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MAGNETIC SWITCHING CORE GEOMETRY

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This brief article documents calculations performed in an effort to identify an optimal geometry for compact low-inductance magnetic switches. The effects of magnetic core geometry on saturated inductance and mass for a constant magnetic switching flux are analyzed. This analysis demonstrates that there is not an exact optimum, but that saturated inductance and mass can be minimized for reasonable dimensional ratios.

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1.0 Introduction

Magnetic switches have gathered significant interest as a high-power, high repetition rate, solid-state approach for driving short-pulse high power microwave (HPM) sources. Magnetic switches provide the simultaneous features of high power handling (GW-class), fast switching, ability to operate at high pulse repetition rates (>>1 kHz), high degree of electrical robustness, exceptionally long lifetimes, relative inexpensive fabrication, and commercial supply chains. However, magnetic switches are physically large and heavy compared to spark gap alternatives when operating at GW-class power levels. This article analytically explores the influence of physical geometry on both saturated inductance and mass in an effort to minimize both.

2.0 Magnetic Switch Geometry Analysis

2.1 Geometric Analysis for Saturated Inductance

The switching flux of a magnetic core is determined by the cross-sectional area of the core and the maximum change of magnetic field in the core, ΔB. Assuming a toroidal core with outer radius R_O, inner radius R_i, and length l_C the switching flux is given by

$$\emptyset_s = \Delta B \, (R_o - R_i) l_c \tag{1}$$

Thus, the following product is a constant.

$$(R_o - R_i) l_c = constant \tag{2}$$

The saturated inductance when the core has switched is calculated by:

$$L = \frac{\mu_r}{2\pi} \, l_c \, Ln[\frac{R_o}{R_i}] \tag{3}$$

Where μ_r is the saturated relative permeability of the core. This is the smallest achievable inductance since the conductors are assumed to have the same dimensions as the core. We can now address the question of whether the inductance can be minimized by an appropriate choice of dimensions. Substituting l_C from the flux equation into the equation for L yields:

$$L = \frac{\mu_r}{2\pi} \frac{\emptyset_s}{\Delta B} \frac{Ln(R_o / R_i)}{R_o - R_i} \tag{4}$$

Since we are concerned with geometry and not overall scale it is convenient to define a new variable ε = $(R_O - R_I)/R_O$. As a function of ε, the equation for the inductance is then:

$$L = \frac{\mu_r}{2\pi}\frac{\emptyset_s}{\Delta B}\frac{1}{R_o}\frac{Ln[\frac{1}{1-\epsilon}]}{\epsilon} \tag{5}$$

If there is a value of ε between 0 and 1 that minimizes the inductance, then dL/dε must be equal to zero for that value of ε. With either some messy calculus or a few numerical evaluations it is clear that there is no such solution. In fact, this function of ε is monotonically increasing with a starting value of 1.0 at ε = 0 and rising to infinity at ε = 1.

Thus, the lowest inductance core configuration is the limiting case ε = 0 for a core of zero radial thickness and infinite length.

2.2 Geometric Analysis for Core Mass

A similar analysis can be performed to address the question of core mass. The mass of a given core geometry is given by:

$$M = \delta\,\pi\left(R_o^2 - R_i^2\right)l_c \tag{6}$$

where δ is the density of the core material. Substituting as before for l_C gives:

$$M = \delta\,\pi\left(R_o^2 - R_i^2\right)\frac{\emptyset_s}{\Delta B}\frac{1}{R_o - R_i} = \delta\,\pi\frac{\emptyset_s}{\Delta B}R_o\,(2-\epsilon) \tag{7}$$

So, once again, we have a monotonic function. In this case the lowest mass, ε = 1, occurs for a solid disk (with infinite saturated inductance) and the highest mass, ε = 0, for the geometry with the lowest saturated inductance.

2.3 Discussion

Despite the lack of an optimal geometry that simultaneously minimizes both saturated inductance and mass, the situation is not too dire. The table below shows the normalized values of l_C, M and L as a function of ε. For ε values around 0.3 the inductance is only 20% over the minimum and the length penalty is not too onerous.

ε	l_C	M	L
0.0	Inf	2.0	1.0
0.1	9.0	1.9	1.054
0.2	5.0	1.8	1.116
0.3	3.33	1.7	1.189
0.4	2.5	1.6	1.278
0.5	2.0	1.5	1.386
0.6	1.67	1.4	1.527
0.7	1.43	1.3	1.720
1.0	1.0	1.0	Inf

3.0 Conclusion

This brief article analytically evaluated magnetic switching saturated inductance and mass. The analytics presented here find that there is not an exact optimal geometry for minimizing both saturated inductance and mass, but that for a dimensional aspect ratio of 0.3 the inductance is only 20% above minimum and

the mass is only 1.7 times the minimum. This analysis supports on-going work in GW-class short pulsed HPM drivers, and will help guide magnetic switching design engineers.

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