MULTICYCLE RESONANT ENERGY RECOVERY FOR INDUCTIVE ENERGY APPLICATIONS

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Abstract

This paper describes an innovative concept for recovering the electrical energy remaining in an inductive energy storage system, such as that left in the barrel of a railgun after the projectile had exited the gun. Previously discussed recovery schemes usually involved the use of a capacitor bank that is capable of storing all the energy to be recovered. In this paper, we describe a circuit that recovers the energy in multiple parcels, each being a small fraction of the overall energy. This concept, herein referred to as Multicycle Resonant Energy Recovery, therefore allows for a significant reduction in the size and weight of the intermediate energy storage elements. The basic circuit and its operation are discussed as well as criteria for component selection, scaling, and tradeoffs. Finally, results from a computer simulation of the energy recovery circuit applied to a railgun model are presented.

Introduction

Operational rail guns require a power supply with the capability to provide megamps of current at voltage levels extending into the kilovolt region. The corresponding gigawatt power levels are required during the typical accelerating time of several milliseconds. Various forms of energy storage are used to provide these high power levels. In practically all existing schemes, the rail gun is powered from an intermediate storage inductor, which acts as a constant current source.

A constant current source is desirable, since it results in a constant force on the projectile and, therefore, constant acceleration. This, in turn, yields the maximum possible velocity for a given length of rail gun barrel. If the current is not kept relatively constant, a longer barrel is required to reach the same velocity, increasing the size and mass of the overall system. Energy stored in an inductor is expressed by $E = 0.5\, L\, I^2$, where L = inductance and I = current through the inductor. It can be shown that the magnetic energy left in the rail gun barrel is equal to or greater than the kinetic energy acquired by the projectile. Thus, constant-current rail guns without energy recovery can never exceed an efficiency of 50 percent. In reality, efficiencies tend to range between 20 and 25 percent.

Shown in Figure 1 is a simplified schematic of an inductive energy storage system connected to a rail gun. With switch S1 closed, current is built up in the storage inductor, Ls, from the prime power source, such as a capacitor bank or a homopolar generator. As the projectile enters the breech of the rail gun, S1 opens and S2 closes, diverting the stored current into the rail gun and accelerating the projectile through the length of the barrel. As the projectile exits the barrel, S3 is closed to crowbar the remaining current in the system and prevent any residual energy from being dissipated in an arc discharge which can cause severe damage to the muzzle sections of the rails.

If the residual energy in the circuit is not extracted in some form, it is lost in the form of heat dissipation in the rails of the gun and in the other current conductors in the circuit loop. For a repetitively pulsed rail gun, this heat dissipation can make thermal management much more difficult and complex to implement. This thermal management is particularly complicated when trying to remove heat generated in the rails themselves, since they must be electrically insulated from other conductors because of the voltage created across the barrel. The rails are also usually buried inside a strong metal casing to withstand the large repulsive forces generated by the high current, making connection problems that much more difficult. Energy required to control these thermal problems, along with the lost residual electrical energy, can combine to effect a significant reduction in the overall system efficiency.

A key performance parameter of mobile rail guns is the system's weight. In certain scenarios, initial fuel for the prime power energy storage system can represent up to 60 percent of this total system weight. Even partial recovery of the residual energy remaining after projectile firing could bring a substantial saving in this weight. Since heat dissipation would also be reduced, the size and weight of the components required for heat transfer and exchange would also be minimized.

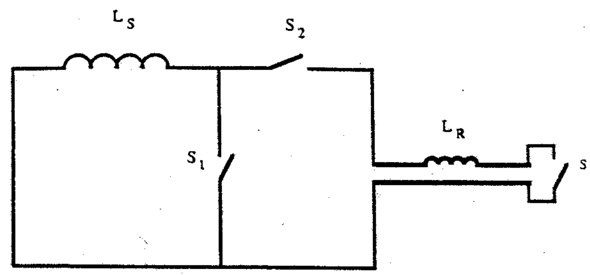

Figure 1. Simplified schematic of an inductive energy storage system connected to a rail gun.

Technical Approach to Energy Recovery

Honig has proposed several methods for energy recovery from a rail gun that either transfer the energy remaining in the rails to the projectile or back to the storage inductor in a single cycle [1]. These methods involve either lengthening the barrel of the rail gun or using resonant circuits in which a single capacitor bank temporarily stores an amount of energy roughly equivalent to that which is delivered to the projectile. The principal technique that we propose, Multicycle Resonant Energy Recovery, involves the transfer of energy in multiple parcels instead of one lump transfer. Each parcel is typically less than 10 percent of the total rail inductive energy. As a result, the intermediate energy storage components may be much smaller than those that store the entire amount of energy, as in the case of energy recovery in a single cycle.

Our proposed energy recovery method is to extract the residual energy stored in the magnetic field between the rails in a series of pulses beginning at the instant the projectile leaves the muzzle, and to return the energy to the prime electrical energy store, thereby reducing the fuel required to produce the next shot. Each of these steps must be performed efficiently to effect a significant fuel saving.

A schematic of the Multicycle Resonant Energy Recovery circuit is shown in Figure 2. The energy recovery circuit basically consists of Switches S3 and S4 and Capacitors C1 and C2. The inductive driver is represented by Inductor L1 and Switches S1 and S2. When the projectile enters the rail gun, S1 opens and S2 closes, thereby providing current for the acceleration of the projectile. As the projectile exits the barrel, S5 must close to limit barrel rail damage at the muzzle. As a result, energy associated with the inductance of the barrel is trapped in the form of circulating current.

To initiate recovery of the energy, S1 closes and S2 opens. An additional switch, S6, has been added to aid in the recovery of S2, since it would have to open a large rail gun current with a relatively high gun voltage present at the time of muzzle projectile exit. As S2 opens, S6 closes for approximately 1 ms, allowing S2 to recover with little voltage stress and allowing the rail gun barrel to recover its voltage holdoff. After the time period is up, S3 closes and, together with a pre-charged capacitor, C1, provides a reverse bias on S6 to assist its recovery. Current trapped in the rail gun barrel loop then begins to charge capacitor C1 in the opposite direction. Once this capacitor voltage reaches a predetermined value (limited by the barrel holdoff voltage), S3 opens and S4 closes. Energy in C1 is then transferred back into the primary storage inductor through S7 while capacitor C2 is charged by the current in

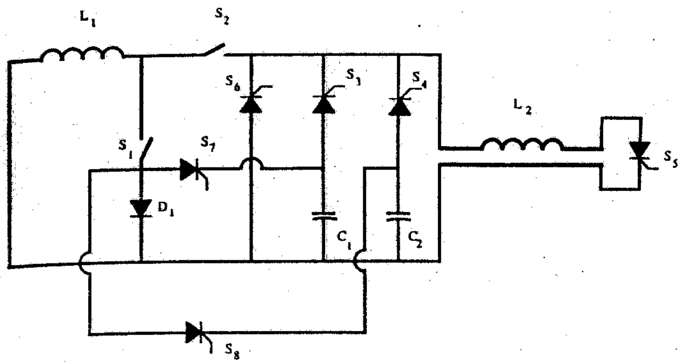

Figure 2. Schematic of Multicycle Resonant Energy Recovery circuit showing use of solid-state switches for returning energy to the storage inductor.

the rail gun barrel inductance, L2. Energy in C2 can then be extracted through S8 back into the inductive energy storage loop while C1 is charged again. In this "push-pull" style of operation, energy is extracted in multiple cycles from the rail gun inductance.

If required, saturable inductors might be added in series with the switches to aid in their recovery. The diode, D1, controls current flow in the storage inductor loop and takes over current flow when all energy has been extracted from the particular capacitor and it has begun to charge in the opposite polarity. Some controls and triggering circuitry (not shown in the schematic) would also have to be added to synchronize switch firing in the proper sequence.

Finally, another, smaller switch (also not shown) would be placed across the C1 capacitor so that on the last extraction cycle, the capacitor could be charged and then the polarity inverted, readying the system for the next multicycle recovery sequence.

There are, however, certain firm constraints. The voltage to which the intermediate storage capacitors are charged may not exceed the barrel voltage holdoff limit. This holdoff limit will vary somewhat with time because of the recovery characteristics. For the first millisecond after the projectile has left the barrel, the voltage probably will have to be limited to less than a few hundred volts. After this period of time has elapsed, the holdoff voltage should increase to the kV range.

Another constraint of the energy extraction process is that the stored energy must be discharged in the same period of time that it takes the other storage capacitor to charge. One way to achieve this is to discharge the capacitor into an inductive energy system with a large constant current that can remove the stored charge quickly.

Arrays of solid state thyristors (SCRs) are candidates for the switches in the energy recovery circuit, since they are highly reliable and unidirectional and can open on command (with a current zero and a slight reverse bias). Triggered vacuum gap switches might also be used in this application. A mechanical rotating switch would probably be used for the two switches associated with the inductive energy store, S1 and S2. These switches could be ganged together and synchronized so that S1 would open when S2 closed, and vice versa. This type of switch has been used before in this application and, advantageously, achieves very low on-state resistances (lower than 1 microhm).

It should be noted from the schematic that each particular solid-state switch is assisted in recovery by the next successive switch's diverting the current flow and applying a reverse bias. The recovery circuit is therefore "self-commutating" and operates in a "symmetrical" fashion.

Shown in Figure 3 is a simplified diagram detailing the relative timing of switch currents and intermediate storage capacitor voltages. Also included is a plot of the difference in capacitor voltages, since it is this value that is seen across either S3 or S4, whichever one is trying to recover at that particular time. This plot should aid in understanding how the switch recovery time relates to the capacitor charge and discharge times.

Circuit Component Selection, Scaling, and Tradeoffs

The switches used in the energy recovery circuit must operate as both closing and opening switches. They must operate at

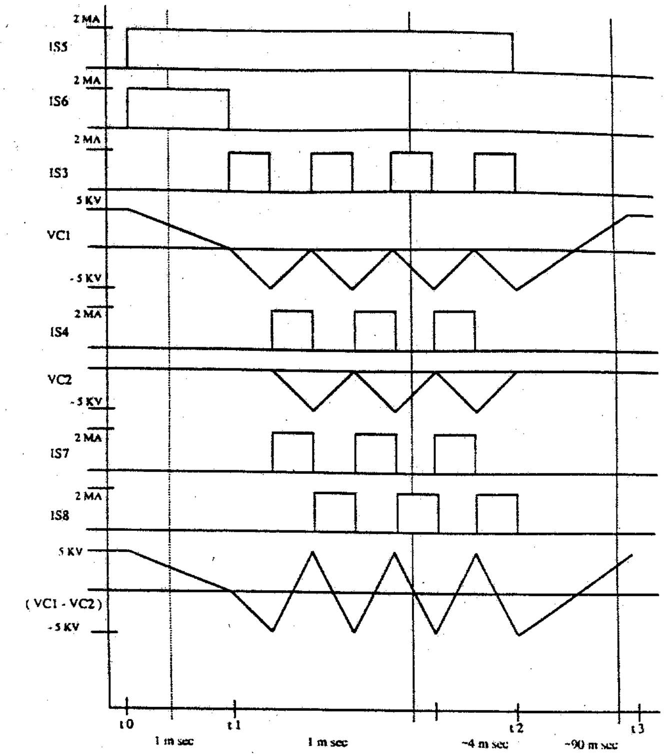

Figure 3. Timing diagram detailing the relative timing of switch currents and intermediate storage capacitor voltages.

relatively high repetition rates (in the kHz range) and have low values of on-state resistance so that the energy dissipated (and therefore lost as heat) in the switch does not become significant. As mentioned previously, solid-state SCRs are possible candidates for the main switch applications because of their ability to meet these requirements. Although no individual semiconductor switch devices currently in production are capable of switching power levels of this magnitude, devices can be operated in arrays to perform as required. Increasing the voltage and current handling capabilties of switches would then reduce the number of individual components required to make up this array.

Recent advancements in solid-state switch technology, resulting from the introduction of "float-zone" crystal growth techniques, promise the production in the near future of large (5" diameter) crystalline silicon wafers of high resistivity and ultra-high purity (an order of magnitude better than those processes used in the late 70s and early 80s). Solid-state switches made from these wafers are likely to have forward and reverse blocking voltage ratings between 12 and 20 kV and corresponding current capabilities of handling 160 kA for durations of 10 to 100 microseconds [2]. Conceivably, a 1 MA, 6 kV switch could be constructed from 8 to 10 of these devices connected in parallel.

Most of the switches, with the exception of the smaller-size switch across C1, will see the same operating conditions. The voltage applied to the switch is the same as that which appears across the rails of the gun (typically 2 to 10 kV); the switch current is the same as that flowing through the gun (on the order of 2 MA). The following discussion shows that a low switch recovery time would also be advantageous.

The intermediate storage capacitor bank is chosen in the following manner. The maximum voltage to be applied to the bank (V) is limited by the barrel holdoff voltage, which is in the range of 5 to 10 kV. Since we know the current (I) from the rail gun and driver is on the order of 2 MA, we may then derive the bank capacitance from the following simple formulas:

$$Q = C\,V \quad \text{or} \quad C \geq Q/V = I\,t/V \ ,$$

where Q is the accumulated charge stored in the capacitor by the current I during the time t. It should be mentioned that t is both the charging time of the capacitor bank and the discharge time, since the time constant for both circuit loops is essentially the same. Thus, while one capacitor bank is charging, the other is discharging at the same rate. Since the difference in capacitor bank voltages is seen across the recovering switch, it can be shown that the time elapsed while this switch is negatively biased is equal to 0.5t. (Refer to Figure 3.) The value for t used in the above formulas should therefore be twice the recovery time of the switch used in the circuit. The bank capacitance and, therefore, size are then proportional to the switch recovery time.

Another practical limitation to the capacitor bank sizing is related to the energy it will store. As stated previously, the basis of our proposed energy recovery scheme is the idea of extracting the energy in a series of smaller pulses so that the intermediate storage components can be sized down. Thus, the energy stored in the capacitor bank should be as small as possible.

The last factor that must be considered when choosing the capacitor bank is the voltage reversal applied to one of the banks. By considering the operation of the circuit, it can be seen that the voltage on the capacitor bank C1 will reverse to a value approaching the charging voltage, since this capacitor is used to counterpulse Switch S6. The energy density of this capacitor bank is therefore reduced somewhat to allow for the reversal.

These capacitors should be of the high-energy-density type to reduce the size and weight of the energy recovery circuit as much as possible. They should also have low equivalent series inductance and resistance values to minimize any energy dissipated within the capacitor.

Since the above values have all been chosen, we can do an iterative calculation to find the number of cycles required to recover the energy and to determine the total recovery time. In our preliminary analysis, we assume a lossless circuit with typical rail gun values of 2 MA initial gun current, 10 MJ energy remaining in the barrel, and 100 µs switch recovery times. By choosing the intermediate capacitor charge voltage, we can calculate the capacitance of the bank and the amount of energy extracted in each cycle. The remaining energy and current in the rails can then be calculated, and the process repeated until all of the energy is extracted, yielding the overall recovery times. A family of curves can then be plotted, as shown in Figure 4. These curves represent the tradeoffs between the capacitor charge voltage and the overall energy recovery times for different amounts of energy extracted.

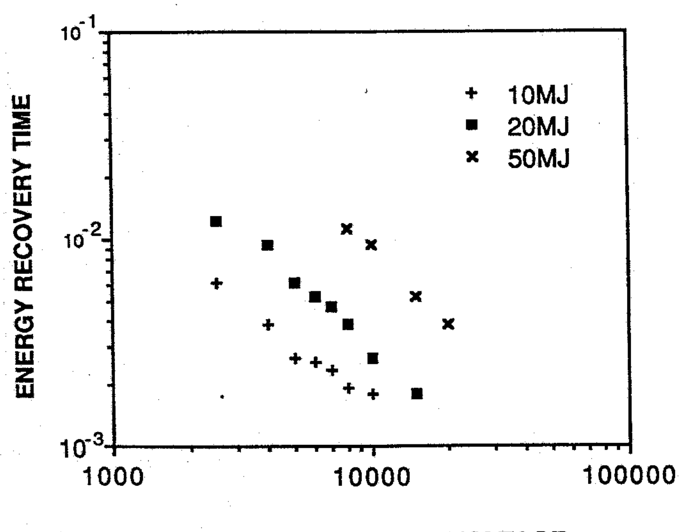

Figure 4. Curves represent the tradeoffs between the capacitor charge voltage and the overall energy recovery times for different amounts of energy extracted.

It should also be noted that limits imposed on each of these variables define an acceptable parameter space, or operating region, of the graphs. As mentioned previously, the capacitor charge voltage is limited by the rail gun barrel holdoff voltage. The total energy recovery time is limited by the characteristic current decay constant of the rail gun inductance (L/R of the rail gun barrel current loop). For an inductance per unit length of 0.5 µH/m and a typical resistance per unit length of 0.1 milliohm/m, this characteristic time constant is of the order of 5 ms. The proposed energy recovery scheme should extract the majority of the energy in less than that amount of time, ensuring recovery of the energy before it is lost in resistive dissipation.

Note that as the capacitor voltage is increased, the time required to extract the energy decreases. This can be understood by considering that the extracted power is approximated by the product of the gun current and the average capacitor voltage. Therefore, a higher voltage will yield a higher power, and for a given amount of energy, less time is then required to extract the energy.

In conclusion, the overall recovery time is inversely proportional to the maximum charging voltage of the intermediate storage capacitor banks and is relatively independent of the switch recovery time. A shorter switch recovery time allows for more extraction cycles in essentially the same recovery period, thereby allowing a smaller size of storage capacitor.

Energy Recovery Circuit Simulation

We have completed a computer simulation of the Multicycle Resonant Energy Recovery circuit integrated into a rail gun system. In this modeling, only those resistive losses associated with the barrel and the inductive energy store have been taken into account. Parameters of the circuit have been chosen to represent the same case as discussed above, where 10 MJ of energy remains in the barrel after projectile exit. This results in a barrel inductance of 5 µH for a gun current of 2 MA. The gun barrel resistance is taken as 1 milliohm. The energy storage inductor is chosen to be of the order of 25 µH with a series resistance of 10 micro-ohm. The remaining value chosen for the simulation is the capacitance, which will be 80 mF for each bank at a rated voltage of 5 kV. The simulated circuit is essentially the same as that shown in Figure 3, with the exception that S6 has been eliminated and the simulation is started at the time this switch would be commutated off by the closing of switch S3 (implying that the barrel has fully recovered its normal voltage holdoff).

Shown in Figures 5 and 6 are the currents flowing in the storage inductor, L1, and the inductance associated with the rails, L2. Zero time on the graphs corresponds to the time when S1 and S3 are closed to initiate the first energy extraction cycle and the storage inductor and gun barrel are isolated from each other by the opening switch, S2. The simulation assumes that 2 MA is flowing in both the storage inductor and the gun barrel at this time. From the figure, it can be seen that energy is extracted from the barrel and delivered to the storage inductor in the about the first 4 ms. At this time, the current flowing in the rails has decreased to negligible values and the energy transfer is completed.

The circuit simulation, therefore, verifies the proposed approach of recovering energy from the rail gun barrel. However, as mentioned above, this simplified analysis has accounted for only one or two of the many areas where energy losses will be produced. Energy will also be lost as the gun current decays during the time S6 is closed and the barrel is recovering its voltage holdoff capabilities.

Conclusion

Any practical repetitively pulsed inductive energy storage system for railgun applications will require the recovery of energy remaining in the barrel after each shot in order to minimize the requirements of the prime power energy source and thermal management subsystems. We have presented the concept of Multicycle Resonant Energy Recovery and described how it can be implemented. Results from computer circuit simulations of the recovery circuit have been shown to verify the approach.

The ability of this technique to recover energy in multiple pulses results in much smaller intermediate energy storage components than those in techniques reclaiming energy in a single pulse. This, in turn, allows for a reduction in total system size and weight, both important parameters for any system, especially those which must be based on mobile platforms.

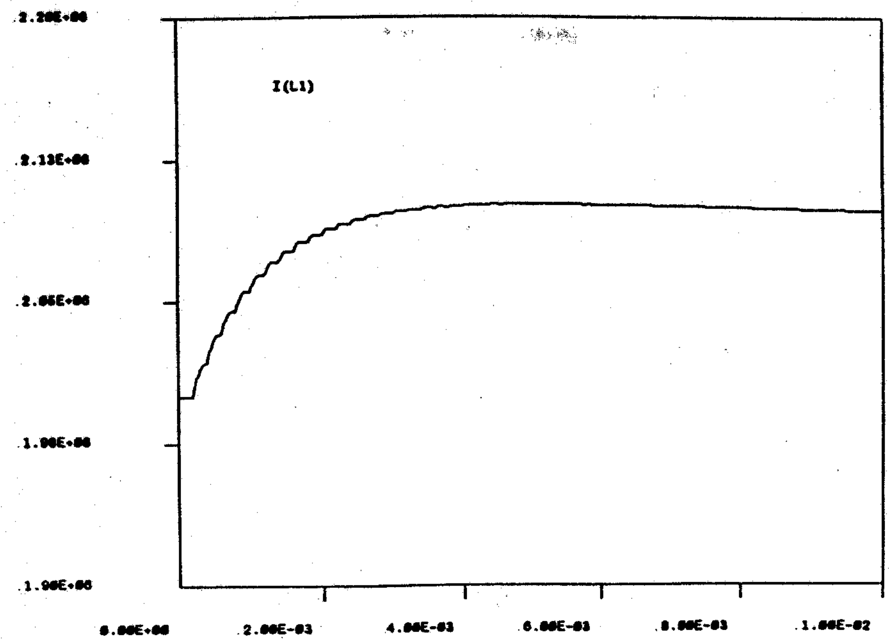

Figure 5. Current flowing in the storage inductor.

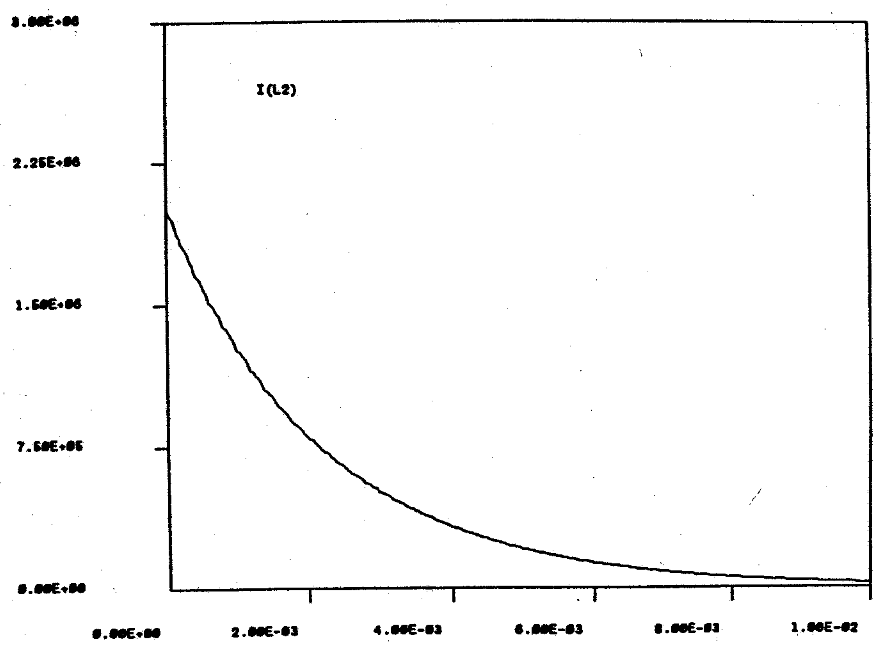

Figure 6. Current in the inductance associated with the rails.

References

[1] E.M. Honig, "Railgun Circuit Considerations," Los Alamos National Laboratory Report No. LA-UR-86-890, March 1986.

[2] S. Kuznetsov and E. Kunhardt, "GTO Semiconductor Devices - Solid-State Working Group Report", Workshop on High Current Opening Switches for EML Applications, Tamarron, CO., March, 1986.