EVALUATION OF MAGNETIC MATERIALS AND INSULATION SYSTEMS FOR REPETITION-RATE PULSE COMPRESSION APPLICATIONS

Kenneth McDonald, Randy Curry and Robert O'Connell
University of Missouri-Columbia
Department of Electrical Engineering
Columbia, Missouri 65211
mcdonaldkf@missouri.edu

Paul Melcher, Richard Ness and Chaofeng Huang
Cymer Inc
17075 Thornmint Court
San Diego, California 92127

Abstract

Efficiency and thermal characteristics are some of the most critical attributes of magnetic materials that are employed as switches for repetition-rate pulse compression applications. Accordingly, a test stand has been constructed at the University of Missouri-Columbia to evaluate the switching properties of magnetic materials suitable for solid-state magnetic modulators for lasers or other loads requiring short duration, high power pulses. The testbed operational conditions can be adjusted to determine the effects of switching frequency. Variables include the voltage, initial pulse shape, time to initial saturation, and switching period.

The data acquisition equipment and methods, data processing, generation of B-H curves, and determination of energy loss and mechanisms are also discussed.

I. INTRODUCTION

Evolving crucial applications for Ultraviolet (UV) excimer lasers demand the pulsed power drivers that are highly efficient and highly reliable [1,2]. Accordingly, there is an ever-increasing need for high peak power modulators to deliver low per-pulse energy but operate at very high repetition rates [3]. The high peak power requirement mandates a voltage step-up transformer and numerous temporal compression stages to keep the first stage within the operational limits of economical solid-state switches. Moreover, the choice of saturable magnetic switch systems is even more critical because low pulse energy, high rep-rate operation is very sensitive to switching losses. Optimization requires that different magnetic systems be employed in the various stages, pursuant to the volt-second product and delta B inherent to the magnetic switch and the 1- cos (ωt) magnetization time inherent to the particular compression section.

The optimal selection of magnetic switches for each compression stage is further complicated by the recent availability of new magnetic and insulation materials, and fabrication/annealing procedures. Emerging magnetic materials are now becoming available because of recent progress in the development of nano-crystalline magnetic materials new insulation materials and schemes [4,5,6]. Moreover, quality control issues can seriously impact the switch performance due principally to annealing methodologies and type of insulation system.

On the positive front, the pulse power designer now has newly available options that can enhance efficacy and attendant system performance. However, the vast matrix of choices and lack of manufacturers data consistent with magnetic switch topologies suggests that a quick method of making both absolute and comparative measurements of the switching and loss properties of switch systems is critical. Even the determination of an appropriate figure of merit to make relative comparisons among the options can be daunting.

II. MAGNETIC MODULATOR CIRCUITS

A typical excimer laser magnetic modulator schematic is shown for reference in figure 1.

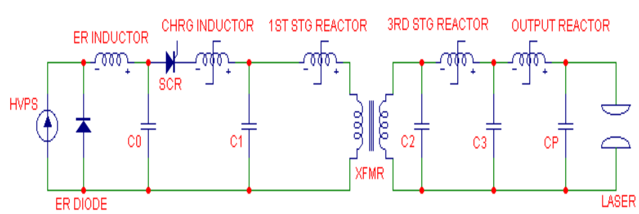

Figure 1. Typical Excimer Laser Magnetic Modulator

The initial energy storage section is consistent with the final pulse energy requirements of the laser head and is designed to remain within the operational limits of efficient, economical, solid-state switches such as SCR's or IGBT's. Principal among these are the voltage, current, di/dt, and average power specifications. A saturable reactor is typically included as a magnetic assist to improve the switch di/dt performance [7]. The remainder of the modulator is designed to accommodate the laser head gas discharge, i.e., the voltage and temporal properties of the pulse

0-7803-7915-2/03/$17.00 ©2003IEEE.

must be matched to the discharge cavity for optimal, reliable, long life performance. Matching is achieved by a series of magnetic compression stages to obtain the requisite (short) pulse length, and a voltage step-up transformer is used to obtain the required voltage at the laser head. The transformer can be of either conventional construction or composed of Linear Induction Adder cells.

The stage capacitances are held relatively the same, and the compression is achieved by successively lowering the effective saturated inductance. The C-L-C circuit topology impresses 1 – cos (ωt) waveforms across the magnetic switches, which are set by ΔB and the effective cross-sectional area to saturate at approximately 95% of the maximum charge on the second capacitor in the compression stage. Typical first stage waveforms are shown in figure 2 for initial and post 50 billion shot tests on a Cymer modulator.

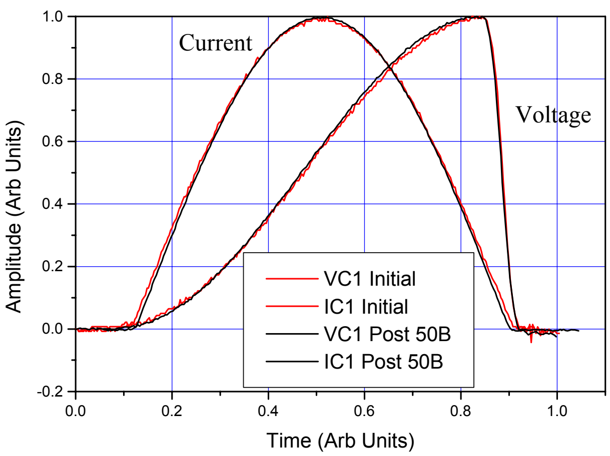

Figure 2. Typical First Stage Current and Voltage Waveforms

A single turn primary is typical for these applications. Consequently, the magnetic switch losses are determined in part by the 1 – cos (ωt) waveforms, which are increasingly faster for each stage. Unfortunately, manufacturers do not provide 1 – cos (ωt) data for their core materials.

III. MAGNETIC SWITCH THEORY REVIEW

Magnetic switches, or saturable reactors used in pulsed power compression circuits are described by the analytical expression

$$\boldsymbol{B = \mu_o H + \mu_o M(H)}$$

where

B	=	magnetic induction
H	=	magnetic field
M(H)	=	magnetization
μ_o	=	vacuum permeability

This expression describes the existence of a linear contribution $\boldsymbol{\mu_o H}$ to the induction $\boldsymbol{B}$, and a nonlinear contribution due to material properties. Equations derived from Faraday and Ampere allow the derivation of core properties from material properties:

$$\Phi = \int_s B ds = A_l B,$$

and

$$I = \int_L H dl = l_l H,$$

Where

S	=	core cross-sectional area
A_l	=	effective core cross-sectional area
I	=	current
l	=	magnetic path into the core
l_l	=	effective core magnetic path length

Numerous papers have documented core losses and Hysteresis loops [8,9,10]

IV. MAGNETIC SWITCH TEST STAND

A test stand suited to evaluating magnetic materials and insulation systems pursuant to magnetic switch design should, at a minimum, include the ability to generate 1 – cos (ωt) waveforms, accommodate high fidelity monitoring of the circuit current and voltage across the core, and be able to operate at modest repetition rates. An example configuration is shown in figure 3.

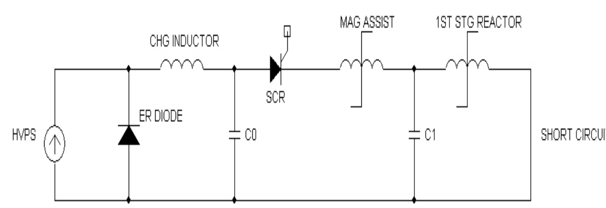

Figure 3. Magnetic Switch Evaluation Test Circuit

The current can be monitored with either a current transformer, or a resistive shunt. The transformer method is slightly preferred because it is not subject to ground loop noise. However, these transformers can have slight phase shifts that must be corrected to be in exact phase with voltage, if high fidelity loss information is to be obtained. The correction can be made digitally after acquisition, but a cable delay method is preferred. The voltage drop across the core can be measured directly or by a transformer secondary wire. A high quality voltage probe is mandatory in either case. For direct data, a differential voltage is required, and a Tektronix 2500V probe is ideal for the transformer method. Additional data acquisition complexities are manifest in the difficulty of determining the exact starting point of the 1 – cos (ωt) waveform; and eliminating digital noise associated with single pulse events. Discrimination of the 1 – cos (ωt) starting point is further complicated by the presence of the magnetic (switch) assist saturable reactor. The voltage collapses across the solid state switch, but substantial currents do not flow until the core saturates, and the 1 – cos (ωt) waveform commences. The first of these deficiencies can be corrected by deploying a B-Dot probe near the switch to accurately determine commencement of the current surge. Acquiring and averaging numerous data sets at low pulse repetition rates can eliminate the second deficiency. The average mode in a digital oscilloscope is ideally suited to this purpose, and 256 – 512 data sets can be averaged with 5 - 10 hertz operation in reasonably short times without affecting the core temperature.

Post data acquisition processing is required to determine switch losses. While digital scopes with math processing functions, including integrals, can be used to evaluate losses according to the $\int vi dt$ method; post processors are essential to generate B-H curves and are recommended for all data. MatLab or LabView are two of many such applications, and the authors used MatLab.

Examples of the current and voltage data sets are shown in figure 4.

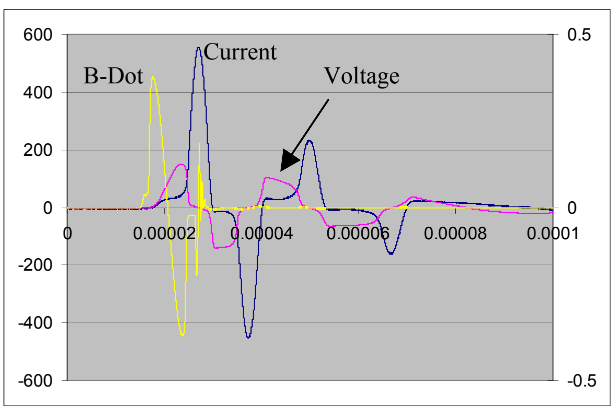

Figure 4. Typical Data Set

The B-H curve, as reconstructed by a MatLab program, is shown in figure 5 for a single data set. This data is obviously incapable of rendering high quality loss data because of the "digital noise". This deficiency is corrected by averaging 256 data sets, as shown in figure 6.

Similarly, the B-H curve is shown for the raw data in figure 7, without correcting for the baseline offset. It can be seen that the successive B-H curves do not lay on top of each other because of an artificial baseline shift in the voltage signal.

MatLab was subsequently programmed to automatically interrogate the voltage signal prior to commencement of the switch trigger. The signal is averaged and re-baselined to zero. This action corrected most of the problem, however it is still necessary to manually fine-tune the baseline by approximately 1/10th of a percent in order to accurately overlay multiple B-H curves commensurate with the number of cycles obtained in the data set, as shown in figure 8.

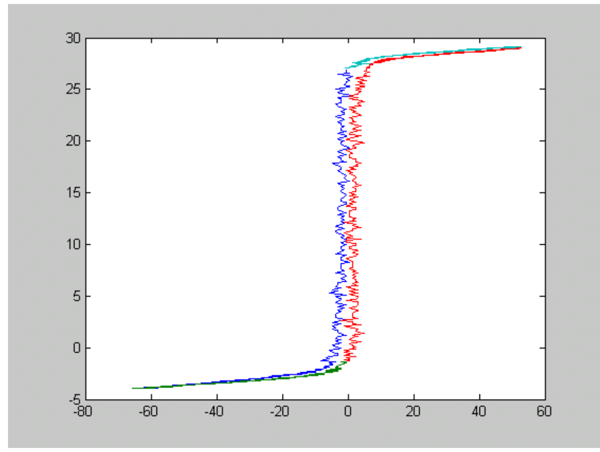

Figure 5. B-H Curve For a Single Data Set

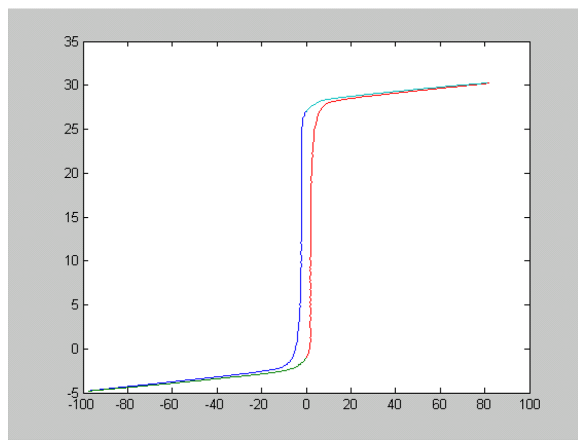

Figure 6. B-H Curve for 256 Averaged Data Sets

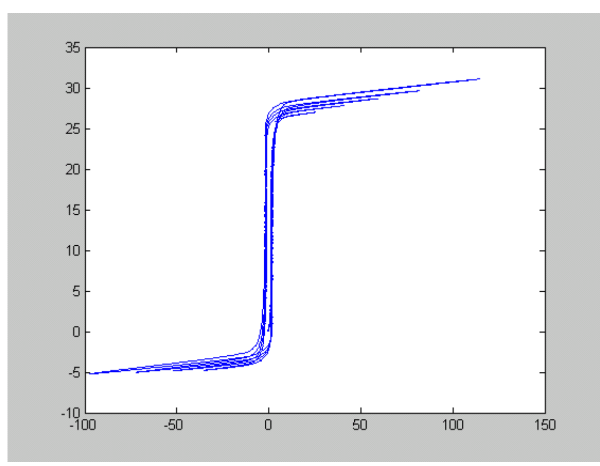

Figure 7. B-H Curve Without Baseline Correction

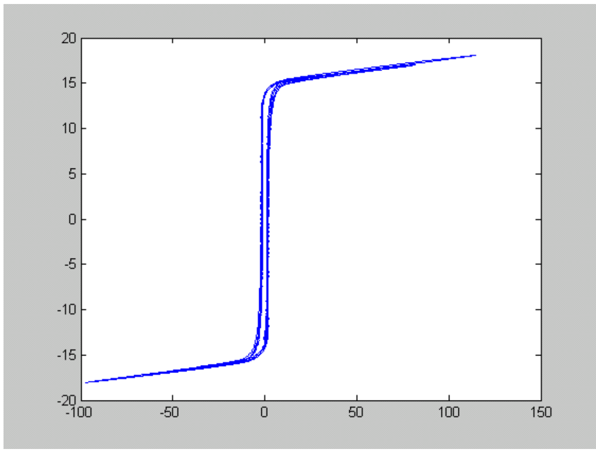

Figure 8. B-H Curve With Baseline Correction

While it is possible to reconstruct the B-H curves from either the current (H) zero crossings or peak crossings, the authors recommend that the zero crossings be used. It is also possible to use either the ∫BdH or the ∫HdB, but both give virtually identical results with our data.

IV. FIGURE(S) OF MERIT

The pulse power designer also has an interesting challenge to determine the appropriate figure of merit to compare core performance. Some factors for consideration include the energy loss vs. the magnetization time, the loss density, the maximum delta B, the stage gain, the size and weight, the saturated inductance, etc. While no single method has, or practically could be, adopted as a standard for magnetic modulator design, the papers by Greenwood, *et. al.* [11] and Barrett [12] offer considerable insight into the problem.

V. SUMMARY

Numerous types of core material and insulation families have been tested to date. The magnetic materials include Nickel-Iron, Amorphous metal alloys, ferrites, and nano-crystalline formulations; including variations in the lamination thickness, etc. The insulation media, thickness and number of layers are also varied. Moreover, at least five cores from the same manufacturing batch have been tested to determine the core performance variation. Finally, each core is tested at a wide range of voltages, commencing at approximately 100 volts, and incrementing in 100 volt steps to a maximum of about 1000 volts.

Final data analysis is in process, and future work will include faster saturation times and thermal considerations.

VI. ACKNOWLEDGEMENTS

The authors would like to thank Tim O'Connell, Adam Toth, Brett Huhman, and Russell Burdt for their superb technical assistance.

REFERENCES

[1] R. Ness, P. Melcher, B. Smith, W. Partlo and D. Birx, "Performance Characterization for an Excimer Laser Solid-State Pulsed Power Module (SSPPM) After 20B Shots," IEEE Transactions on Plasma Science, Vol. 28, No.5, October 2000.

[2] P. Melcher, D. Johns, R. Ness, and B. Partlo, "Lifetime and Reliability Data of Commercial Excimer Laser Power Systems Modules," Cymer Inc. San Diego, CA 92127

[3] W. Partlo, R. Sandstrom, I.Fornenkov, and P. Das, "A low cost of ownership Krf excimer laser using a novel pulse power and chamber configuration, Proc. SPIE, vol. 2440, pp. 90-100, 1995

[4] C. Strowitzki, A. Gortler, M. Baumann, "Losses in Magnetic Switches", Tuilaser AG, Industriestr, 15, Bavaria, Germany

[5] R. Wood and R. Lathlaen, "Exciting New Coatings for Amorphous Glass Pulse Cores," National-Arnold Magnetics, Adelanto, California

[6] C.H. Smith, B.N. Turman, H.C. Harjes, "Insulations for Metallic Glasses in Pulse Power Systems", 19th Power Modulator Symposium, June 28, 1990, San Diego CA

[7] K.F. McDonald, "Evaluation of Solid State Switches for a Space Based Laser Modulator", Oral presentation at the 9th IEEE Int. Pulsed Power Conf., Albuquerque, NM., June, 1993.

[8] G. Orenchak, "Measuring Soft Ferrite Core Properties", Electrical Electronics Insulation Conference 1995 and Electrical Manufacturing and Coil Winding Conference Proceedings, September 18-21, 1995

[9] N. Schmidt and H. Guldner, "A Simple Method to Determine Dynamic Hysteresis Loops of Soft Magnetic Materials", IEEE Transactions on Magnetics, Vol. 32, No. 2, March 1996

[10] C.H. Smith, "Permeabilities of Metallic Glasses at High Magnetization Rates",

[11] M. Greenwood, J. Gowar, and B.M. Bird, "A Comparability Parameter for Amorphous Magnetic Materials", University of Bristol, Bristol England

[12] D.M. Barrett, "Parameters Which Influence the Performance of Practical Magnetic Switches", Digest of Technical Papers, 10th IEEE Pulsed Power Conference, Vol 2. 1995, pp. 1154-1159.