-03	2.144E+00
7.700E+06	1.603E-03	2.289E+00
7.800E+06	1.603E-03	2.433E+00
7.900E+06	1.603E-03	2.575E+00
8.000E+06	1.603E-03	2.716E+00
8.100E+06	1.603E-03	2.855E+00
8.200E+06	1.604E-03	2.994E+00
8.300E+06	1.604E-03	3.131E+00
8.400E+06	1.604E-03	3.266E+00
8.500E+06	1.604E-03	3.401E+00
8.600E+06	1.605E-03	3.534E+00
8.700E+06	1.605E-03	3.666E+00
8.800E+06	1.605E-03	3.797E+00
8.900E+06	1.605E-03	3.928E+00
9.000E+06	1.606E-03	4.057E+00
9.100E+06	1.606E-03	4.185E+00
9.200E+06	1.606E-03	4.312E+00
9.300E+06	1.606E-03	4.438E+00
9.400E+06	1.607E-03	4.564E+00
9.500E+06	1.607E-03	4.688E+00

FREQ	I(VSE)	IP(VSE)
9.600E+06	1.607E-03	4.812E+00
9.700E+06	1.607E-03	4.935E+00
9.800E+06	1.608E-03	5.057E+00
9.900E+06	1.608E-03	5.178E+00
1.000E+07	1.608E-03	5.299E+00


```

* FILE: XY10K.OUT
*TRANSFORMER MODEL.
*CORE: YF41003TC N1=N2=10 FROM LMSC GRAPH VII.
*PRIMARY SIDE DATA |Z|=0.525 AT F=0.5MEGHZ
*SHORTED ENDS GRAPH IX
*LOAD = 10K
VIN 1 0 AC 1V
VSE 1 2 0V
R1 2 0 1.6625K
L1 2 3 167.1UH
RW 3 0 0.1
C1 2 0 3.88PF
C2 6 0 3.88PF
*****
* IDEAL TRANSFORMER *
*****
E1 5 0 1 0 1
VTO 5 6 0V
F1 2 0 VTO 1
*****
* LOAD *
*****
RL 6 0 10K
*****
CSH 2 5 6.47PF
*****
.WIDTH IN=72 OUT=72
.AC LIN 100 100KHZ 10MEGHZ
.PRINT AC I(VSE) IP(VSE)
.END

```

19-APR-88 * SPICE 2G.6 3/15/83****09:12:59****

**** AC ANALYSIS TEMPERATURE = 27.000 DEG C

FREQ	I(VSE)	IP(VSE)
1.000E+05	9.549E-03	-8.573E+01
2.000E+05	4.809E-03	-8.159E+01
3.000E+05	3.244E-03	-7.750E+01
4.000E+05	2.473E-03	-7.351E+01
5.000E+05	2.019E-03	-6.965E+01
6.000E+05	1.722E-03	-6.595E+01
7.000E+05	1.516E-03	-6.242E+01
8.000E+05	1.365E-03	-5.907E+01
9.000E+05	1.252E-03	-5.590E+01
1.000E+06	1.163E-03	-5.291E+01
1.100E+06	1.094E-03	-5.010E+01
1.200E+06	1.038E-03	-4.746E+01
1.300E+06	9.917E-04	-4.498E+01
1.400E+06	9.538E-04	-4.265E+01
1.500E+06	9.221E-04	-4.046E+01
1.600E+06	8.953E-04	-3.841E+01
1.700E+06	8.725E-04	-3.648E+01
1.800E+06	8.530E-04	-3.467E+01
1.900E+06	8.361E-04	-3.297E+01
2.000E+06	8.215E-04	-3.136E+01
2.100E+06	8.087E-04	-2.984E+01
2.200E+06	7.975E-04	-2.840E+01
2.300E+06	7.876E-04	-2.704E+01
2.400E+06	7.789E-04	-2.575E+01
2.500E+06	7.711E-04	-2.452E+01
2.600E+06	7.641E-04	-2.336E+01
2.700E+06	7.579E-04	-2.225E+01
2.800E+06	7.524E-04	-2.119E+01
2.900E+06	7.474E-04	-2.017E+01

FREQ	I(VSE)	IP(VSE)
3.000E+06	7.429E-04	-1.920E+01
3.100E+06	7.388E-04	-1.828E+01
3.200E+06	7.351E-04	-1.738E+01
3.300E+06	7.317E-04	-1.653E+01
3.400E+06	7.287E-04	-1.570E+01
3.500E+06	7.260E-04	-1.491E+01
3.600E+06	7.234E-04	-1.415E+01
3.700E+06	7.212E-04	-1.341E+01
3.800E+06	7.191E-04	-1.269E+01
3.900E+06	7.172E-04	-1.200E+01
4.000E+06	7.155E-04	-1.133E+01
4.100E+06	7.139E-04	-1.068E+01
4.200E+06	7.125E-04	-1.005E+01
4.300E+06	7.111E-04	-9.443E+00
4.400E+06	7.100E-04	-8.848E+00
4.500E+06	7.089E-04	-8.269E+00
4.600E+06	7.079E-04	-7.705E+00
4.700E+06	7.070E-04	-7.156E+00
4.800E+06	7.062E-04	-6.620E+00
4.900E+06	7.055E-04	-6.096E+00
5.000E+06	7.049E-04	-5.585E+00
5.100E+06	7.043E-04	-5.085E+00
5.200E+06	7.038E-04	-4.596E+00
5.300E+06	7.033E-04	-4.118E+00
5.400E+06	7.029E-04	-3.649E+00
5.500E+06	7.026E-04	-3.189E+00
5.600E+06	7.023E-04	-2.739E+00
5.700E+06	7.021E-04	-2.297E+00
5.800E+06	7.019E-04	-1.863E+00
5.900E+06	7.017E-04	-1.437E+00
6.000E+06	7.016E-04	-1.018E+00
6.100E+06	7.015E-04	-6.068E-01
6.200E+06	7.015E-04	-2.020E-01

FREQ	I(VSE)	IP(VSE)
6.300E+06	7.015E-04	1.963E-01
6.400E+06	7.015E-04	5.883E-01
6.500E+06	7.016E-04	9.743E-01
6.600E+06	7.017E-04	1.355E+00
6.700E+06	7.018E-04	1.729E+00
6.800E+06	7.020E-04	2.099E+00
6.900E+06	7.022E-04	2.463E+00
7.000E+06	7.024E-04	2.823E+00
7.100E+06	7.026E-04	3.177E+00
7.200E+06	7.028E-04	3.527E+00
7.300E+06	7.031E-04	3.873E+00
7.400E+06	7.034E-04	4.214E+00
7.500E+06	7.037E-04	4.552E+00
7.600E+06	7.041E-04	4.885E+00
7.700E+06	7.044E-04	5.215E+00
7.800E+06	7.048E-04	5.540E+00
7.900E+06	7.052E-04	5.862E+00
8.000E+06	7.056E-04	6.181E+00
8.100E+06	7.060E-04	6.496E+00
8.200E+06	7.065E-04	6.808E+00
8.300E+06	7.070E-04	7.117E+00
8.400E+06	7.074E-04	7.423E+00
8.500E+06	7.079E-04	7.726E+00
8.600E+06	7.084E-04	8.025E+00
8.700E+06	7.090E-04	8.322E+00
8.800E+06	7.095E-04	8.617E+00
8.900E+06	7.101E-04	8.908E+00
9.000E+06	7.106E-04	9.197E+00
9.100E+06	7.112E-04	9.483E+00
9.200E+06	7.118E-04	9.767E+00
9.300E+06	7.124E-04	1.005E+01
9.400E+06	7.131E-04	1.033E+01
9.500E+06	7.137E-04	1.060E+01

FREQ	I(VSE)	IP(VSE)
9.600E+06	7.143E-04	1.088E+01
9.700E+06	7.150E-04	1.115E+01
9.800E+06	7.157E-04	1.142E+01
9.900E+06	7.164E-04	1.169E+01
1.000E+07	7.171E-04	1.196E+01

APPENDIX H
SPICE LISTING FOR THE SATURABLE
TRANSFORMER MODEL

```

*TRANSFORMER MODEL USING THE
*INDUCTOR SATURABLE MODEL WITH NAND GATE SWITCH
*CORE : YF41003TC N1:N2=10:10
*FILE : YFNTR.CKT
VIN 1 0 SIN(0 22V 100KHZ)
VS1 1 18 0V
RS1 18 2 9
*****
* SWITCH *
*****
EWP 2 16 POLY(2) 1 0 13 0 0 0 0 0 0.8
RWP 16 0 0.1
*****
* INDUCTOR MODEL *
*****
R1 2 0 1.6625K
L1 2 3 180UH IC=-194.5MA
RW2 3 0 1
C1 2 0 4PF
*****
* IDEAL TRANSFORMER *
*****
ETR 50 0 2 0 1
VTO 50 51 0V
C2 51 0 4PF
RL 51 0 1K
CHS 2 50 6.47PF
FTR 2 0 VTO 1
*****
* FLUX CIRCUIT *
*****
GF 0 4 2 0 0.3U
CF 4 0 1PF
D1 4 5 DIO
V1 5 0 5.5V
D2 6 4 DIO
V2 0 6 5.5V
*****
* NAND GATE (POSITIVE) *
*****
EFP 7 0 POLY(2) 30 0 20 0 0 1 -1.67MEG
HCP 8 0 POLY(2) VSE1 VSE2 0 2.1MEG -20
DP1 9 7 DIO
DP2 9 8 DIO
DP3 9 10 DIO
RP1 12 9 10K
RP2 12 11 1K

```

```

Q1 11 10 0 TR
VCP 12 0 10V
ERP 13 0 11 0 0.1
RRP 13 0 1
*****
* REFERENCE(B-H CURVE) *
* VRMS=4.44*F*N*A*B      *
*****
VF 20 0 3UV
RF 20 0 1
*****
* SQUARE OF THE CURRENT *
*****
IC 0 21 0.16A
VSE2 21 22 0V
RC 22 0 1
*****
* SQUARING SOURCES      *
*****
ESQ 30 0 4 0 0 0 0.16666667
RSQ 30 0 1
FSQ 0 40 VS1 0 0 1
VSE1 40 41 0V
RSC 41 0 1
*****
.MODEL DIO D
.MODEL TR NPN CJC=0.1PF CJE=0.1PF
.WIDTH IN=72 OUT=72
.TRAN 100NS 40US UIC
.PRINT TRAN V(2) I(VS1)
.PRINT TRAN V(50) I(VTO)
.OPTION METHOD=GEAR
.OPTION LIMPTS=1K ITL5=20K
.END

```