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Investigation of Battery-Charged Capacitor Pulsed Power Systems for Electromagnetic Launcher Experiments

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Candidate pulsed power systems for electromagnetic launchers constitute two broad categories: rotating machinery and nonrotating devices. Rotating machinery for this purpose is under development at several industrial and educational institutions around the world. Nonrotating 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 (Reference 1) identified several attractive pulsed power systems for electromagnetic launchers. Battery-charged capacitor pulsed power systems were among those identified as promising for electromagnetic launcher systems.

The basic equations governing the battery-charging capacitor sequence and the capacitor discharge into an electromagnetic launcher are the subject of this report. A battery-charged capacitor system powering an electromagnetic launcher has also been built and tested. 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.

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PREFACE

This work was funded by the Wright Laboratory, Armament Directorate, Analysis and Strategic Defense Division, Electromagnetic Launcher Technology Branch (WL/MNSH) under the Kinetic Energy Weapons program of the Strategic Defense Initiative. Personnel from WL/MNSH performed the work during the period of January 1990 to April 1991 at Eglin Air Force Base FL 32542-5000.

This report documents a design analysis of an electrolytic capacitor based rapid fire electromagnetic launcher power system. This report expands a paper that was presented at the Third European Symposium on Electromagnetic Launcher Technology in London, England on 16-18 April 1991 and the 8th IEEE Pulsed Power Conference in San Diego, California on 17-19 June 1991.

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LIST OF ABBREVIATIONS AND ACRONYMS

γ	Gamma
δ	Delta, Skin Depth
η	Eta
λ	Gamma, Flux Linkage
π	Pi
Ω	Omega
C	Capacitor
CCA	Cold Cranking Amps
C_{eq}	Equivalent Capacitor
d	Distance Between Plates
DC	Direct Current
I	Current
K	Dielectric Constant
L'	Inductance Per Unit Length
P	Power
R'	Resistance Per Unit Length
R_A	Armature Resistance
R_{INT}	Internal Resistance
S	Area In Square Centimeters
SCR	Silicon Controlled Rectifiers
SOC	State of Charge
τ	Tau, Time Constant
V	Velocity
V_A	Mass, Armature
V_{Cap}	Capacitor Voltage
V_{oc}	Open Circuit Voltage
V_{switch}	Closing Switch Voltage
W	Energy
$\therefore$	Therefore
Σ	Summation, Sigma
μ	Micro, mu
$\approx$	Approximately Equal
$\int$	Integral

SECTION I

INTRODUCTION

When using a battery charged capacitor pulsed power system to discharge into a transient load (in this case an electromagnetic launcher), operation can be divided into three distinct regimes. The first regime is the charging of the batteries by an external direct current (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 report 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. Silicon controlled rectifiers (SCR's) 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 report, SCR's are used to ensure controlled switching into the transient load.

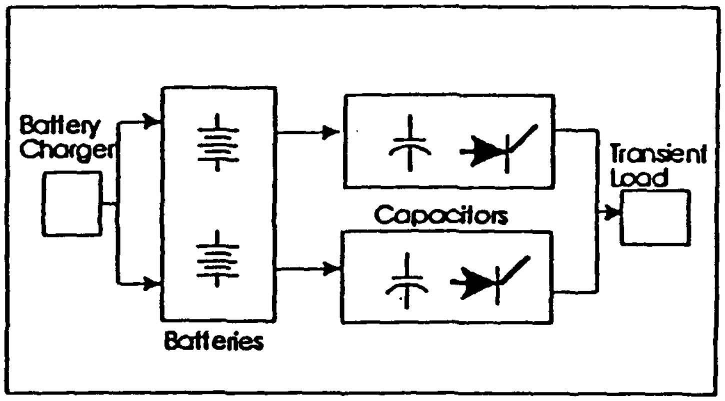

Figure 1. Power System Schematic

SECTION II

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--for example, lead-acid, nickel-cadmium, nickel-zinc, lithium systems, silver systems, hydrogen systems, and bipolor configurations of these. For this analysis, the standard cell, 12 volt, lead-acid batteries were considered. It was also assumed the basic battery string consisted of 60 batteries in series.

For the charging process, a high current electrical power was used to reform the active chemicals of the batteries to a high energy charge state. Lead-acid systems involve 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 restoration of 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:

$$I = Ae^{-t} \tag{1}$$

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 manufacturer's recommendations. The charging sequence can take several minutes; it has the longest event duration of the three operating regimes and, hence, the least interesting for the purposes of this report. But, unless properly designed, the charging system for the battery system can affect the operating efficiency of the battery-charged capacitor system. Table 1 shows the relevant battery parameters assumed for this discussion.

TABLE 1. 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-second pulse	
2800 A	- Maximum current average over 100 ms pulse	
10^7 Joules	- Approximate energy storage	

SECTION III

CAPACITOR-CHARGING SEQUENCE

As previously mentioned, the discharge energy store is made up of electrolytic capacitors, which are by no means a new technology. Some of the first electrolytic capacitors were fabricated in Germany in the 1800s (Reference 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 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:

$$C = \frac{q}{V} \tag{2}$$

where q is the charge in coulombs and V is the voltage potential between the conductors. If the potential of the capacitor rises by 1 volt when it receives a charge of 1 coulomb, it would have a capacitance of 1 farad. Practical electrostatic or electrolytic capacitors have capacitances of microfarads ($\mu F=10^{-6}$ farad), or picofarads ($\mu F=10^{-9}$ farad). Equation 2 can also be expressed in terms of the physical properties of the capacitor itself as follows (Reference 3):

$$C = 0.0885 \frac{KS}{d_c} \tag{3}$$

where
- C is the capacitance in pF
- K is the dielectric constant
- S is the area of one plate in square centimeters
- d is the distance between plates in centimeters

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 dielectric is a very thin film of oxide of the metal that constitutes the metallic plate of the first conductor (Reference 3). 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 specifications for the electrolytic capacitors for this system are listed in Table 2.

TABLE 2. 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 charge rating and 48 of these series pairs in parallel with each other. This arrangement of capacitors has a total capacitance of 84 μF. In this configuration, the capacitor module stores 27 kJ at 800 V (the maximum capacitor voltage rating).

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

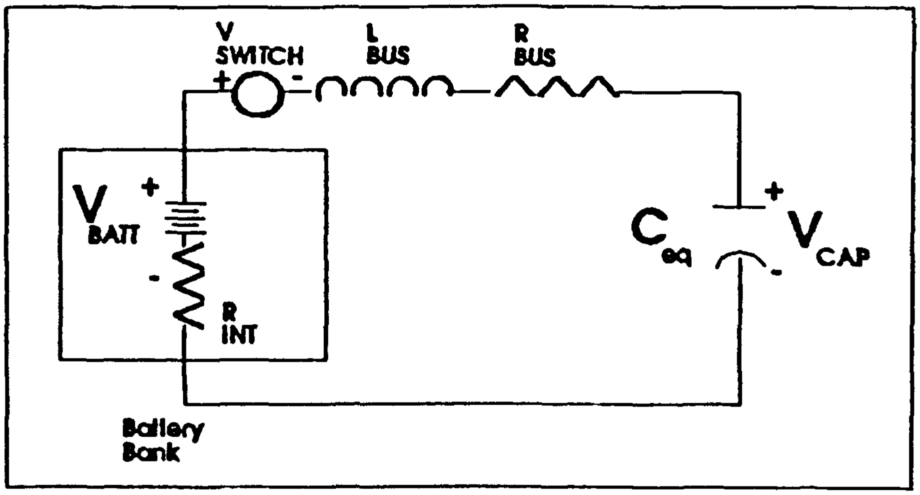

Figure 2. Battery-Charging Schematic

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 (Reference 4). 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 (Reference 5). At currents of 2000 A, the steady state internal resistance is approximately 4 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. Over a 5-second pulse, the average resistance is 4.0 mΩ, and the resistance continues to increase as time progresses and the conductors heat (Reference 6). In this case, the battery-charging current pulse is less than 100 ms. The bus resistance is assumed to be approximately 300 $\mu\Omega$ with an inductance of 200 ηH using standard 2/0 cable. For any large string of batteries, say more than 10 in series (that is, $R_{Int} \approx 40$ 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 millisecond) time constant that allows the researcher to ignore the bus inductance (Reference 7).

The equation relating the final open circuit voltage (V_{OC}) to the dynamic charging voltage (V_{Cap}) is given as follows (Reference 7):

$$V_{Cap} = V_{OC} \left(1 - e^{-t/\tau} \right) \tag{4}$$

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 4 as follows:

$$t = -\tau \ln \left(\frac{V_{Cap}}{1-V_{OC}} \right) . \tag{5}$$

The maximum charge current was approximated by

$$I_{MAX} = \frac{V_{OC}}{R_{INT}} . \tag{6}$$

Now by assuming the current has reached the maximum value, the time-varying expression for the current is written as follows (Reference 7):

$$I(t) = I_{MAX} \left(e^{-t/\tau} \right) . \tag{7}$$

This allows the researcher to calculate the magnitude of the current and by rearranging, the time for the current to drop to any value can be determined from

$$t = \tau \ln \left(\frac{I(t)}{I_{MAX}} \right) . \tag{8}$$

To get an idea for the magnitude of the parameters in Equations 4 through 8, consider a 60-battery series string (V_{OC} =765V, R_{INT} =240 mΩ [180-210 mΩ at time zero]), charging the 84 μF capacitor bank to 700 V. From these initial calculations, a battery system could charge the capacitor bank in less than 100 ms (10 Hz) for voltages and capacitances similar to the example. The maximum charging current capability of the batteries and the time that the batteries can remain at that level must also be considered.

TABLE 3. EXAMPLE CHARGING CIRCUIT

<u>Example Charging Circuit</u>

$\tau = R_{Int}\ C_{eq}$	= 20 ms
Charge time, t	= 49 ms
I_{MAX}	= 3188 A (Batteries)
Energy storage	= 21 kJ

<u>Current Decay Times From Peak</u>

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 (References 6 and 8). Currents of 3000 to 4000 A have also been demonstrated from time periods of several hundred milliseconds to several seconds (Reference 6). 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 $X10^5$ C (As) at 100 percent state of charge (SOC) (Reference 9). It also has a cold cranking amp (CCA) rating of 875 A that relates to its automotive origins. The CCA means that the battery has been tested by the manufacturer and is capable of discharging 875 A for 30 seconds (Reference 6). Assuming that this occurs at slightly below peak power, the energy discharged is 189 kJ. For this 23 Kg battery (Reference 6), the energy density under CCA conditions is 8 kJ/Kg. High discharge rates of 2000 A for 5 seconds have demonstrated pulsed energy densities of up to 170 kJ/Kg and a 5 percent reduction in the SOC (Reference 6). Assuming the battery could be discharged to 0 percent SOC and 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 less than 50 percent SOC have been demonstrated, storing over 1.0 MJ (Reference 6). Therefore, it appears that lead-acid batteries are more than adequate to output hundreds of short current pulses without damage.

SECTION IV

CAPACITOR DISCHARGE SEQUENCE

In a battery-charged capacitor electromagnetic launcher 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 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 electromagnetic launcher circuit.

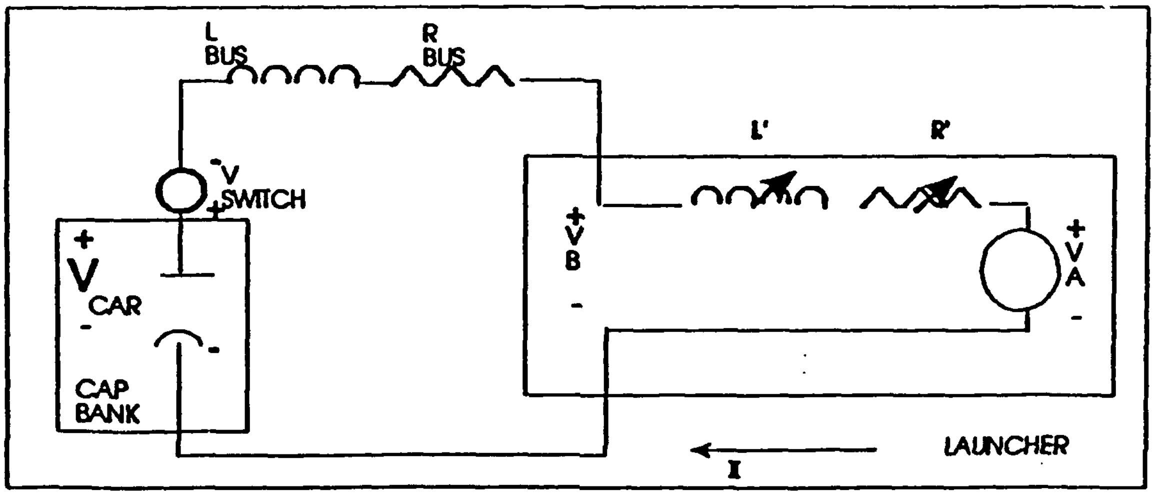

Figure 3. Capacitor-Driven Launcher

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, a battery in this case. 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 barrel loop using Kirchoff's voltage law (Reference 7), an expression for the breech voltage of the launcher can be determined as follows:

$$V_B = IR_{Rail} + IR_{Armature} + \frac{d}{dt} (L(x)\ I) \qquad (9)$$

$$V_B = IRx + V_A + [L(x) \frac{dI}{dt} + I \frac{dL}{dx}\frac{dx}{(dt)}] \ . \qquad (10)$$

The $IR_{Armature}$ term is replaced by V_A when using a plasma armature as shown in Equation 10. 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 $L(x)=L'x$,

$$V_B = IR'x + V_A + L'x \frac{dI}{dt} + IL'v \qquad (11)$$

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 11, 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 at 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 ($\therefore R' = 600\ \mu\Omega/m$). 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 (Reference 10). 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 (References 11 through 14). 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 (Reference 15). 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 approximately 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 projectile creates. Assuming an electrically linear system whose flux linkages can be expressed in terms of a spatial inductance, the flux linkage is written as shown in Reference 16:

$$\lambda = L(x)I \ . \qquad (12)$$

The voltage drop across this inductance is expressed as follows (Reference 7):

$$V_L = \frac{d\lambda}{dt} = \frac{d}{dt}(L(x)I) \qquad (13)$$

$$V_L = L(x)\,\frac{dI}{dt} + I\left(\frac{dL}{dx}\right)\left(\frac{dx}{dt}\right) \qquad (14)$$

Now substituting $L' = dL/dx$, and $L(x) = L'x$ for the functional inductance of the expanding loop, and $v = dx/dt$, generates

$$V_L = L'x\,\frac{dI}{dt} + IL'v \qquad (15)$$

or

$$V_L = V_{trans} + V_{Speed}\ . \qquad (16)$$

The V_{trans} term is the voltage drop resulting from a time-varying current, which 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 (Reference 16). Substituting the results of Equations 12 through 16 into Equation 11, generates

$$V_B = V_{Rail} + V_A + V_{trans} + V_{Speed}\ . \qquad (17)$$

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 because 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).

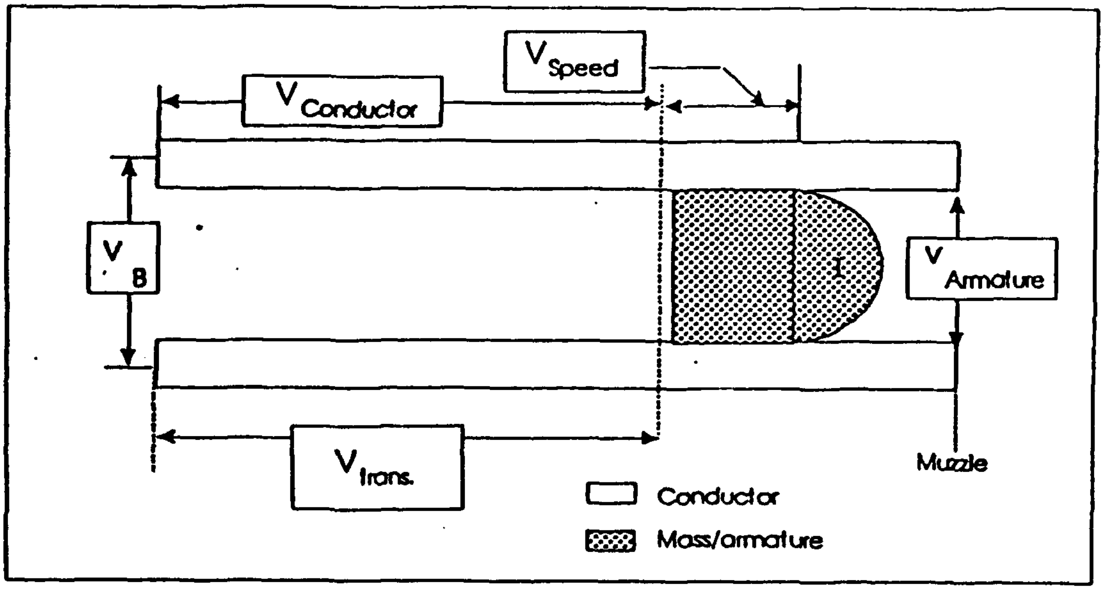

Figure 4. Breech Voltage Components

The relative magnitudes of the breech voltage components can vary significantly. As an example, consider a breech voltage calculation using the fictional launcher parameters of Table 4.

TABLE 4. EXAMPLE LAUNCHER PARAMETERS

Conductor separation	= 100 mm
Launcher length	= 5 m
Current	= 5.0 MA
L'	= 0.5 μH/m
R'	= 25 μΩ/m
V_A	= 1000 V
Velocity	= 2 km/s

Substituting the given values into Equation 11 and assuming dI/dt = 0, yields

$$V_{RAIL} = 625\ V$$
$$V_A = 1000\ V$$
$$V_{SPEED} = \underline{5000\ V}$$
$$V_B = 6625\ V$$

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 that has the highest value (with plasma armatures).

There now exists 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 (see Figure 5), Kirchoff's voltage law can be rewritten to obtain the power system voltage equation. The capacitor system voltage will now be related to gun parameters.

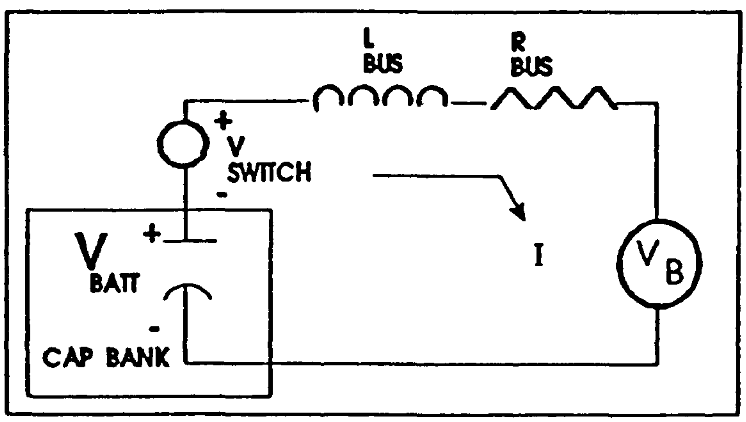

Figure 5. Simplified Capacitor-Driven Launcher

The instantaneous capacitor voltage at any time during the discharge is represented by Equation 18.

$$V_{Cap} = V_{Switch} + L_{Bus}\left(\frac{dI}{dt}\right) + IR_{Bus} + V_B \ . \qquad (18)$$

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 (>100 kA), which implies low resistance, and experience very high current rise rates (dI/dt) without failure. The switch voltage will be ignored in the following equations.

The bus inductance and resistance are assumed constant during the current pulse. Inductance in the circuit will not contribute a voltage drop during constant current (that is, 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 projectile.

SECTION V

ENERGY-BASED CAPACITOR DISCHARGE CIRCUIT ANALYSIS

The initial energy stored by the capacitor bank is written as shown in Reference 4:

$$W_C = \frac{1}{2} C_{eq} V^2_{OC} \tag{19}$$

where V_{OC} is the open circuit voltage of the capacitor bank prior to the discharge.

Now write the energy equations that allow the selection of the appropriate value for the circuit elements. The launcher circuit is a conservative system with respect to energy when the resistances or time-dependent energy loss components are ignored. The inductive components appear in both the ideal and real systems. Therefore, a general energy equation representing the initial energy, intermediate, and final energy of the system is written as

$$W_{Initial} = W_{Intermediate} = W_{Final} \ . \tag{20}$$

The initial energy of the system is represented by Equation 19 when the capacitor bank has been fully charged. During the discharge, the capacitor bank energy decreases and the circuit elements store or dissipate energy while the mass gains kinetic energy. Wiyh inductive energy of the circuit being conservative and the resistive not, the implication is that the energy dissipated by the resistors is dependent on the time history of the current during the discharge, whereas the inductively stored energy is not. The final system is composed of any remaining energy in the capacitor bank, the final kinetic energy of the mass, and the sum of the stored and resistively dissipated energy in the circuit.

The energy equation for the launcher circuit, including the resistive components, is written as follows:

$$\frac{1}{2} C_{eq} V^2_{OC} = \frac{1}{2} C_{eq} V^2_{Cap} + \frac{1}{2} L_{Bus} I^2 + \frac{1}{2} L'x\, I^2 + \int (R_A + R_{Bus} + R'x)\, I^2\, dt + \frac{1}{2} m v^2 \tag{21}$$

where R_A represents the armature resistance. Now rewriting Equation 18 to include the breech voltage components generates

$$V_{Cap} = IR_{Bus} + L_{Bus} \frac{dI}{dt} + V_A + IR'x + L'x\frac{dI}{dt} + L'Iv \ . \tag{22}$$

The right-hand side of Equation 21 is composed of the instantaneous energy of the capacitor bank (which ideally should be zero at the end of the discharge) as well as the integrals of all the voltage components multiplied by the system current (power), and integrated over the launch time ($E=\int Pdt$, Reference 16). Therefore, the right-hand side of Equation 21 represents the energy of the circuit for all time. The $\frac{1}{2}LI^2$ terms are the inductive energy terms, and the integral terms represent the time history of the resistive energy losses.

To illustrate a process by which a launcher system designer can determine the circuit performance, calculate the velocity of the mass with the circuit parameters given.

Examining Equations 21 and 22, it is seen that v (dx/dt), I (dI), V_{Cap}, and x are not known. To determine them, at least four simultaneous equations are required. Proceed by selecting small dt's and calculating the unknowns using those equations.

First, the kinetic energy of the mass can be related to the circuit parameters of the launcher for the third relation, and the velocity/distance equations can be determined for the fourth. The instantaneous force on the projectile is written as

$$F = \tfrac{1}{2}L' I^2 \ . \tag{23}$$

The mass energy is given by the integral of the force times the differential distance traveled (Reference 16)

$$W_{Mass} = \int F \, dx = \int (\tfrac{1}{2}L' I^2) \, dx = \tfrac{1}{2}L' \int I^2 \, dx, \tag{24}$$

and recalling the kinetic energy equation for a moving mass

$$W_{Mass} = \tfrac{1}{2}mv^2 = \tfrac{1}{2}L' \int I^2 \, dx \ . \tag{25}$$

The kinetic energy of the projectile has now been expressed in terms of the launcher parameters. The current I is an unknown with respect to x, as is the velocity. From basic physics (Reference 17), and assuming that the initial position and velocity are equal to zero generates

$$x = \tfrac{1}{2}at^2 \tag{26}$$

and

$$v = at \ . \tag{27}$$

Equations 26 and 27 together form the fourth relationship needed to solve for the velocity of the projectile at any time during the shot. The procedure used is an iterative solution to the simultaneous equations represented by Equations 21 through 27. The designer chooses small dt's and steps through these equations to solve for the unknown parameters over the duration of the discharge.

Initially, the capacitor is charged to V_{oc}, and I_0, v_0, and x_0 are equal to zero. The first dI is determined by choosing a small dt and solving Equation 20 as follows:

$$V_{oc} = V_A + L_{Bus} \frac{dI}{dt_1} \text{ or } \left(\frac{V_{oc} - V_A}{L_{Bus}} \right) dt_1 = dI_1. \tag{28}$$

With dI determined, the value of the current is known for the first time interval. Solving Equation 25 for v and combining Equations 26 through 27 to determine x, solve Equation 21 for the capacitor voltage (V_{Cap1}) at the end of the first time interval. At this point the next iteration begins and the new capacitor voltage is substituted into Equation 22, the next time step is chosen, and dI_2 is calculated. For the second time interval, x, v, and I are nonzero such that

$$dI_2 = \frac{V_{Cap\,1} - V_A - I_1 R' x_1 - L' I_1 v_1}{L_{Bus} + LX_1} . \qquad (29)$$

The total current will now be equal to $I = dI_1 + dI_2$, and the next velocity increment and distance traveled down the launcher are calculated using Equations 21 through 27, as before. In general, the current is represented by

$$I_n = \sum_0^n dI_n . \qquad (30)$$

With the new velocity and distance calculated, the capacitor voltage at the end of time period 2 is calculated from Equation 21. In summary, the relevant equations are presented together as follows:

$$\tfrac{1}{2} C_{eq} V^2_{oc} = \tfrac{1}{2} C_{eq} V^2_{Cap} + \tfrac{1}{2} L_{Bus} I^2 + \tfrac{1}{2} L' x I^2 + \int \left(R_A + R_{Bus} + R' x\right) I^2 dt + \tfrac{1}{2} m v^2$$

$$V_{Cap} = IR_{Bus} + L_{Bus} + \frac{dI}{dt} + V_A + IR' x + L' x \frac{dI}{dt} + L' I v$$

$$W_{MASS} = \tfrac{1}{2} m v^2 = \tfrac{1}{2} L' \int I^2 dx$$

$$x = \tfrac{1}{2} a t^2$$

$$v = at.$$

Using this iterative method, the velocity profile for the entire discharge can be computed for the given mass and circuit parameters.

The circuit parameters can also be calculated from a desired mass and velocity. The same equations can be used as a basis for computing the circuit parameters, but the task becomes more difficult due to the greater number of unknowns. Computer programs can and have been written that allow the designer to change the circuit parameters and calculate the mass velocity over the duration of the discharge with relative ease. But the iterative technique discussed here can always be used as an initial design tool to determine the velocity of the mass.

SECTION VI

CONCLUSIONS

Using the simple circuit equations and the iterative techniques presented here, a basic battery-charged capacitor pulsed power system to drive an electromagnetic launcher 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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