Magnetic Cores for Pulse Compression

Tape Wound Cores by *Magnetics* for Use in High Voltage Pulsed Power Applications

A growing field of applications for tape wound cores involves pulse compression techniques to increase peak current levels while still delivering a constant energy to the load (often a laser system). These compression requirements often arise as a means to reduce the stress imparted to the main power switch (reference Figure 1) due to excessive peak current flowing through it. By compressing the current waveform downstream of the switch, lower peak currents are 'seen' by it, yet the necessarily high peak current can still be delivered to the laser load.

Figure 1 shows a circuit comprised of a switch, 2 capacitors, and an inductor. After C1 is charged from input voltage V_{max}, the switch is closed. This action dumps C1's collected energy into the LC circuit made up from L and C2, and sets up a current waveform with a sinusoidal shape, as shown. The frequency (and therefore the width) of this half sine wave is determined by the relative values of L and C1 plus C2. Therefore careful choice of component values will narrow the current pulse while increasing its peak value (because total energy in the system will remain constant).

Figure 2 details a three-stage compression circuit. The current pulse rises in peak amplitude after each stage, but has its duration shortened. Depending on the particular circuit configuration, the voltage waveform (and V_{max}) can either be amplified (and compressed) in a similar manner to I_{peak}, or might simply have its duration compressed while retaining the same peak value. Although energy transfer tends to be more efficient if V_{max} remains unchanged through each stage (because raising V_{max} implies different capacitor values and therefore poor power matching from one stage to the next), many designers opt to increase V_{max} so that progressively smaller capacitors may be used at each stage further downstream of the switch (for fixed charge on all capacitors, higher voltage implies smaller capacitance). Figure 2 shows pulse compression with progressively smaller capacitor values.

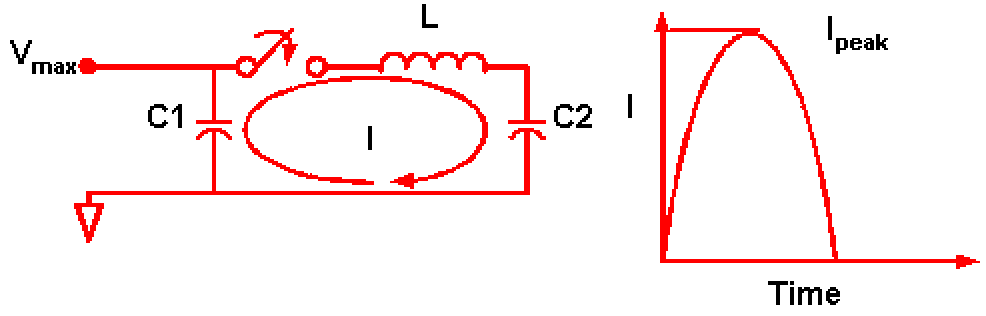

Figure 1

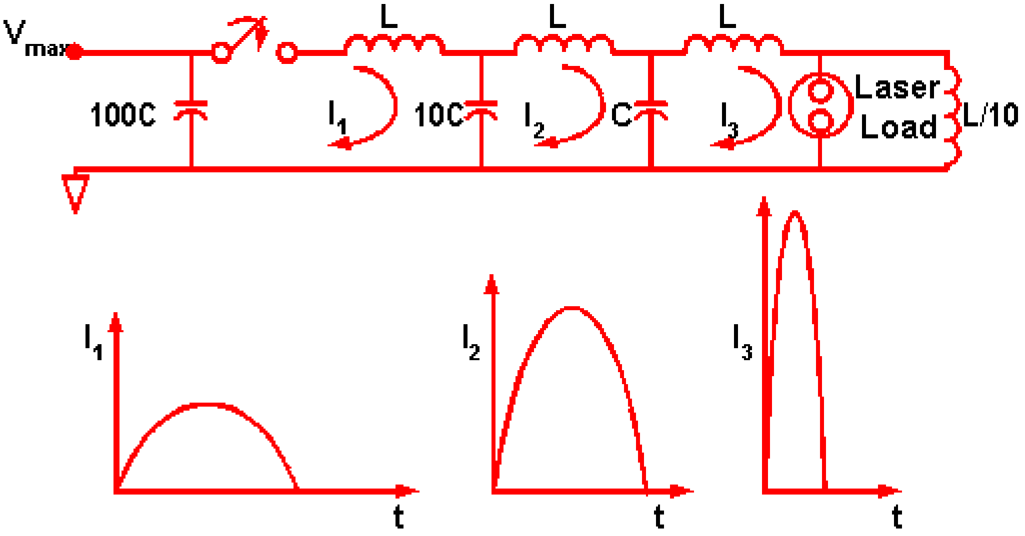

Figure 2

Note that while each stages capacitor value decreases from that of its predecessor, the voltage across it will be twice that of its neighbor upstream. In the case of Figure 2, each inductor core is actually used as a saturating inductor. That is, when the capacitor to the left of it is fully charged, the energy from that capacitor is dumped into the inductor. As the inductor stores more and more energy, it eventually saturates, allowing its energy to cascade into the next capacitor downstream, and so on.

Core Material Considerations

The ideal core material for these types of saturating inductors should be processed to have:

1. High saturation flux density
2. Low losses
3. Very high interlaminary insulation
4. Very low magnetostriction

High saturation flux density allows the core size to be kept to a minimum or, more importantly, to allow high voltages to be developed across each inductor just prior to its saturation. Faraday's law may be rearranged into the following form:

$$V = (N \times A_c \times \Delta B)/(100 \times \Delta t)$$

where:

V = Voltage across inductor (V)

N = Inductor turns

A_c = Effective core cross sectional area (cm^2)

ΔB = Total flux swing in core (G)

Δt = Voltage pulse duration (μsec)

Therefore if the core is biased to its $-B_R$ point (negative remanence) and is allowed to proceed to positive saturation ($+B_{sat}$), then a very square BH-loop, high B_{sat} material is desirable. Orthonol (A material), with a saturation flux density of over 14kG and squareness ratio of more than 94% is ideal for this application, and will yield a flux excursion of over 27kG.

Core losses develop more readily in the inductor material as frequency increases (or equivalently as the pulse width shortens). Of course better efficiency will be obtained by using material with the lowest possible core loss. This criterion may be satisfied in one of two ways. First, the core material thickness may be decreased by going to thinner and thinner foils to wind the core. For example, Orthonol can be processed to strip thicknesses as low as 0.0005". The 'price' to be paid for this advantage is a smaller effective core area for a given overall core size, because the stacking factor is smaller for thinner tapes (i.e., less of the core area is actual magnetic material, and more is insulation between wraps and open space between layers). A second tactic to reduce core losses is to simply choose a more efficient material, such as Permalloy 80 (D material). Although the core should be less lossy, Permalloy has saturation flux density and squareness values significantly lower than those of Orthonol, and as such will only yield a flux swing of about 12kG.

Because the peak voltage levels in pulse compression designs can be exceptionally high, and because this naturally implies very large flux swings, the potential exists for breakdowns and shorts between the individual wraps of material that comprises the core. If we examine the above equation with an eye toward the voltage stress put between layers of tape, this becomes apparent. As an example, consider a case using 0.001" thick, 2" wide (area equal to 0.0129 cm^2) Orthonol tape for the core structure, and flux swing of 27kG. If the pulse width is 0.2μs (a typical value), then the voltage from one wrap to the next can be up to 17.4 Volts. Considering that typical insulation layers may accommodate 2-3 V before they break down, this is a true concern. Magnetics has developed strip-coating methods that can apply our interlaminary insulation to provide far in excess of this value. Additionally, if the interlaminary voltage becomes too large for a practical design, several smaller-height cores may be stacked with insulating washers between them as opposed to one solid core. This strategy reduces the interlaminary voltage, as the total voltage is then divided evenly across the stacked smaller height cores.

The last requirement, low magnetostriction, may seem to be a minor concern, as this phenomenon (which causes magnetic materials to expand and contract as they are excited) typically manifests as a nuisance noise or buzzing if the core is operated at an audible frequency. However, if the excitation signal is very large and the pulse width very small, this effect can actually impart a large amount of mechanical stress to the core. In other words, as the voltage peak ‘hits’ the core, the material will suddenly (and in some cases violently) react by expanding quickly. The most noticeable consequence of the magnetostrictive effect is lower efficiency as the core material is stressed and damaged. Other second order effects may cause the interlaminary insulation to break down prematurely as is it stressed and damaged by core movement. Orthonol and Permalloy 80 (and in fact most NiFe alloys) are exceptionally low magnetostriction materials, and therefore are both appropriate candidates to overcome this design constraint.

Combining all of the above requirements into one over-reaching material choice is generally not possible, as each design requirement is generally satisfied at the expense of one (or more) of the others. However, industry designs tend to consider very thin (0.0005”) foils of Orthonol, with Permalloy being considered for even lower loss designs.

References

1. W.C. Nunnaly, "Magnetic Switches and Circuits,” *Los Alamos National Laboratory,* 1982.