INVESTIGATION OF BATTERY CHARGED CAPACITOR PULSED POWER SYSTEMS FOR ELECTROMAGNETIC LAUNCHER EXPERIMENTS

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ABSTRACT

Candidate pulsed power systems for electromagnetic launchers (EMLs) constitute two broad categories: rotating machinery and non-rotating devices. Rotating machinery for this purpose is under development at several industrial and educational institutions around the world. Non-rotating hardware includes capacitors, batteries, and inductors. These too are the subject of research programs, but as yet, are much larger than rotating supplies of equal power and energy capability. In 1988, system studies [1] identified several attractive pulsed power systems for EMLs. Battery charged capacitor pulsed power systems were among those identified as promising for EML systems.

The basic equations governing the battery charging capacitor sequence and the capacitor discharge into an EML are the subject of this paper. A battery charged capacitor system powering an EML has also been built. This experiment not only validates the system concept with presently available hardware, but can be used to establish a baseline for evaluation of future systems when technology in capacitor and battery power and energy densities improve.

Introduction

When using a battery charged capacitor pulsed power system to discharge into a transient load (in this case an EML), operation can be divided into three distinct regimes.

The first regime is the charging of the batteries by an external DC source. The second operational subdivision is the charging of the capacitor system by a current pulse from the batteries. The result of this sequence is a fully charged capacitor system with the appropriate stored energy required by the design of the system for discharge into a static or transient load. Finally, the capacitors are discharged into the load. This third operating regime is characterized by a much shorter time interval than the previous two sequences.

This paper discusses these three phases of operation for a battery charged capacitor system for discharge into a generic transient load. Figure 1 shows a simplified schematic of such a system.

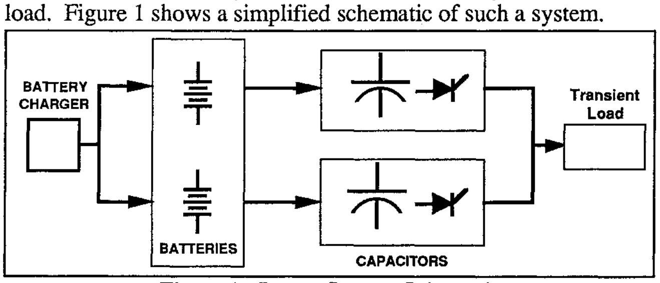

Figure 1. Power System Schematic

In Figure 1 silicon controlled rectifiers (SCRs) are shown as the devices by which the capacitors are discharged into the transient load. Other forms of switching can be used, as can no switching at all for a "hot rail" system. For the purposes of this paper SCRs are used to ensure controlled switching into the transient load.

Battery Charging Regime

Charging requirements for the battery portion of the system vary depending upon the type of battery selected. Several types of batteries are commonly in use today, such as lead-acid, nickel-cadmium, nickel-zinc, lithium systems, silver systems, hydrogen systems, bipolar configurations, and many more examples. For this analysis we will consider standard cell, 12 V, lead acid batteries. We will also assume that the basic battery string consists of 60 batteries in series.

For the charging process we must use high current electrical power to reform the active chemicals of the batteries to their high energy charge state. For lead-acid systems this involves the conversion of lead sulfate in the positive electrodes to lead oxide, the conversion of lead sulfate at the negative electrode to metallic lead, and restoring the electrolyte to a high concentration sulfuric acid solution. The rate at which the charging process can occur depends upon how many amp-hours have been previously discharged from the battery system. In general, batteries follow the ampere hour recharge rule as follows:

$$I = Ae^{-t}, \qquad (1)$$

where I is the charging current and A is the number of amp-hours previously removed. As the battery is recharged the voltage increases and the charge current is reduced according to the manufacturers recommendations. The charging sequence can take several minutes. The charging sequence has the longest event duration of the three operating regimes and, hence, the least interesting for the purposes of this paper. But, unless properly designed, the charging system for any battery supply can affect the operating efficiency of the battery charged capacitor system. Table 1 shows the relevant battery parameters assumed for this discussion.

Table 1. Battery Parameters

Single Battery parameters
$V_{oc} = 12.76$ V
$R_{INT} = 4.00$ mΩ
$I_{MAX} = 5000$A (< ms peak current)
1520 A - Maximum current for impedance matching
2000 A - Maximum current for a 5 s pulse
2800 A - Maximum current average over 100 ms pulse
10^7 Joules - Approximate energy storage

Capacitor Charging Sequence

As previously mentioned the discharge energy store is made up of electrolytic capacitors. Electrolytic capacitors are by no means a new technology. Some of the first Electrolytic capacitors were fabricated in Germany in the 1800s [2]. Improvements have been made in the efficiency of the electrochemical reaction and packaging since the early days but, the basic operation remains the same and is governed by the same equations.

A capacitor has three essential parts. Two of those are conducting, usually metal, plates that are separated by the third component called a dielectric. The quality of the dielectric is measured by its ability to insulate the two conducting plates and store electrical charges, versus the amount of voltage developed across the conductor plates. The electrical capacity of the capacitor is expressed as follows:

$$\text{(Capacitance), } C = \frac{q}{V} \qquad (2)$$

where q is the charge in coulombs and V is the voltage potential between the conductors. If a capacitor's potential rises by one volt when it receives a charge of one coulomb, it would have a capacitance of 1 Farad. Practical electrostatic or electrolytic capacitors have capacitances of micro-Farad's (μF = 10^{-6} Farad), or pico-Farad's (pF = 10^{-9} Farad).

Electrolytic capacitors differ from conventional types of electrical capacitors in that only one of the conducting surfaces is a metallic plate. The other conductor is formed by a conducting chemical or electrolyte. The oxide dielectric does have a higher resistance than the standard conductor. Hence, electrolytic capacitors have higher internal resistances than other electrostatic energy storage capacitors.

The electrolytic capacitor specifications for this system are listed in Table 2.

Table 2. Electrolytic Capacitor Specifications

Electrolytic Capacitor Specifications (Single)
Maximum, charge Voltage = 450 V
Maximum current output = 6000 A
Capacitance = 3500 μF
Stored energy at 450 V = 354 J
Internal resistance = 41 mΩ

Constructing a single bank composed of these capacitors requires two in series to exceed the 765 V battery string maximum

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charge rating, and 48 of these series pairs in parallel with each other.

This arrangement of capacitors has a capacitance of 84 mF. In this configuration the capacitor module stores 27 kJ at 800 V (the maximum capacitor voltage rating).

The battery string must be designed to charge the capacitor module prior to a discharge according to the circuit in Figure 2.

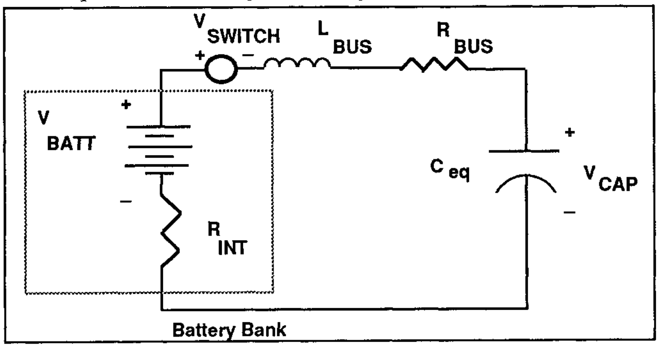

Figure 2. Battery Charging Schematic

A single make/break mechanical switch is used to initiate and interrupt charging current. After the charge voltage capability of the battery string and the circuit parameters of the system have been defined, the performance of the circuit can be calculated.

When the switch is closed, the batteries discharge current through the bus to the capacitor bank causing it to collect charge and develop a potential. The batteries here are standard "automotive" lead acid batteries with a fully charged open circuit voltage of 12.76 V. The internal resistance of the batteries depends on the discharge current level [3]. At currents of 2000 A the steady state internal resistance is approximately 4.0 mΩ. The internal resistance for a fully charged battery of the type used here rises from 3.25 to 3.5 mΩ in the first few milliseconds of the discharge. In this case the battery charging current pulse is less than 100 ms. The bus resistance is assumed to be approximately 300 μΩ with an inductance of 200 ηH using standard 2/0 cable. For any large string of batteries, say more than 10 in series (i.e., $R_{Int} \approx 40$ mΩ), the internal resistance is much greater than the bus resistance allowing us to neglect the connection resistance. Also the inductive time constant ($\tau = L_{Bus}/(R_{Bus} + R_{Int})$, in μs) for the circuit is very short when compared to the capacitive ($\tau = RC$, in ms) time constant which allows us to ignore the bus inductance [4].

The equation relating the final open circuit voltage (V_{OC}) to the dynamic charging voltage (V_{Cap}) is given as follows [4]:

$$V_{Cap} = V_{oc}\left(1 - e^{-t/\tau}\right) \qquad (3)$$

where $\tau = R_{Int}C_{eq}$.

The time to reach a given capacitor voltage when the open circuit voltage of the battery string is known was found by rearranging Equation 3 as follows:

$$t = -\tau \ln\left(1 - \frac{V_{Cap}}{V_{OC}}\right) \qquad (4)$$

The maximum charge current was approximated by:

$$I_{MAX} = \frac{V_{OC}}{R_{INT}} \qquad (5)$$

Now by assuming the current has reached the maximum value, the time varying expression for the current is written as follows [4]:

$$I(t) = I_{MAX}\left(e^{-t/\tau}\right) \qquad (6)$$

This allows us to calculate the magnitude of the current and by rearranging we can determine the time for the current to drop to any value.

To get an idea for the magnitude of the parameters in Equations 3-6, consider a 60 battery series string ($V_{OC} = 765$ V, $R_{INT} = 240$ mΩ [180 - 210 mΩ at time zero]), charging the 84 mF capacitor bank to 700 V.

From these initial calculations a battery system could charge the capacitor bank in less than 100ms (10Hz) for voltages and capacitances similar to the example (Table 3).

Table 3. Example Charging Circuit

Example Charging Circuit
$\tau = R_{INT}C_{eq} = 20$ ms
Charge time, t = 49 ms
$I_{MAX} = 3188$ A (batteries)
Energy storage = 21 kJ
Current Decay Times from Peak
to 1000 A, t = 23 ms
to 100 A, t = 69 ms

Lead acid batteries used here have shown current discharge capabilities of 2000 A for 5 seconds. Currents of 3000 to 4000 A have also been demonstrated from time periods of several hundred milliseconds to several seconds [5]. Therefore, initial estimates of battery discharge currents at energy levels comparable to the example appear practical.

A single lead acid battery as used here stores 3×10^5 C (As) at 100% state of charge (SOC) [6]. They also have a cold cranking amp (CCA) rating of 875 A that relates to their automotive origins. The CCA means that the battery has been tested by the manufacturer and is capable of discharging 875 A for 30 seconds. Assuming that this occurs at slightly below peak power, the energy discharged is 189 kJ. For this 23 kg battery the energy density under CCA conditions is 8 kJ/Kg. High discharge rates of 2000 A for 5 s have demonstrated pulsed energy densities of up to 170 kJ/Kg and a 5% reduction in the SOC. Assuming the battery could be discharged to 0% SOC at 2000 A, the total battery energy storage is over 3.0 MJ (The resistance rises and current decreases with decreasing SOC, so 3.0 MJ is impossible to realize but, discharges to <50% SOC have been demonstrated; storing over 1.0 MJ). Therefore, it appears that lead acid batteries are more than adequate to output hundreds of short current pulses without damage.

Capacitor Discharge Sequence

In a battery charged capacitor EML system, the capacitor bank must supply the current pulse to the launcher. The initial capacitor bank energy is dissipated in the resistive ohmic losses, stored by the circuit inductance, and transferred to the kinetic energy of the accelerated mass. The shape of the current pulse determines the shape of the acceleration curve and, hence, the acceleration profile of the mass. Figure 3 depicts a capacitively driven EML circuit.

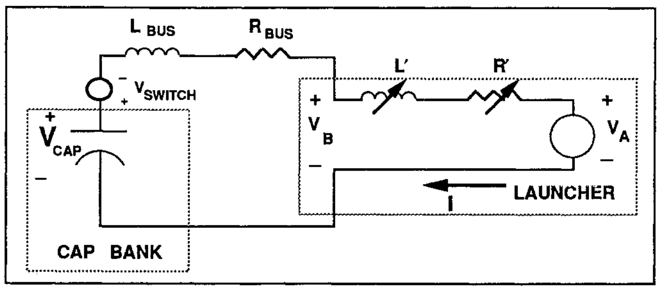

Figure 3. Capacitor Driven Launcher

The capacitor bank discharges an electrical current pulse through the connecting bus to the breech of the launcher after the closing switch (represented by V_{Switch}) has been activated. This assumes that the bank had been previously charged to an open circuit voltage (V_{OC}) by another system, in this case a battery. The launcher is assumed to have a constant L′ (μH/m), and R′ (μΩ/m), and the voltage drop of the mass armature is represented by (V_A).

By writing the voltage equation around the launcher barrel loop using Kirchoff's voltage law [4], we can determine an expression for the breech voltage of the launcher as follows:

$$V_B = IR_{Rail} + IR_{Armature} + \frac{d}{dt}(L(x)I) \qquad (7)$$

$$V_B = IR'x + V_A + \left[L(x)\frac{dI}{dt} + I\frac{dL}{dx}\left(\frac{dx}{dt}\right)\right] \qquad (8)$$

The $IR_{Armature}$ term is replaced by V_A when using a plasma armature as shown in Equation 8.

Remembering that the change in inductance per unit length is a constant (dL/dx=L′), and that the inductance of the launcher as a function of distance x down the bore is L(x) = L′x,

$$V_B = IR'x + V_A + L'x\frac{dI}{dt} + IL'v \tag{9}$$

where v is the instantaneous velocity of the projectile.

In order to develop an understanding for the origin and meaning of terms on the right hand side of Equation 9, each term is discussed separately.

The first term (left to right) represents the resistive voltage drop along the rails (V = IR). As the mass moves down the launcher the current must flow through a longer length of conductor material to reach the armature. With complete current penetration of typical small launcher rails, $R' = 84\ \mu\Omega/m$ and using $\delta = 7.1 \times 10^{-3}$ m @ 1 kHz, $R' = 1.1\ m\Omega/m$. Although the actual value of R′ changes with the depth of penetration of current into the conductors, a constant value of R′ is assumed here as the average of the complete and 1 kHz current penetration resistances ($\therefore R' \approx 600\ \mu\Omega/m$). With a constant resistance gradient of R′, the total resistance will be R′x, resulting in a voltage drop of IR′x.

The second term is the voltage drop caused by the current flowing through the armature. The armature voltage is assumed constant here, but the electrical dynamics of a plasma are much more complicated than this simple assumption indicates. Plasma armature research has been conducted for many years resulting in a large volume of modeling and experimental data. Several references concerning these results are provided to allow the reader to develop a better understanding of plasma armature physics [7, 8, 9, 10]. For launchers, the plasma armature voltage can be estimated by an equation that is a function of the bore dimension and the current density. This equation is derived and presented by Parker [11]. Assuming a 15 mm conductor separation for the launcher, with 250 kA driving current, the plasma voltage consists of a constant 45 V plus 3200 V/m of bore height for a total plasma voltage ≈ 93 V.

The remaining two terms of breech voltage arise from the voltage drop across the inductance of the barrel when the current is changing and the consequence of the expanding current loop the moving mass creates. Assuming an electrically linear system whose flux linkages can be expressed in terms of a spatial inductance, the flux linkage is written as [12]:

$$\lambda = L(x)I \tag{10}$$

The voltage drop across this inductance is expressed as follows [4]:

$$V_L = \frac{d\lambda}{dt} = \frac{d}{dt}(L(x)I) \tag{11}$$

$$V_L = L(x)\frac{dI}{dt} + I\left(\frac{dL}{dx}\right)\left(\frac{dx}{dt}\right) \tag{12}$$

Now substituting L′ = dL/dx, and L(x) = L′ x for the functional inductance of the expanding loop, and v = dx/dt, we have:

$$V_L = L'x\frac{dI}{dt} + IL'v \tag{13}$$

$$V_L = V_{trans.} + V_{speed} \tag{14}$$

The $V_{trans.}$ term is the voltage drop resulting from a time varying current. This shall be referred to as the transformer voltage. The second term is developed along the rails as the armature moves through the magnetic field and is referred to as the speed voltage. [12]. Substituting the results of Equations 10-14 into Equation 9, we now have:

$$V_B = V_{Rail} + V_A + V_{trans.} + V_{speed} \tag{15}$$

Figure 4 depicts a simplified side view of a launcher and the general orientation of the breech voltage components.

The armature voltage (V_A) is often termed "muzzle voltage" since it can be measured across the muzzle of the launcher. The speed voltage results from the addition of differential inductance segments as the mass moves down the launcher. Therefore, it is difficult to represent the location of a voltage tap that would be used to measure the speed voltage in a static illustration. Figure 4 attempts to illustrate that the speed voltage is a result of the moving mass (dotted line represents the previous mass position).

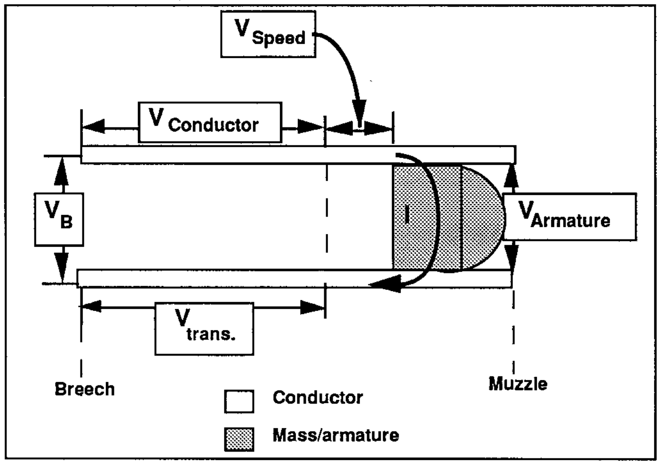

Figure 4. Breech Voltage Components

As the velocity of the mass increases, the speed voltage begins to dominate the breech voltage equation. For low velocity launchers, the speed voltage is not as important as the armature voltage, which has the highest value (with plasma armatures).

We now have an equation for the breech voltage that the power system must provide to the launcher. Simplifying Figure 3 and representing the launcher with the breech voltage symbol (Figure 5), we can rewrite Kirchoff's voltage law to obtain the power system voltage equation. The capacitor system voltage will now be related to launcher parameters.

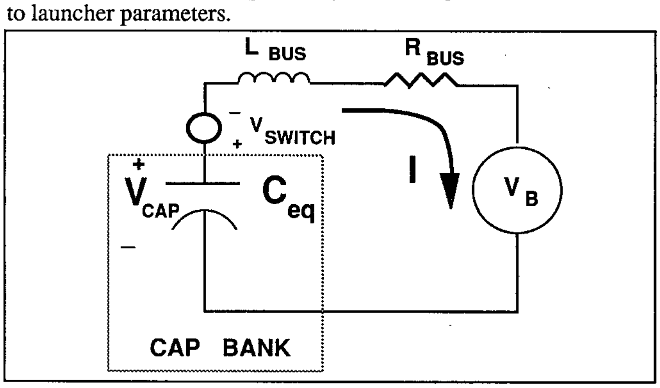

Figure 5. Simplified Capacitor Driven Launcher

The instantaneous capacitor voltage at any time during the discharge is represented by:

$$V_{Cap} = V_{Switch} + L_{Bus}\frac{dI}{dt} + IR_{Bus} + V_B \tag{16}$$

The switch voltage is the resistive drop across the closing switch and is assumed constant during current conduction. The magnitude of the switch voltage should be designed to be very low compared to either the breech or initial capacitor voltages ($V_{Switch} = V_{Cap}/1000$). Although the voltage drop is small, the switch must conduct very high currents (>100kA), which implies low resistance, and experiences very high current rise rates (dI/dt's) without failure.

The bus inductance and resistance are assumed constant during the current pulse. We know that any inductance in the circuit will not contribute a voltage drop during constant current (i.e., dI/dt = 0). However, the inductance will directly affect the rate at which the current rises. A low bus inductance combined with a high initial capacitor voltage will generate a quickly rising current pulse after switch closure; whereas, a very inductive circuit will tend to stretch out the current pulse in time and result in a lower peak current value. The initial open circuit voltage of the capacitor system must be high enough to drive the current to its maximum value in a short time (as dictated by acceleration and jerk limits) after the switch is closed. The rate at which the current is designed to rise due to the initial buss and barrel inductances (plus an armature breakdown voltage term) will determine the initial capacitor voltage required. The equivalent capacitance and open circuit voltage determine the amount of stored energy available to support the losses in the circuit and for conversion to muzzle energy of the mass.

Conclusions

Using the simple circuit equations a basic battery charged capacitor pulsed power system to drive an EML can be designed. This initial design can then be modified to include realistic parameter values emulating the actual hardware.

In order to make an accurate determination of the viability of the battery charged capacitor concept, a detailed engineering parameter analysis must be conducted that would then lead to the detailed design of an effective system. Successful completion of the detailed design and a well instrumented test series could then lead to educated conclusions pertaining to real applications of the battery charged capacitor system.

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