Costs of computer design time are still relatively high, 15 dollars per minute, or 900 dollars per hour. In addition, the problems of getting a program written, debugged, and operational are time consuming and thus expensive.

One approach to solving this problem is the use of "conversational programs" with a time-sharing computer doing the mathematical work while the design engineer does the thinking in some areas. For example, the author has written two programs which are now operational. One program is for design of linear coil transformers, using either cut *C* cores, *EI* laminations, or *DU* laminations. The other program is being used to design toroidal transformers.

In the first program called NEWTXI, wire data, diameter over insulation, area in square miles, resistance per thousand feet, and weight per thousand feet of round wires from number 40AWG to number 8 are stored in memory. Standard cores, margins, overbuilds, core insulations, and layer insulations are also available in memory if the designer desires to use them. In use, the engineer calls up the program and instructs it to run (FORTRAN IV is the language used). The computer then asks for details of the desired design such as input and output voltage and current, type of winding (noncenter tap; or center tap, i.e., bifilar), approximate flux density, standard or nonstandard core and tolerances. The computer calculates turns and actual flux density and asks for estimated wire size for each winding in turn. The computer prints out turns per layer and percent of layer filled and requests engineers to decide if larger or smaller wire gauge is to be used. If so, it recalculates until all windings are acceptable. Then the computer calculates and prints out wire size, resistance, reactance, turns per layer, etc., for all windings as well as total copper losses, weights, etc.

The second program called TOROID works on the same principles except each layer of winding is different because of the decreasing ID of the device as more and more layers of wire are applied, mathematically.

Sample calculations showing input data of the NEWTXI program (Fig. 1) and printout of both programs illustrate the conversational program's versatility.

Computerized Toroidal Transformer Design

DONALD J. HOPPER

A computer program has been written in FORTRAN II that will design toroidal transformers. The program selects the core, the primary and secondary wire sizes, and the primary and secondary turns. The program has a library of 97 cores and 37 wire sizes from which to choose. The input requirements are engineering data normally required for transformer design. The program will handle up to 9999 transformers at a time. The computer will select a core that will have a window area approximately 40-percent filled. The computer run time is about one minute for each transformer.

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Pulse Properties of Large 50–50 NiFe Tape Cores

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***Abstract*—Over 400 cores of 1-mil 50–50 NiFe, each core containing 40 or more pounds of material, are used in a linear induction accelerator, which is a part of a controlled thermonuclear research experiment. Each core couples a constant voltage pulse of approximately 10 kV lasting 350 ns to an electron beam whose current is in the hundreds of amperes range. To achieve reasonable operation of the accelerator it is essential that the drive power to the cores, both during the forward pulse and reset, be kept to a minimum.**

Since cores of this size and constant voltage drives of this magnitude are both rarities, potential manufacturers of these cores have been reluctant to guarantee the pulse performance. To overcome this reluctance a study program consisting of both a theoretical analysis and experimental tests was conducted. Specifically, the purpose of the study was to find answers to three key questions. 1) What is the minimum current required in an optimum core? 2) What are the major contributors to deviations from the minimum current? 3) What can be done to insure consistently good cores? Results of the study for cores made of both 1-mil and 1/2-mil tape are discussed; the major findings being that at these drive levels, eddy currents both within individual wraps and between wraps cause the dominant losses. Recently about 200 such cores were obtained. The measured pulse values are compared with the predicted values.

I. INTRODUCTION

ONE approach being investigated in the quest for controlled thermonuclear fusion is the Astron concept in which relativistic electrons provide a confining field for a hot plasma [1]. The relativistic electrons are obtained by accelerating a pulsed beam of electrons to an energy 4 MeV or greater and then injecting them into an appropriate magnetic field. The cores whose pulse properties are the subject of this paper couple energy from pulse forming networks to the electron beam within the accelerator. Four hundred cores having a cross sectional area of 24 cm^2 are used at the present time, each one coupling about 10 kV to the beam as it passes through their centers. A similar accelerator exists at Dubna, USSR, and a third one which will use ferrite cores is being designed for use at Lawrence Radiation Laboratory, Berkeley, Calif.

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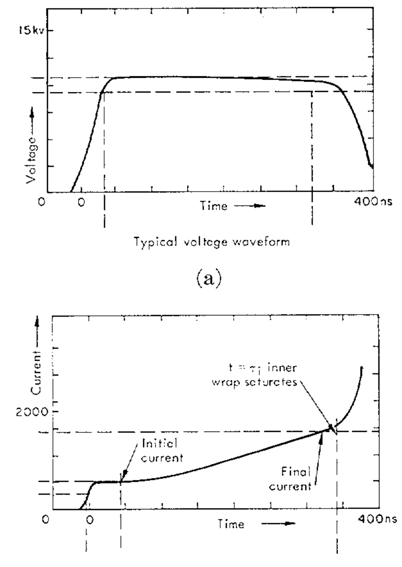

(a)

(b)

Fig. 1. Typical core pulses during test. (a) Voltage. (b) Current.

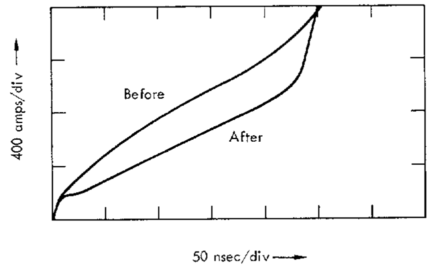

Fig. 2. Excitation current of core before and after rewinding with Mylar.

II. Pulse Shapes

The cores are designed to support a 9-kV pulse for 350 ns. To keep the voltage constant it was found that the primary excitation current had to be increased throughout the pulse. This is accomplished by having a reactive compensating network connected in parallel with the core. During the first half of the pulse, the compensator extracts current from the drive cable, which it returns during the second half. The design is such that the change in current is essentially linear during the pulse. When testing the cores, a constant voltage is applied to the cores by discharging a large capacitor through a low-inductance primary. The capacitor is sufficiently large so that voltage droop is slight until after the core saturates. Typical voltage and current pulses for cores made of 1-mil tape are shown in Fig. 1. The rise time of the voltage pulse is limited mostly by inductance in the primary circuit. Some droop can be seen during the main part of the pulse. This is due primarily to increased voltage drop across a current monitoring resistor. At the end of the pulse pronounced droop occurs because the voltage drop across the primary inductance increases as the rate of change of current increases. The main features of the primary current are that it begins with a step, rises essentially linearly through most of the pulse, and then at the end of pulse rises faster and faster as the core becomes saturated.

Because so little data existed when the first set of cores was purchased, manufacturers were not prepared to guarantee their performance, so the cores were bought on a "best-efforts" basis. When the cores were tested it was observed that a large number, perhaps 10 percent, had poor pulse properties. Some required excessive drive current to support the desired voltage while others had sudden steps in voltage level. More cores are going to be needed in the future, so a study program was initiated to educate ourselves and core manufacturers as to what could be expected from cores. It was hoped that information derived from this study program would enable us to write pulse specifications which the manufacturers could accept.

III. Study Program

The study program consisted of two parts. One was an empirical determination of the factors which make a core have excess losses, the other an analysis of how flux reversal proceeds in cores which do not have excess losses. It was hoped that manufacturers would learn from the empirical tests where to concentrate their efforts to produce consistently good cores and from the analytical study just how low the excitation current might be.

The empirical tests rapidly pointed out that poor wrap-to-wrap insulation was the dominant cause of excess losses in the cores. This was best illustrated in a test in which a small scale core which was bad was unwound and rewrapped with 1/8-mil Mylar insulation between the wraps. The results are shown in Fig. 2. Although the squareness of the material deteriorated during the operation, the reduction of losses is striking. Following this test, other cores which started out having good pulse properties had their insulation degraded in a variety of ways. When retested, the pulses showed all the characteristics of the earlier bad ones: higher current, sudden increases in current, with corresponding droop, and sudden steps in voltage. The shape of the pulse depended on how the insulation was degraded. An attempt was made to correlate the pulse performance with the resistance from the inner to outer wrap with little success. Cores having a resistance over 1000 ohms invariably had good pulse properties, but so did some with resistance as low as 20 ohms. The reason this is possible is that to have interwrap eddy currents it is necessary to have contact between wraps at both edges of the tape. It is possible to have one entire edge of the core welded together, giving zero resistance from inner to outer wrap, and still have a good core if the other edge is free from shorts. Similarly, no other dc or low-frequency tests gave a clear indication of whether or not a core would have good pulse properties, but since these tests were not exhaustive this does not mean that such a test does not exist.

While the empirical tests were being performed, a theoretical basis was being developed to establish the minimum excitation current required for cores without interwrap

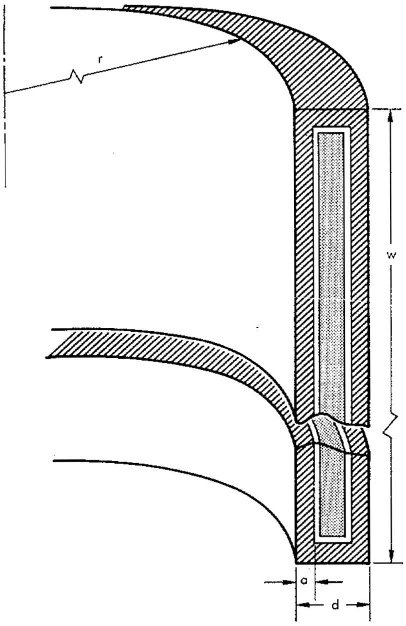

Fig. 3. Saturation wave regions in the tape during flux reversal (exterior, intermediate, interior).

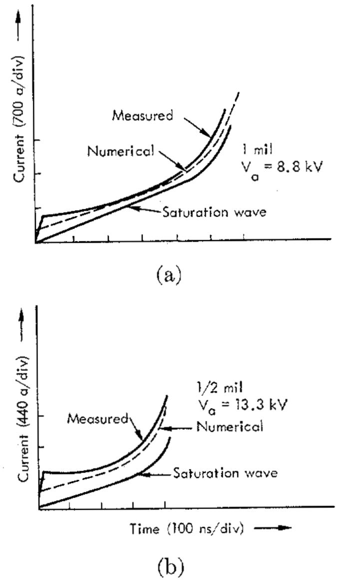

Fig. 4. Current of cores as measured, calculated from saturation wave theory, and computed numerically. (a) Core made of 1-mil tape. (b) Core made of 1/2-mil tape.

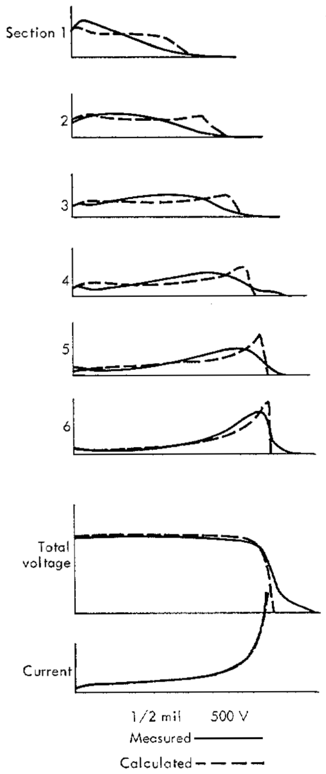

Fig. 5. Sectioned core responses used to determine α and H_0.

eddy currents. The model which appeared to offer the closest fit qualitatively to the observed pulses was the "saturation-wave theory" proposed by Ganz [2]. This theory was extended to include the ratio of outer to inner diameters by Voelker [3] and further extended to include nonconstant drive voltages by Kuenning [4], [5]. The fundamental principle of this theory is that during flux reversal, each wrap of tape can be divided into three regions, as shown in Fig. 3, an interior region in which no flux reversal has occurred, an exterior region which is totally saturated, and an intermediate region in which flux reversal is taking place. Eddy currents flow in the exterior and intermediate regions, shielding the interior, which is why no significant flux reversal takes place there. As the outer edge of the intermediate region saturates, this region moves inward, continuing until the tape becomes saturated. One simplifying assumption used in the analysis is that the width of the intermediate region, which is thin [6], can be assumed to be zero, leaving only the interior and exterior regions.

This analysis leads to a number of significant results. As one may suspect, the innermost wrap is the first part of the core to become entirely saturated. This occurs at a time τ_i. If the applied voltage V_a is constant for $t \leq \tau_i$, then τ_i can be expressed by

$$\tau_i = (\Delta B_s / V_a) W S (\mathrm{ID}) [(\mathrm{OD}/\mathrm{ID})^{1/2} - 1] \tag{1}$$

where ΔB_s is the change in induction in the tape, S is the stacking factor of the core, W is the width of the tape, and ID and OD are the inner and outer diameters. If the voltage is not constant then τ_i can be obtained from

$$\int_0^{\tau_i} V_a \, dt = \Delta B_s W S (\mathrm{ID}) [(\mathrm{OD}/\mathrm{ID})^{1/2} - 1]. \tag{2}$$

Prior to inner-wrap saturation, the excitation current i_e is given in general by

$$i_e(\tau) = \frac{\pi V_a d^2 \int_0^\tau V_a(t) \, dt}{4 \rho \Delta B_s W^2 S^2 (\mathrm{ID}) [(\mathrm{OD}/\mathrm{ID})^{1/2} - 1]^2} \tag{3}$$

where ρ is the resistivity of the tape material, and for

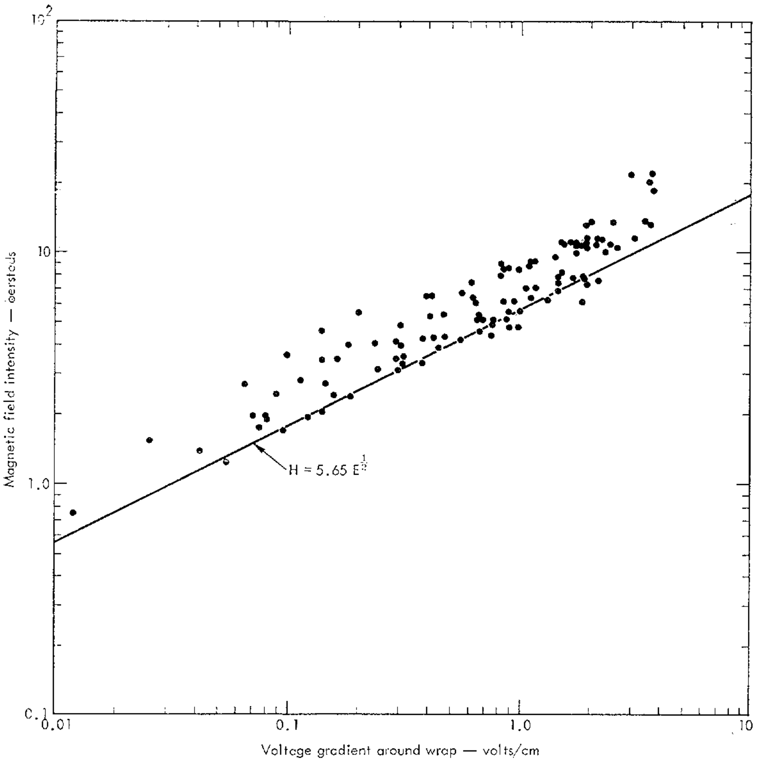

Fig. 6. Initial step measurements.

constant applied voltage the integral becomes $V_a\tau$. From the onset of saturation at the inner wrap until the core is completely saturated i_e is

$$i_e(\tau) = \frac{\pi V_a d^2}{4\rho WS}\left[\frac{1}{1-\left(1-\frac{\mathrm{ID}}{\mathrm{OD}}\right)^{1/2}\left(1-\frac{\int_0^\tau V_a\,dt}{\Delta\phi_{\max}}\right)^{1/2}}-1\right]^{-1} \tag{4}$$

where $\Delta\phi_{\max}$ is the total flux change available in the core.

For constant applied voltage it is seen from (3) that the excitation current should rise linearly from the beginning of the pulse until τ_i. Following τ_i the current rises increasingly faster. Fig. 4 shows the measured and predicted excitation currents for 1-mil and 1/2-mil cores. It is seen that for 1-mil cores the measured curve and the one predicted by the saturation wave theory are in reasonable agreement after 150 μs, but the saturation wave theory does not predict the step at the beginning of the pulse. Fig. 4(b) shows that the discrepancy between the predicted and measured curves is even greater in the 1/2-mil core. This is because eddy currents play a less dominant role in this case. In general, the analytical solution of saturation wave theory gives good usable results when eddy currents are the dominant source of loss. This is the case whenever the excitation current at τ_i is three or more times that of the initial step.

The theory was modified to produce an initial step in current by making the inward velocity of the intermediate region v_w dependent on the magnetic field intensity present H_w. The relation which best fits the data qualitatively is

$$v_w = \alpha\{H_w - H_0[1 - \exp(-H_w/H_0)]\} \tag{5}$$

where α is a constant of proportionality and H_0 represents a threshold. For $H_w \gg H_0$

$$v_w \simeq \alpha(H_w - H_0).$$

Unfortunately, a closed analytic solution for τ_i and i_e could only be obtained for the case $H_0 = 0$, which is essentially equivalent to the unmodified theory. However, the problem can be treated numerically. The program developed to do this divides the core into small sections. Then, based on past and present values of current, section voltage, and wall position, new values of voltage and wall position can be determined at the ends of short time intervals. If the sum of the voltages of the sections equals the applied voltage, those values just determined are saved and the time increased. Otherwise the current is changed and new values computed. While this program was being written and debugged, several 1-mil and 1/2-mil cores consisting of six concentric sections were obtained and tested. The excitation current and voltage across each of the sections were measured for a given applied voltage and compared with corresponding computed results to determine values for α and H_0. Fig. 5 shows a set of values for $H_0 = 1.3$ Oe and $\alpha = 1500$ cm·sec^{-1} Oe^{-1} which gave the closest fit with the measured data. Using these values the excitation current was computed for full size 1-mil and 1/2-mil cores. Typical results are included in Fig. 4. The agreement is

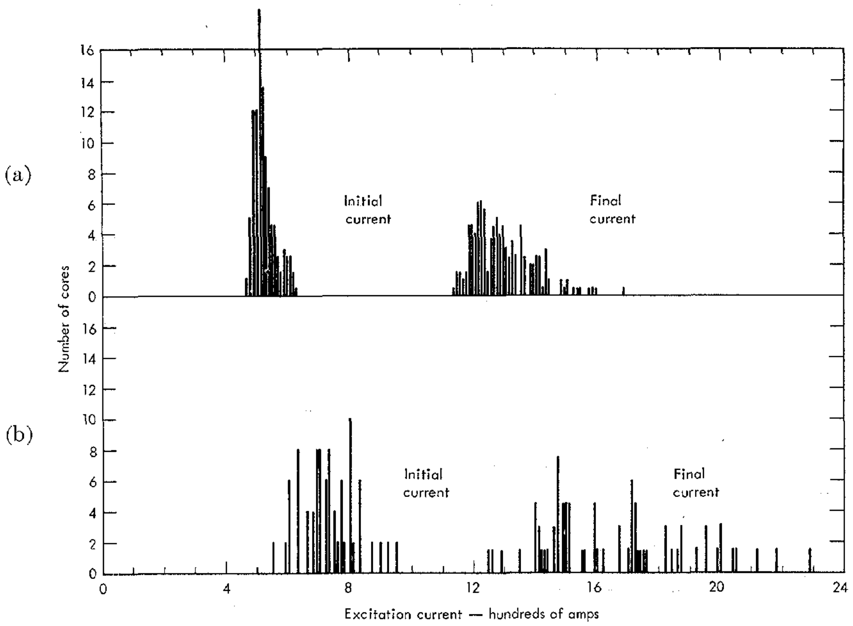

Fig. 7. Initial and final currents of old and new cores. (a) Latest order, using improved insulating techniques. (b) Earlier orders, using standard manufacturing techniques.

quite good although there is still an overshoot at the beginning of the pulse. A number of attempts have been made to explain and control this overshoot, but no conclusive results have been obtained. To facilitate writing the specifications for new cores, the initial current height was measured for a large number of cores of various sizes and tape thicknesses at a number of voltages. The results are shown in Fig. 6 in which H at the surface of a wrap of tape is plotted against E the voltage gradient around the same wrap of tape. H varies approximately as $E^{1/2}$ with the lower limit being $H = 5.65E^{1/2}$. Most of the good cores tested lie within 50 percent of this value. The current derived from this plot is used to set the initial current value for core specifications.

Reset Requirements

Of almost equal importance to having low excitation currents is the need to have repeatable performance from pulse to pulse. To achieve this it is necessary that the cores be driven into saturation during the reset pulse. Unfortunately, the reset voltage level available on the Astron accelerator may vary by ±10 percent. Even with this variation it is possible for properly prepared cores to reach the same reset value of B_r to within ±1 percent by making H_c sufficiently low and sacrificing some squareness of the hysteresis loop.

Summary

The study has shown that interwrap eddy currents are the major cause of excess core loss at high drive levels. In addition, they can also shield part of the core during the pulse, making the rest of the core saturate prematurely. This results in irregularities in the voltage pulse. Knowing these facts, core manufacturers have concentrated on reducing contact between wraps of tape by reducing burrs at the edges, applying insulation carefully, and avoiding the removal of insulation during the annealing process. Recently 200 additional cores were purchased. The awareness on the manufacturer's part of the importance of good insulation resulted in high-quality cores. Fig. 7 shows histograms of the current near the beginning and end of the pulse for the cores just purchased and for cores acquired previously. The improvement is obvious both in the figure and in the accelerator.

With the equations from the saturation wave analysis it is easy to determine the effect of changes in core dimensions, tape thickness, stacking factor, etc., leading to an optimum design for a given application. The excitation current required can then be determined with the computer program.

Acknowledgment

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