DESIGN CRITERIA FOR A MAGNETIC SWITCH WHEN USED TO DISCHARGE A PULSE FORMING LINE*

D. M. Barrett
University of California
Lawrence Livermore National Laboratory
Livermore, CA 94550

Abstract

Much has been written concerning the design of magnetic switches in Melville line pulse compression networks. In these networks, magnetic switches are used to discharge one capacitor into another. Pulse compression is achieved by discharging each capacitor at a faster rate than it was charged. The relationship between the circuit parameters of the Melville line and the individual magnetic switches is fairly well understood. However, magnetic switches are sometimes cast in roles which depart from their traditional use in a Melville line network. One such application is that of a magnetic switch being used to discharge a pulse forming line (PFL) into a load. In this paper, the requirements of such an application are discussed. Relationships between the PFL discharge parameters (i.e., pulse energy, risetime, and pulsewidth) and the magnetic switch parameters are derived. A design example of a magnetic switch for use in a PFL discharge application is presented and the design trade-offs are also discussed.

Introduction

Some devices, such as linear induction accelerators, klystrons, kicker magnets and certain types of lasers, must be driven with precisely shaped rectangular pulses. In most cases, it is desired to minimize the rise and fall times of the pulse while maintaining a peak amplitude variation of a few percent or less. For pulsewidths of less than a few hundred nanoseconds, a pulse-forming-line (PFL) is often used to generate the desired pulseshape. When this technique is used, the PFL is typically charged on a time scale which is significantly longer than the output pulsewidth. Once the PFL is fully charged, an output switch discharges the PFL into the load. Traditionally, gas discharge switches such as spark gaps and thyratrons have been used for this application. However, the reliability of such switches limits the performance of these systems at high average power levels.

More recently, saturable reactors have been used as PFL discharge switches [1,2,3]. Magnetic switches do not suffer from many of the limitations associated with discharge switches such as relatively long recovery times and serious electrode erosion problems. Unfortunately, the performance of a magnetically switched PFL circuit is limited by the losses associated with the magnetic switch. The principal parameters which determine the loss of a magnetic switch are the loss characteristics and the volume of the magnetic material which is being used in the reactor core.

The purpose of this paper is to develop relationships between the desired PFL circuit performance and the required magnetic switch parameters.

Operation of Magnetically Switched PFL Circuits

A magnetically switched PFL network is shown in Fig. 1. Here, a transmission line having a characteristic impedance and a one-way transist time of Z_o and $t_p/2$, respectively, is used as the PFL. For this discussion, it is assumed that the load impedance R_l is matched to Z_o. Upon closure of switch S_1, energy initially stored in C_1 is transferred to the PFL charging it with a voltage waveform as shown.

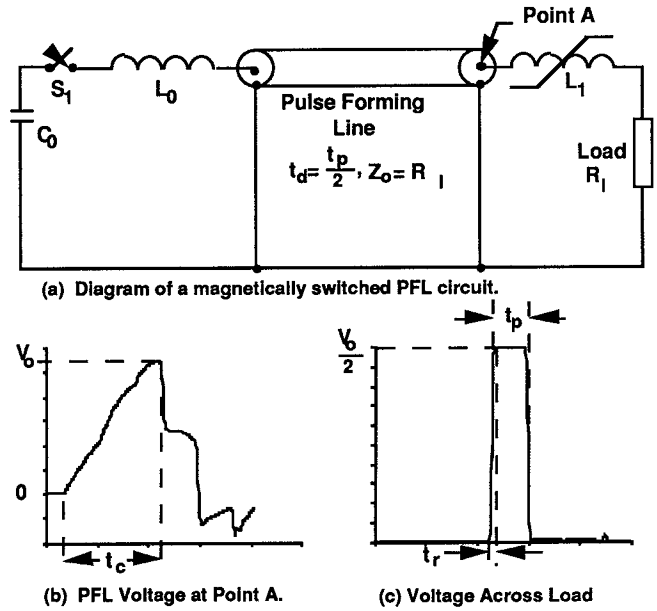

Fig. 1. Circuit diagram and typical voltage waveforms for a magnetically switched PFL circuit.

The charging waveform departs slightly from the traditional (1-cosine) voltage waveform due to reflections which propagate back and forth on the PFL as it is being charged. As the PFL charge time decreases, the reflection and hence the distortion of the charging waveform becomes increasingly pronounced. However, the integral of the voltage waveform is modified only slightly. When the PFL is fully charged, the output reactor L_1 saturates discharging the PFL into the load. Since $R_l = Z_o$, The maximum load voltage is half of the PFL load voltage as shown. Therefore, the energy content of the output pulse is

$$E_o = \frac{V_o^2}{4 R_l} t_p \qquad [1]$$

where V_o = maximum PFL charge voltage
R_l = load impedance

and t_p = width of the output pulse.

The risetime of the load voltage pulse is determined by the L/R time constant of the PFL discharge path and is given by

$$t_{L/R} = \frac{L_{sat}}{Z_o + R_l} = \frac{L_{sat}}{2 R_l} \qquad [2]$$

where L_{sat} = saturated inductance of the output reactor.

In many applications, the pulse risetime is defined as the duration over which the leading edge of the pulse rises from 10% to 90% of its peak value. Under this constraint t_r (10%-90%) = 2.2 L/R. However, in applications such as linear induction accelerator drive systems [4], where the useable portion of the pulse begins within a few percent of the flat-top, this definition of

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14. ABSTRACT

Much has been written concerning the design of magnetic switches in Melville line pulse compression networks. In these networks, magnetic switches are used to discharge one capacitor into another. Pulse compression is achieved by discharging each capacitor at a faster rate than it was charged. The relationship between the circuit parameters of the Melville line and the individual magnetic switches is fairly well understood. However, magnetic switches are sometimes cast in roles which depart from their traditional use in a Melville line network. One such application is that of a magnetic switch being used to discharge a pulse forming line (PFL) into a load. In this paper, the requirements of such an application are discussed. Relationships between the PFL discharge parameters (i.e., pulse energy, risetime, and pulsewidth) and the magnetic switch parameters are derived. A design example of a magnetic switch for use in a PFL discharge application is presented and the design trade-offs are also discussed.

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risetime is inappropriate. In such applications, the risetime must be defined as the duration over which the pulse rises from 0% to 100% of its peak value. As a result, t_r in these applications is given by

$$t_r = 5\, t_{L/R} = \frac{2.5\, L_{sat}}{R_l} \qquad [3]$$

Derivation of Minimum Magnetic Material Volume

In order to achieve the most efficient magnetic switch design, it is necessary to minimize the volume of the given magnetic material. The minimum magnetic material volume is determined by the saturated inductance required to yield the specified pulse risetime as well as the cross-section area required to yield a specified volt-second product. Typically, a magnetic switch is constructed on a toroidal core having an inner radius, outer radius and a height of r_i, r_o and h, respectively, as shown in Fig. 2. The core is surrounded by a winding which is displaced a distance x from the surface of the core. The magnetic cross-section area A_m is the product of the core cross-sectional area A_c and the core stacking factor f_s. The winding area A_w is defined as the cross-sectional area enclosed by the winding and the packing factor f_p is defined as the ratio of A_m to A_w.

The saturated inductance of the magnetic switch is given by

$$L_{sat} = \frac{\langle\mu_{sat}\rangle A_w N^2}{\langle l\rangle} = \frac{\langle\mu_{sat}\rangle A_m N^2}{f_p \langle l\rangle} \qquad [4]$$

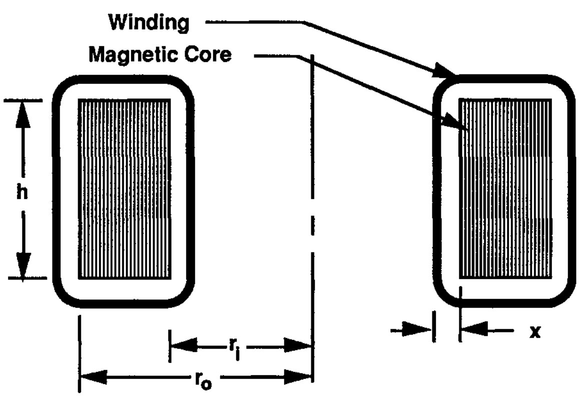

Fig. 2. Typical geometry of a magnetic switch.

where N = number of turns on the core
$\langle l\rangle$ = mean magnetic path length

and $\langle\mu_{sat}\rangle$ = saturated permeability of the core averaged over A_w.

Since the magnetic volume $Vol_m = A_m\langle l\rangle$, Vol_m can be expressed as

$$Vol_m = \frac{\langle\mu_{sat}\rangle A_m^2 N^2}{f_p L_{sat}} \qquad [5]$$

The volt-second product of the magnetic switch is defined as

$$\langle vt\rangle = N A_m \Delta B = \frac{V_o t_c}{2} \qquad [6]$$

where ΔB = flux swing in the magnetic core.

Rearranging Eq. [6] and substituting into Eq. [5], Vol_m can be rewritten as

$$Vol_m = \frac{\langle\mu_{sat}\rangle V_o^2 t_c^2}{f_p L_{sat} 4 \Delta B^2} \qquad [7]$$

Using Eq. [3], L_{sat} can be expressed in terms of the required pulse risetime and substituted into Eq. [7] yielding

$$Vol_m = \frac{2.5 \langle\mu_{sat}\rangle}{t_r} \frac{V_o^2}{4 R_l} \frac{t_c^2}{f_p \Delta B^2} \qquad [8]$$

Using Eq. [1], Eq. [8] can be rewritten as

$$Vol_m = \frac{2.5 \langle\mu_{sat}\rangle}{f_p \Delta B^2} E_o \frac{t_c^2}{t_r t_p} \qquad [9]$$

$\langle\mu_{sat}\rangle$ represents the saturated permeability of the magnetic core averaged over the cross-sectional area of the winding and therefore can be written as

$$\langle\mu_{sat}\rangle = \frac{\mu_o[\mu_{sat} A_m + (A_w - A_m)]}{A_w} = \mu_o[f_p(\mu_{sat} - 1) + 1] \qquad [10]$$

where μ_{sat} = saturated permeability of the magnetic material.

Therefore, Eq. [9] can be rewritten as

$$Vol_m = f_v \frac{2.5 \mu_o E_o}{\Delta B^2} (\text{gain})^2 \qquad [11]$$

where f_v = magnetic volume factor

$$= \frac{f_p(\mu_{sat} - 1) + 1}{f_p}$$

and $$\text{gain} = \frac{t_c}{\sqrt{t_r t_p}} .$$

Eq. [11] indicates that the magnetic volume is directly proportional to the energy which is being switched as well as the square of the gain of the magnetic switch. The volume is inversely proportional to the square of the flux swing in the core. In addition, Vol_m is proportional to the volume factor f_v which is determined by the saturated permeability of the magnetic core as well as the packing factor. The magnetic volume factor as a function of the packing factor for two values of μ_{sat} is shown in Fig. 3. As can be seen, the required volume of magnetic material increases rapidly as the packing factor decreases. In addition, volume factor increases as the value of μ_{sat} increases.

Fortunately, the value of μ_{sat} is usually about 1.1 for a magnetic switch having a drive field in excess of 5 kA-T/m [5]. The value of f_p is determined by the core and winding dimensions. In order to achieve the most efficient magnetic switch design, the value of f_p must be maximized. The packing factor of the magnetic switch shown in Fig. 2 is given by

$$f_p = \frac{A_m}{A_w} = \frac{f_s A_c}{4x^2 + 2x\left(h + \frac{A_c}{h}\right) + A_c} \qquad [12]$$

where x = winding margin
h = core height.

In a perfect magnetic switch, the stacking factor is equal to one and the windings rest directly on the core. As a result, x=0, $f_s = f_p = 1$ and $f_v = 1$. In the less ideal case, the core has a stacking factor of less than one, but the winding continues to rest directly

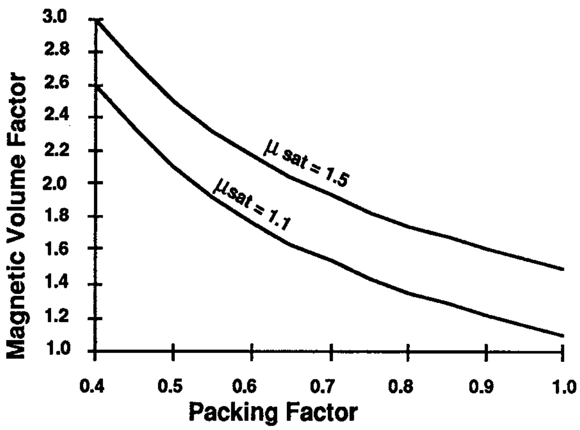

Fig. 3. Magnetic volume factor graphed as a function of the switch packing factor for two values of saturated permeability.

of the core ($f_s < 1$ and $x = 0$) so that $f_s = f_p < 1$ and $f_v > 1$. Finally, for the case when the winding is spaced off the core ($f_s<1$ and $x>0$), $f_p < f_s$ resulting in a further increase of f_v.

Design of a Practical PFL Discharge Magnetic Switch

Unfortunately, practical considerations such as a limited choice of core heights, electric field stress limits, or a preferred core aspect ratio may cause the design of the output switch to deviate from a minimum magnetic volume geometry as specified by Eq. [11] and [12]. For example, when it is required to maintain spacing between the winding and the core ($x>0$), f_p is maximized by making A_c as large as possible. This implies a single-turn switch design. However, when a single-turn switch is designed for low pulse energies, the ratio of the core height to mean diameter of the core can be very large. Construction of such a switch may be impractical due to electric field stress limitations. A multiple turn switch, on the other hand, may provide a more favorable aspect ratio at the cost of increasing the amount of magnetic volume in the core. As a result, the efficiency of the output switch is decreased.

When a switch design is initiated, the required values of L_{sat} and <vt> are known. The selection of a magnetic material for the switch core also specifies ΔB and f_s. Finally, physical constraints may determine other parameters such as the height h and inside radius r_i of the core. If the effect of the winding margin is initially neglected, then the six parameters L_{sat}, <vt>, ΔB, f_s, h and r_i specify a core design completely. The parameters of this initial core design can then be iterated to yield a practical magnetic core design.

The value a L_{sat} of the magnetic switch can be rewritten using Eq. [4] as

$$L_{sat} = \frac{\mu_o [f_s(\mu_{sat} - 1) + 1] N^2 A_m}{2\pi f_s\left(r_i + \frac{A_m}{2 f_s h}\right)} \qquad [13]$$

Eq. [13] can be rewritten to yield a quadratic expression for N as follows

$$\frac{\mu_o \langle vt\rangle [f_s(\mu_{sat} - 1) + 1]}{2\pi f_s L_{sat} \Delta B} N^2 - r_i N - \frac{\langle vt\rangle}{2 \Delta B h f_s} = 0 \qquad [14]$$

From Eq. [14], N and therefore A_m can be calculated for various values of r_i and h. As a result, f_v can be expressed in terms of either r_i or h as well as the winding margin.

The design of a PFL discharge switch can be best illustrated by solving Eq. [11] and Eq. [14] for a specific application. For example, it is desired to drive a load with a 80 J, 125 kV, 100 ns FWHM pulse. The desired risetime of the drive pulse is 15 ns. The design requirements for the PFL discharge magnetic switch are listed in Table 1.

Table 1.
PFL Discharge Magnetic Switch Design Requirements
for the 80 J, 125 kV, 100 ns FWHM Application

Electrical Requirements	
PFL Charge Voltage	250 kV
PFL Energy	80 J
PFL Charge Time	300 ns
Output Pulsewidth (FWHM)	100 ns
Output Pulse Risetime	15 ns
Load Impedance	19.5 ohm
Physical Requirements	
Approximate Inside Radius of Core	10 cm
Winding Margin	0.40 cm

For this design, Metglas 2605 SC amorphous material has been selected for the core. This material has a ΔB of about 3 T. For a material thickness of 25.4 µm, the stacking factor is approximately 0.80.

The calculated gain of the desired discharge switch as defined in Eq. [11] is 7.74 and the required value of L_{sat} is 117 nH. For an ideal switch design ($\mu_{sat} = 1.0$, $f_s = 1$ and $x = 0$), the required Vol_m as calculated by Eq. [11] is 1.67×10^{-3} m^3. However when $f_s = 0.8$, the required magnetic volume is 2.25×10^{-3} m^3, an increase in magnetic volume of 35%. This is the minimal magnetic volume and can only be achieved when the winding margin is zero. For non-zero values of x, additional magnetic material is required to achieve the necessary saturated inductance. The least amount of additional material is required when N = 1. Under these conditions, $A_m = 1.25 \times 10^{-2}$ M^2, $A_c = 1.56 \times 10^{-2}$ m^2 and <r>=2.8×10^{-2} m. As a result, the core must be long and have a thin build. It may be desired to decrease the length of the core by increasing the number of turns on the core.

Keeping with the desire to maintain an inside radius of about 10 cm as listed in Table 1, the required number of turns can be calculated for various values of h using Eq. [14]. Rounded values of N can then be used to calculate the required magnetic cross-sectional area of the core. Since the stacking factor is specified, the volume factor can be graphed as a function of x for various values of N as shown in Fig. 4. When the winding margin is zero, f_v for each value of N is 1.35. This indicates that 35% more magnetic material is required because the core has a stacking factor of 0.80 as opposed to an ideal core which has a stacking factor of unity. Displacing the winding from the surface of the core is accompanied by an increase in the magnetic volume factor. The increased magnetic volume that accompanies an increase in x is a result of additional magnetic path length which is required to compensate for the increase in winding area.

For the switch requirements as listed in Table 1, it is observed from Fig. 4 that a four-turn switch design minimizes the magnetic volume of the core at large values of x. However, at large values of x (x = 0.40 cm), the volume factor increases 45% resulting in a f_v of about 1.6.

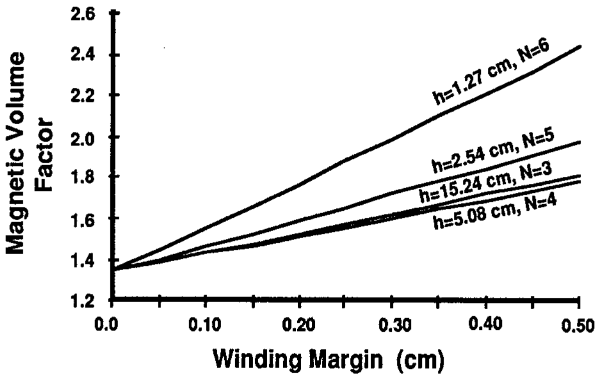

Fig. 4. Magnetic Volume factor graphed as a function of winding margin (x) for various values of h and N.

Summary

The requirements of a PFL magnetic discharge switch have been discussed. An expression for the minimum magnetic volume of such a switch has been derived. In addition, factors which influence the required magnetic volume and hence the efficiency of a practical PFL discharge switch have been discussed. It was shown that the required magnetic volume is significantly influenced by the stacking factor of the magnetic core as well as the packing factor of the switch. Specifically, a non-zero winding margin can significantly increase the amount of magnetic material required for a switch resulting in a less efficient discharge switch. However, the required increase in magnetic volume can be minimized by the design of a core with the appropriate dimensions.

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