Magnetic Characteristics of Amorphous Metal Saturable Reactors in Pulse Power Systems

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Abstract

Saturable reactors, fabricated from ferromagnetic amorphous metal alloy ribbons, are finding increased use in pulse power systems used in particle accelerators and lasers. The magnetic characteristics of these amorphous metals are discussed in relation to optimizing the performance of saturable reactors in such applications. Formulas are given for selecting core dimensions for switch protection. To aid in optimizing core size and alloy selection, new data are presented comparing core losses of amorphous alloys. Finally, core sizes for an example of a two-stage pulse compression network are calculated, and the efficiency of the network is predicted.

1 Introduction

In the constant quest for greater peak power, higher repetition rate, and longer life in pulsed power systems, the limiting circuit element is often the output switch in the system. Either the lifetime or the clearing rate of the switch is insufficient for high repetition rates, or the *di/dt* capability of the switch restricts the output rise time and the peak power. The appearance in the late 1970s of a new magnetic material, amorphous alloys, with excellent high frequency properties, encouraged pulse power designers to resurrect magnetic pulse compression techniques invented in the 1940s for radar and apply them to pulse power supplies for lasers and accelerators [1],[2],[3]. Results of these and other projects utilizing amorphous alloys are discussed elsewhere [4].

Magnetic material selection is dominated by two conditions inherent in pulse power systems: short output pulses and high power densities. Delivering output power in short pulses requires high magnetization rates which result in high eddy current losses. Minimization of system size requires materials with large saturation induction, further increasing magnetization rates. Core losses not only limit system efficiency, but also cause heating and, thereby, limit the maximum pulse repetition rate.

2 Losses in Amorphous Alloys

Loss measurements on commercial amorphous alloys under pulsed conditions, and loss mechanisms in terms of domain wall dynamics, have been presented before including references to earlier works [5]. To summarize the observations concerning the losses of thin, amorphous alloy ribbons over the range of 0.1 to 30 T/μs, the losses are, in general, proportional to slightly less than the first power of the magnetization rate at high magnetization rates, and proportional to its square root at lower magnetization rates. Also the losses are proportional to the thickness of the ribbon to the first power except for ribbons thicker than those commercially available.

To generate the data in this paper, cores were wound on the same equipment used to manufacture cores for commercial laser power supplies. The cores were made with 25 mm wide METGLAS® alloy ribbon co-wound with 4 μm thick mylar insulation. [METGLAS® is a registered trademark of Allied-Signal, Inc. for alloys of metals.] Table I gives the dimensions of the cores and magnetic properties as measured by a hysteresisgraph.

Table I: Dimensions and dc properties of cores.

METGLAS alloy	2605CO	2605CO	2705M
thickness (μm)	23	15	17
B_s(T)	1.80	1.80	0.75
core dia. (mm)	115x124	115x124	115x135
weight (g)	260	230	540
packing fraction (%)	70	65	67
H_c(A/m)	2.0	2.5	1.0
B_r(T)	1.58	1.66	0.72
Flux swing B_r+B_s (T)	3.38	3.46	1.47

The cores were tested under constant *dB/dt* excitation as described elsewhere [5]. The 20 ns/pt digitized waveforms of current and induced voltage were post-processed with a PC to yield dynamic B-H loops and loss-per-cycle for various times to saturation. The losses for times to saturation between 100 μs and 200 ns are shown in Fig. 1. Average flux swing from negative remanence to saturation under pulsed conditions are given in the figure.

Dynamic losses were also made with 1-cosine excitation in a pseudo-Blumlein line configuration. Two capacitors were charged in parallel with the primary on the core connected between their positive terminals. One of the capacitors was resonantly inverted through an inductor providing a 1-cosine excitation of the core. The losses of the 2705M core increased less than 40% under 1-cosine excitation. Calculations based on domain models place the increase in losses at 20% if losses under constant *dB/dt* excitation increase as the square root of *dB/dt* and 80% if the losses are proportional to its first power [4].

3 Saturable Reactor Applications

Saturable reactors are used for switch protection for two purposes: to hold off rapid current increase until the switch becomes fully conductive and to prevent reverse current after discharge. The calculation of core size and number of turns is relatively simple. First, the hold-off time

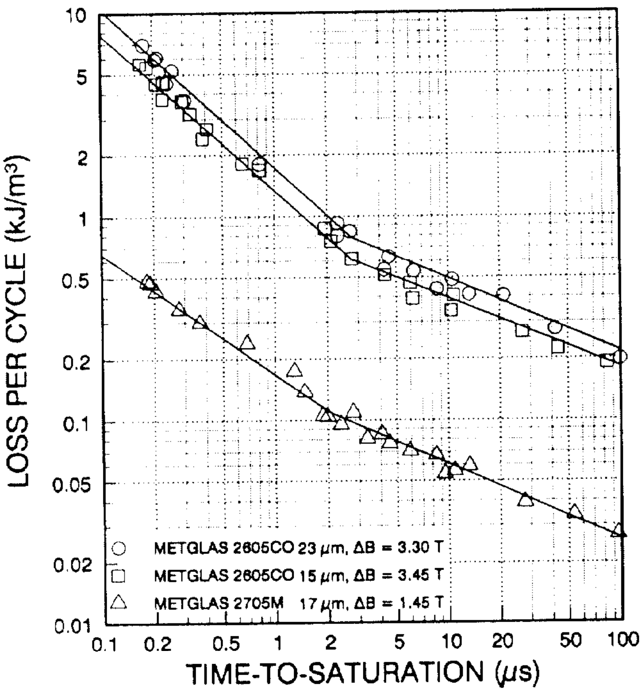

Figure 1. Loss-per-pulse of amorphous alloy cores under constant dB/dt excitation.

for the switch must be known as well as the voltage it is switching. For typical thyratrons it may be of the order of 50 ns before the voltage across the thyratron has fallen to its conducting value. Second, the desired rate of current rise and any other limiting inductances in the system need to be estimated. Finally, the repetition rate of the system is used to calculate temperature rise in the cores based on magnetic loss and whatever cooling is available. The time Δt that a magnetic core will hold off a voltage V is dependent on its change in induction ΔB, its cross section area A_c, and the number of turns N on the core.

$$\Delta t = \Delta B\, N A_c \;/\; V \tag{1}$$

The saturated inductance L_{sat} of the core, to which must be added any other inductance in the system in order to calculate the rise time of the output pulse, is just,

$$L_{sat} = IF\, \mu_o N^2 A_c \,/\, l_m, \tag{2}$$

where μ_o is the permeability of space, l_m is the magnetic pathlength of the core, and IF is an inductance factor, between 2 and 6, which takes into account the leakage flux and the ratio of winding area to core area. Greenwood et. al [6] measured factors of up to 3.3 times calculated inductance due to leakage flux alone on sample inductors with limited numbers of turns. The inductance factor also takes into account the ratio of turn area to net core area. Combining equn. (1) and (2) we find that the core volume is independent of the number of turns.

$$A_c\, l_m = \mu_o V^2 \Delta t^2\, IF \,/\, (\Delta B^2 L_{sat}). \tag{3}$$

The volume can be calculated once the magnetic material is selected. Then area and magnetic pathlength can be traded off to achieve practical core dimensions and turns.

Numerous examples of magnetic pulse compression networks have been published either as design studies or as reports on finished systems. Recently an extensive bibliography was published in the proceedings of an International Magnetic Pulse Compression Workshop [7]. These systems cover a wide range of different designs due to differing requirements such as overall gain, number of stages, and load characteristics. Some circuits include step-up transformers so that the primary switch does not handle the full output voltage, others include delay lines to provide flat-top output pulses. A goal of all of the projects, however, was to reduce the peak current through the primary switch.

The calculation of core sizes and configurations will vary with the requirements of the application. Some discharge pumped lasers, for example, have extended electrodes geometries which lend themselves to stripline power feed with racetrack shaped cores [3]. A basic two-stage magnetic pulse compression circuit with a resistive load and switch protection is shown in Fig. 2 with voltage and current waveforms of various stages. The following formulae will serve as a starting point for core design [8].

The gain of a single stage is the charging time of a capacitor divided by its resonant discharge time to an equivalent capacitor through its saturated inductance. This charging time is the saturation time in equn. (1) with the voltage replaced by the average voltage or $V/2$. The discharge time t_d is given by

$$t_d = \pi\, (L_{sat}\, C/2)^{1/2}, \tag{4}$$

where the saturated inductance is given by equn. (2). The gain per stage g can be calculated to be

$$g = 2\, \Delta B [A_c\, l_m / (\pi^2\, IF\, \mu_o\, \tfrac{1}{2} C\, V^2)]^{1/2}. \tag{5}$$

The energy E_p stored in each capacitor is just $\frac{1}{2}CV^2$, and the volume of the core material is $A_c\, l_m$. With these identities the core volume for the stage can be written

$$VOL = (\pi/2)^2\, (IF\, \mu_o\, E_p)(g/\Delta B)^2. \tag{6}$$

Note that the volume is proportional to $(g/\Delta B)^2$. High saturation induction material can save considerable volume.

The gain per stage in a multi-stage pulse compressor is usually chosen to minimize either total system weight or volume. Minimizing only magnetic material would result in choosing a gain per stage of only $\sqrt{e}=1.65$. This choice would result in a large number of stages. Practical designs, which also consider the number of capacitors required, typically use a gain of 3-5 per stage. Recent work has shown that reducing the gain of the final stage, which experiences the highest magnetization rates, can reduce the total losses [9]. Other works have shown that core volume can be reduced by allowing each inductors to saturate somewhat before the peak voltage is reached on the capacitor [10].

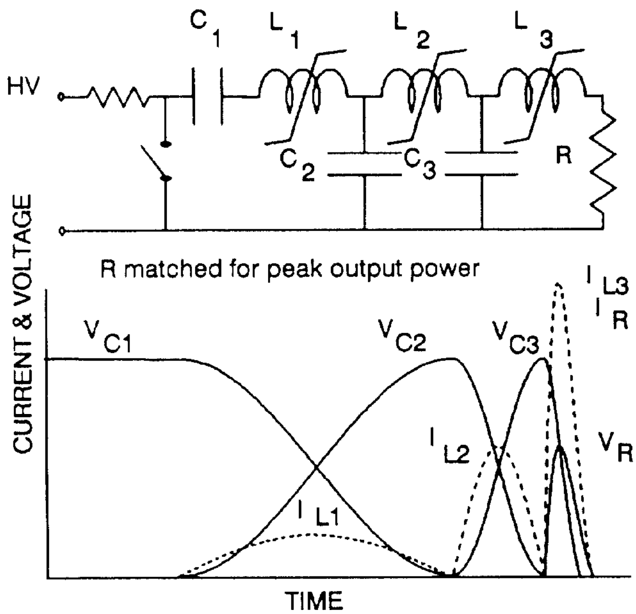

Figure 2. Circuit diagram and waveforms for a series two-stage magnetic pulse compressor with magnetic switch protection.

Calculation of core sizes is best done using a spread sheet program and iterating various parameters to reach core design choices [11]. Each stage can be calculated starting with the output stage. The stages can be coupled through the spread sheet to keep total gain constant and to calculate total core mass and efficiency. By using parallel columns for design options, one can explore design trade offs. A single turn coaxial winding corresponds to the lowest IF and, hence the lowest core volume once energy, gain, and ΔB are chosen. Given the core volume and the number of turns, the area is calculated from the voltage and time to saturation. Losses can be calculated from a power law fit as time to saturation changes. The simplified equations in this paper will give the minimum core volume required. If significant inductances or losses exist elsewhere in the circuit, they must be taken into account. For example, an inductance in addition to the saturated inductor, equal to half the allowable inductance for resonant discharge, can be compensated by doubling the IF which will, in turn double magnetic pathlength and core volume.

Table II. Cores for a two-stage pulse compressor with 30 J, 30 kV 100 ns output.

Stage 1	Alloy	2605CO	2605CO	2705M
	Δt (ns)	1000	1000	1000
	gain/turns	3.3/6	3.3/6	3.3/3
	mass (kg)	2.11	2.07	11.7
	core (mm)	109x132x50	107x130x50	113x164x100
	loss (J)	0.59	0.57	0.36
Stage 2	Alloy	2605CO	2705M	2705M
	Δt (ns)	300	300	300
	gain/turns	3/1	3/1	3/1
	mass (kg)	1.64	9.32	9.32
	core (mm)	32x73x50	99x146x100	99x146x100
	loss (J)	1.2	0.56	0.56
Total	mass (kg)	3.75	11.4	21.08
	loss (J)	1.79	1.14	0.92
	efficiency (%)	94.4	96.3	97.0

As a design example we have chosen a two-stage magnetic pulse compression network with a gain of 10 delivering 100 ns, 30 kV, 30 J pulsed to a laser load represented by a 67 nF peaking capacitor. Three examples are given in Table II: two stages of 15 µm METGLAS alloy 2605CO, one stage each of 15 µm METGLAS alloy 2605CO and 17 µm 2705M, and two stages of 17 µm METGLAS alloy 2705M. Note that the system with the alloy with the highest ΔB has the least core mass, but the greatest loss. The largest increase in efficiency is achieved by using the lower loss material in the final stage.

4 Conclusions

We have presented new data on losses in amorphous metal cores produced for laser power supplies. Basic guidelines for calculating core dimensions for switch protection and for magnetic pulse compression were given, and cores for of a two-stage magnetic pulse compressor were calculated for three alloy combinations.

5 References

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