STRETCH MEAT GRINDER: A NOVEL CIRCUIT TOPOLOGY FOR REDUCING OPENING SWITCH VOLTAGE STRESS*

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Abstract

The Slow TRansfer of Energy Through Capacitive Hybrid (STRETCH) meat grinder is an inductive-capacitive current multiplication circuit that reduces switching requirements and achieves a high degree of current multiplication while possessing an energy density approaching that of a purely inductive system. Initially, the STRETCH meat grinder operates like a single-stage meat grinder; it increases the current through an inductor by switching out a coupled inductor. However, during switching in generic meat grinder circuits, leakage flux caused by imperfect coupling and the sudden change in current induces a voltage across the opening switch well beyond what modern solid-state switches can handle. The STRETCH meat grinder mitigates these problems by using a capacitor to recapture the energy in the leakage flux and to slow down the turnoff of current in one of the inductors. The energy from the leakage flux is then used to reverse the current on the turned-off inductor, thereby further increasing the current multiplication. A system comprising several STRETCH meat grinders in parallel can develop currents in the mega-ampere range without exceeding the capabilities of solid-state switches. Such a system could be used to power a railgun.

I. INTRODUCTION

A power supply for railguns must be able to deliver mega-amperes of current for relatively long (3-7 millisecond) pulses. Capacitors are generally used to develop these pulses in laboratories, but the relatively low energy density of capacitors essentially excludes them from use in fieldable systems, except perhaps for large ships. Most research on fieldable systems has focused on pulsed power sources using rotational kinetic energy storage due to its extremely high energy density; however, these systems have proven to be difficult to implement [1]. Although its energy density is somewhat lower, inductive store has a number of advantages over kinetic store.

Inductive store is static in nature, easy to cool, and can use a low-voltage prime power source [2]. Inductive store has some drawbacks, such as high coil losses, lack of power-dense prime power, and the lack of an available, repeatable, high-voltage opening switch [2].

Coil losses can be minimized by shortening charge times and using thicker conductors. Using superconductors or supercooled metals to construct the inductors would essentially eliminate coil losses, but they also introduce problems of their own.

There have been recent developments in advanced power-dense batteries [3], but they still fall well short of the power density required to directly drive a large, practical railgun system. One solution to this problem is to use a pulse-compression circuit such as a meat grinder [4] or an XRAM [5], [6] to increase the power of the pulse while decreasing the duration. Both these systems have considerable switching requirements, in terms of turnoff current and blocking voltage; for solid-state switches, blocking voltage is of greater concern.

This paper addresses switching considerations with a novel circuit topology. The operation of the STRETCH meat grinder is initially similar to that of a single-stage meat grinder that does not have any series opening switches [7], [8]. Figure 1 shows a schematic of such a circuit.

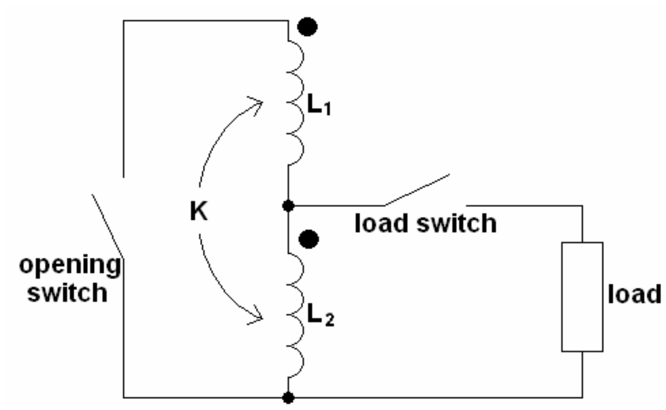

Figure 1. An implementation of a single-stage meat grinder.

With the opening switch closed and the load switch open, inductors L_1 and L_2 are carrying current *I*. The meat grinder is connected to the load with the closing switch, and L_1 is switched out by opening the opening switch. If the coupling between the two inductors is perfect, that is, there is no leakage flux, then all the energy in L_1 is transferred to L_2. However, in the case of imperfect coupling, the uncoupled flux in L_1 will try to maintain the current in L_1 after it has been switched out, producing a large voltage across the switch.

An even bigger problem for high-current inductive loads is that the electromotive force (emf) that is reflected back through the mutual inductance shows up across the

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switch. If the load has an inductive component, the sudden increase in current will produce a large voltage across the load. Generally, L_1 is larger than L_2, to give good current multiplication, but this also results in good voltage multiplication.

To alleviate these problems, the STRETCH meat grinder adds a capacitor across the inductors so that the inductors have an alternate conduction path during the energy transfer from L_1 to L_2, as seen in Figure 2. For a purely resistive load, it is not necessary to have L_2 snubbered with the capacitor, but it helps mitigate the initial change in current for inductive loads. The diode D_1 allows L_1 to freewheel in reverse and prevents the capacitor from reversing. D_2 prevents the capacitor from forming an oscillator with the inductors if the load is opened while current is still flowing. If the load is opened, D_2 forces the capacitor to hold its charge.

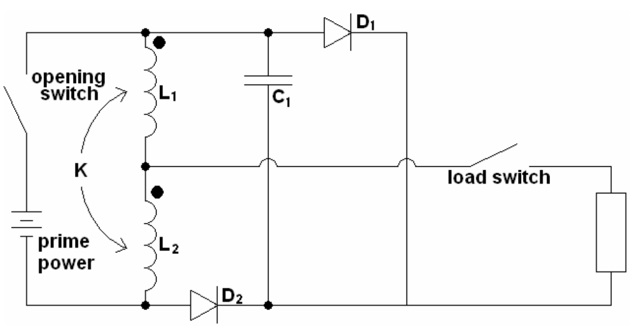

Figure 2. An implementation of the STRETCH meat grinder circuit. D_2 prevents the inductors from being shorted out during charge. D_1 allows the capacitor to discharge through the load while preventing the capacitor from reversing and allowing L_1 to freewheel in reverse.

II. OPERATIONAL OVERVIEW

The STRETCH meat grinder produces a distinct pulse shape. The exact shape depends on the implementation of the circuit, but the pulses share some characteristics. The rise time on the pulse is slow compared to a traditional meat grinder. After the peak, there is a period of more rapid decay, a knee, and then the traditional resistive-inductive (RL) decay. If the load is opened, the energy left in the inductors can be recovered into the capacitor. This process can be broken up into five phases. Figure 3 shows typical waveforms for the five stages of STRETCH meat grinder operation.

Before the first phase, the inductors have been charged to an initial current, and the load has been connected with a load switch. The first phase begins when the opening switch opens. The current in L_1 only has one path—through the capacitor. However, because it is coupled to L_2, it does not transfer all its energy to the capacitor. With an inductive load the capacitor is charged by both the leakage flux and the emf, which is reflected across the inductors. L_2 has a path through the load and also through the capacitor. L_2 can discharge into the capacitor until it can overcome the back emf. During this phase, the circuit behaves basically like a meat grinder. The current in L_1 decays to zero, causing the current in L_2 to increase to support the coupled flux of L_1.

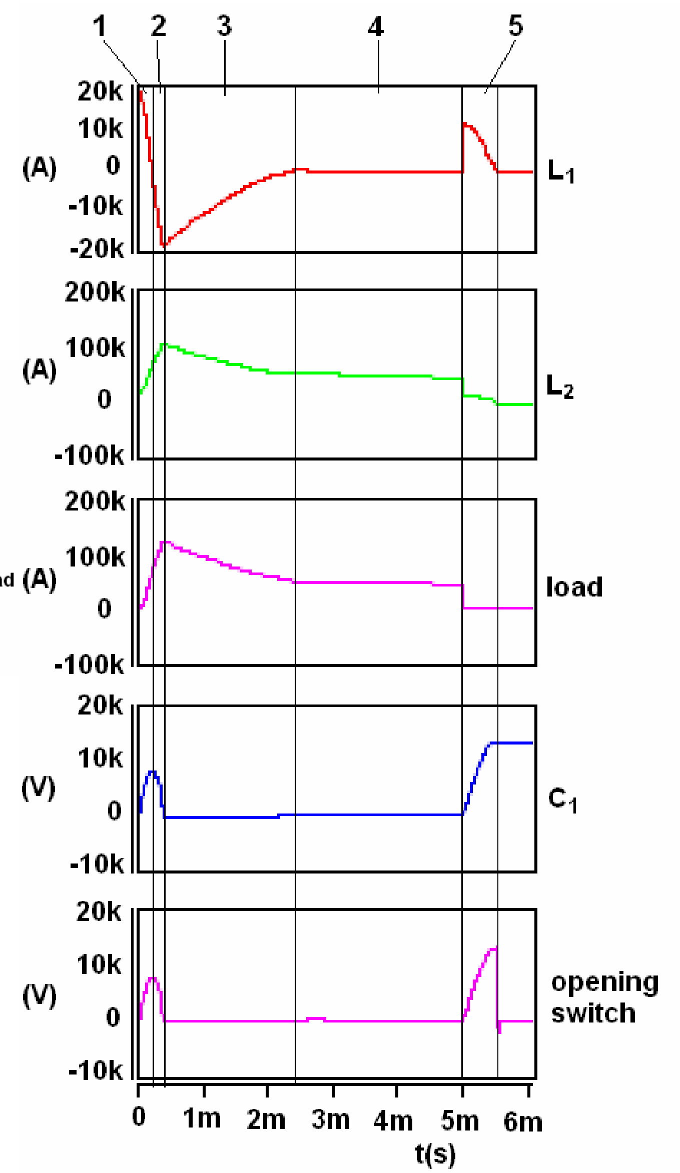

Figure 3. Typical STRETCH meat grinder waveforms for various components.

The second phase begins when the current in L_1 is zero and the capacitor is fully charged. The capacitor has only one discharge path, back through L_1 and through the load. The capacitor reverses the current in L_1 to nearly its original value. This further increases the current in L_2.

Once the capacitor is fully discharged, the circuit enters the third phase. At this point, the circuit behaves somewhat like an XRAM, with the inductors in parallel driving the load. However, due to the coupling, the inductance seen by the load is very close to that of parallel coupled inductors, as given in the following equation:

$$L_{eq} = \frac{L_1 * L_2 - M^2}{L_1 + L_2 + 2M} \, . \tag{1}$$

Once the current in one of the inductors has decayed, the circuit enters the fourth phase. In this phase, the circuit behaves like a conventional inductive source circuit.

In the fifth stage, the load switch is opened, and the circuit recovers most of the energy left in L_1 and L_2. When the load switch opens, it produces a large voltage across L_2. Since L_1 is coupled to L_2, the voltage gets reflected across it. The voltage across the inductors creates a current through the inductors, which charges the capacitor. The capacitor cannot reverse because of D_2, so it holds the charge. The addition of a single closing switch from the positive terminal of the capacitor to the positive terminal of the source could allow the energy stored in the capacitor to charge the prime power. Figure 4 shows how this might be implemented.

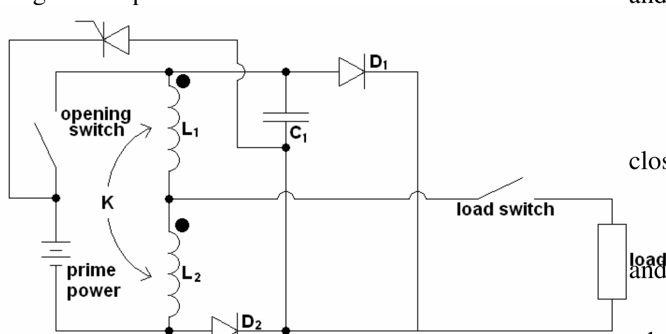

Figure 4. An implementation of the STRETCH meat grinder with an SCR added to allow the capacitor to discharge back into the prime power after the fifth stage. The inductors help limit the current rise.

III. THEORETICAL ANALYSIS

In order to gain a greater understanding of how changes in the various parameters affect the circuit's operation, an analytical analysis of the circuit topology during the first two phases was done. The circuit is "ideal" in the sense that there are no inductor resistances included; however, k values less than 1 are considered. The analysis only includes the first two phases because the major limiting actions, such as peak switch voltage and peak output current, occur during these phases. Fig. 5 shows a circuit schematic; Eqs. (2)–(3) are the loop equations.

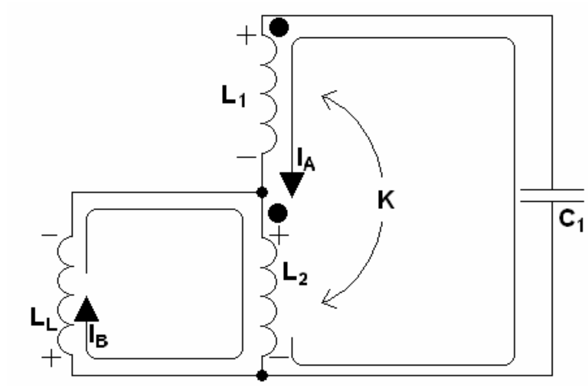

Figure 5. Equivalent circuit of a STRETCH meat grinder implementation during phases one and two.

Valid for $0 \le \omega t \le \pi$:

$$0 = L_1 \dot{I}_A + M\left(\dot{I}_A + \dot{I}_B\right) + L_2\left(\dot{I}_A + \dot{I}_B\right) + M \dot{I}_A + \frac{1}{C_1}\int I_A \, dt \tag{2}$$

and

$$0 = L_1\left(\dot{I}_A + \dot{I}_B\right) + M \dot{I}_A + L_L \dot{I}_B \, . \tag{3}$$

Solving the differential equations yields the following closed-form solutions. Valid for $0 \le \omega t \le \pi$:

$$I_A = I_0 \cos(\omega t) \tag{4}$$

and

$$I_B = I_0 \gamma (1 - \cos(\omega t)) \, , \tag{5}$$

where

$$\omega = \sqrt{\frac{1 + \frac{L_2}{L_L}}{C_1\left(L_1 + L_2 + 2M + \left(1 - k^2\right) L_1 \frac{L_2}{L_L}\right)}} \tag{6}$$

and

$$\gamma = \frac{L_2 + M}{L_2 + L_L} \, . \tag{7}$$

From these equations, one can derive an equation for the peak capacitor voltage, which is also the peak switch voltage in terms of the initial current L_1, L_2, L_L, and k:

$$V_{C_{peak}} = \sqrt{\left(\frac{C_1\left(L_L + L_2 + 2M + \left(1 - k^2\right) L_1 \frac{L_2}{L_L}\right)}{1 + \frac{L_2}{L_L}}\right)} I_0 \, . \tag{8}$$

It is evident that the system's performance depends on several intertwined parameters. There are, however, a few design points to highlight.

The maximum amount of energy is transferred to the load when the ratio of L_1 to L_L is 1. In fact, in the case of perfect coupling and if $L_1 = L_2 = L_L$, the system would theoretically transfer 100 percent of the energy to the load. The drawback of matching L_2 to L_L is that a large amount of the initial energy must be stored in the capacitor during the switching. Ratios of L_2 to L_L less than 1 result in less energy being transferred to the load and more energy being stored in the capacitor than happens at a ratio of 1. Thus, a ratio of L_2 to L_L less than 1 offers no advantages. Ratios of L_2 to L_L greater than 1 store less energy in the capacitor during the transition, but less energy is transferred to the load.

The ratio of L_1 to L_2 is also important. If one increases the ratio of L_1 to L_2, current multiplication will increase, as will the switch voltage. The peak switch voltage can be reduced by increasing the size of the capacitor, but this also increases the rise time.

On an ideal system with an inductive load, the capacitor only affects the circuit during the current rise. Varying the amount of capacitance does not change the maximum amount of energy stored in the capacitor, assuming no resistance in the system. However, the amount of capacitance does affect the output current rise time and the maximum switch voltage.

Matching L_L and L_2 is often not practical for low-inductance loads. One can achieve the same effect with a system of STRETCH meat grinders, each having a larger L_2. By symmetry, the equivalent L_L will appear to be $n * L_L$ to any of the STRETCH meat grinders, where n is the number of parallel units. It is simple to model the system from the perspective of a single system driving a load of $n * L_L$ and a current of $n * I_B$.

IV. CONCLUSION AND FUTURE DIRECTION

Inductive store is an attractive, and perhaps nearer-term, alternative to kinetic store. The STRETCH meat grinder is a hybrid inductive-capacitive circuit that addresses the switching considerations of inductive store systems and provides pulse compression. The operation of the circuit is controlled by the number of systems driving the load, the initial current, L_1, L_2, L_L and k.

Interdependencies exist within the major circuit character-istics. For instance, increasing the ratio of L_1 to L_2 would increase the current multiplication, increase the peak capacitor voltage, and increase the rise time. In order to maximize the amount of energy transferred to the load, L_2 should be close to the same size as L_L. For low-inductance loads, one can drive the load with n STRETCH meat grinder circuits, each of which has an L_2 significantly larger than the load. Since each circuit only contributes $1/n$ of the current to the load, the load appears to have n times more inductance, where n is the number of driving units.

There may be some merit in switching additional units in at later times to shape the pulse. The units could be used to maintain the current in the load, as resistive losses in a non-ideal system will cause the current to decay. It is also possible to add units to extend the current rise in the load. If energy density is important to the application, it maybe possible to have the units share capacitors.

Replacing the diode D_1 with an active switch would allow part of the current multiplication to be delayed. This would give the system more flexibility in pulse shaping and, for single systems, allow the removal of D_2.

V. ACKNOWLEDGMENT

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