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# Battery–Inductor Parametric System Analysis for Electromagnetic Guns

**Prof. Pawar Gitanjali R[1], Miss. Bhujbal Radhika[2], Miss. Bhor Sneha[3], Miss. Bhutkar Priya[4], Mr. Deore Chetan[5]**

Assistant Prof. Chemistry Department [1]

Students, AIDS Engineering Department [2]

Students, Computer Science Engineering Department [3,4,5]

Adsul's Technical Campus, Ahilyanagar, India

**Abstract:** *Growing interest in battery performance and cost reduction for hybrid and electric vehicles has restimulated interest in the United States in the use of high-power batteries as a potential source of pulsed power. Recent progress in high-power density lithium-ion batteries and high-power semiconducting switches has suggested that a battery–inductor-based pulsed power system could become a viable option to pulsed alternators for electromagnetic (EM) launchers and other pulsed loads in the megajoule range. Approximate system sizing and a parametric study are presented, showing the effects of battery and inductor parameters on the overall efficiency and system size for a conceptual 2-MJ muzzle energy EM launch system utilizing the STRETCH circuit topology. The results show the relationship between potential increases in future component performance on overall system size reduction and efficiency.*

**Keywords:** Battery–inductor, parametric study, pulsed power supply, STRETCH, system sizing

## I. INTRODUCTION

T His Paper concerns a pulsed power supply option that has become of interest in the last few years as lithiumion battery technology has advanced to supply the needs of hybrid electric vehicles, portable computers, and other applications. Such batteries, as has been the case for all batteries for many years, have primarily provided high-energy-density capability but not high-power capability, particularly at the levels needed for loads such as railguns. However, in recent years, the Institute for Advanced Technology has worked with battery suppliers to investigate what can be done to improve short-pulse-power delivery from advanced batteries. This has resulted in a demonstrated cell performance of > 40 kW/kg and a current delivery of > 20 kA/kg—values that far exceed previously available battery performance [1]. This capability has been explored in the small demonstration STRETCH battery–inductor concepts described by Sitzman et al. [2], [3], where a pair of series-connected magnetically coupled air-core inductors is configured to act as an autotransformer (referred to simply as the inductor). Having shown that such a concept can work at a small scale, the next issue to be addressed is how it might scale to large sizes and how possible future component improvements could affect the system size and efficiency. This paper first presents approximate sizing equations of a generalized battery–inductor system driving a railgun. A specific case is then included as an example to show the volume, mass, and efficiency of a 2-MJ muzzle energy system. Key parameters are then varied to give the system volume, mass, and efficiency for various configurations that are either achievable presently or predicted to be sometime in the future.

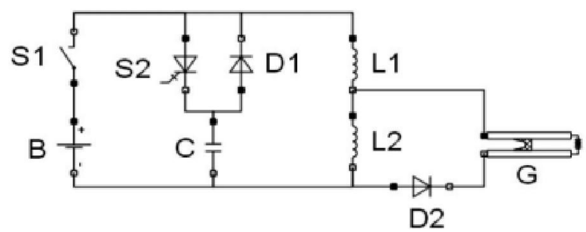


Fig1: Schematic of basic circuit, which has been slightly modified from that given in [3] for clarity.

## II. APPROXIMATE SYSTEM SIZING

### A. Basic Circuit

The basic circuit under consideration is shown in Fig. 1. In operation, when switch S1 is closed, current flows from the batteries to the inductor (L1 and L2). As the current increases in the inductor up to the chosen charge value Ic, a magnetic field B is established in which the energy stored is given by

$$E_{\text{ind}} = \frac{B^2}{2\mu_0\mu_r} = \frac{L_{\text{ind}} I_c^2}{2} \qquad (1)$$

Where μr is the permeability of the core of the inductor relative to that of free space μ0 and Lind is the combined inductance of the primary (L1) and secondary (L2) coils of the inductor. Since the inductor is air cored with a permeability approximately equal to that of free space, a value of μr =1 is used. When the desired charge current has been reached, switch S1 is opened, commutating the current to the capacitor (C). As the capacitor charges, the current in L1 decreases to zero, causing the magnetic field of the inductor to be supported by L2, which is in series with the railgun. Provided the primary and secondary windings are closely coupled, this is a relatively efficient energy transfer mechanism, and to a first approximation, the induced current in the secondary (output) winding (I2) can be obtained from an equation like (1)

$$E_{\text{ind}} = \frac{L_2 I_2^2}{2} \qquad (2)$$

where L2 is the inductance of the secondary side of the inductor. If we assume that EP = ES for a first approximation, the ratio of inductance in the primary and secondary inductor windings is L1 L2 = γ2. (3) The peak current in the secondary is then given by I2,peak = γI1,peak (4) where I1,peak is the desired charge current Ic. Thus, for an example current multiplication factor of γ =5, the inductance ratio L1/L2 = 25. Since the inductance is largely determined by the number of turns, this, together with the required currentcarrying capability and the need for close coupling, determines the overall coil configuration.

### B. Required Railgun Current

Pharmacology" For an idealized constant-current two-rail unaugmented railgun, the average gun current needed to achieve a muzzle energy Emuz in an acceleration length s is given by

$$I_{\text{gun,avg}} = \sqrt{\frac{2E_{\text{muz}}}{sL'_{\text{gun}}}} \qquad (5)$$

where L gun is the launcher inductance per meter. Since most power supplies are unable to provide a constant current throughout the launch, the actual maximum current that needs to be supplied is larger than this by the piezometric ratio p, which is the ratio of the peak to average pressure. Since the accelerating pressure in the railgun is a function of I2 gun, the peak railgun current needed will be 1/ √p larger than the average railgun current, specifically

$$I_{\text{gun,peak}} = \frac{1}{\sqrt{p}} I_{\text{gun,avg}}. \qquad (6)$$

To achieve a ratio closer to one, S2 is closed after the capacitor is fully charged, allowing the capacitor to discharge into the gun, delaying the drop in the gun current.

### C. Charging Circuit

The charging circuit comprises the battery pack (lithium-ion cells arranged in series and parallel to provide the required charging voltage and current), the inductor, and an opening switch. Bus losses are ignored for the moment. The transformer action of the coupled inductors dictates that the required charging current is inversely proportional to the square root of the inductance ratio given in (3)

$$I_c = \frac{1}{\gamma} I_{\text{gun,peak}} \qquad (7)$$

vith the current rising according to

$$I_{\text{ind}}(t) = \frac{V_{\text{pack}}}{R_{\text{tot}}}(1 - e^{-\alpha}) \qquad (8)$$

### D. Mass Volume of component

The volume of the battery pack is calculated as the total number of cells multiplied by the rectangular volume of the cylindrical cell, including the connections. This gives the volume of the battery pack if the cells were simply placed adjacent to each other, which is larger than a comparable pack made of prismatic cells. The mass is taken as the cell mass multiplied by the total number of cells. The mass and volume of busing are omitted in these calculations for simplicity. The volume of the inductor is calculated as the rectangular volume encompassing the toroid, including the conductors. This gives a larger volume than is actually occupied but is used for simplicity. The inductor mass is calculated using only the mass of the conductor, without consideration for the support structure or any cooling system if included. An energy volume density of 2 J/cm3 and an energy mass density of 2 J/g are used to size the capacitor, where the volume and mass are the peak energy stored in the capacitor multiplied by the respective energy-density value. These values are representative of current commercial technology. The mass and volume of the solid-state switches are calculated, including only the silicon junctions and some associated insulators based upon extractions from present commercial technology. Packaging and busing mass and volume are not included in this paper, as these are particular to specific devices. The number of devices needed in series and parallel is calculated using a device voltage rating of 3.3 kV and a specific current rating less than 100 A/cm2

## III. PARAMETRIC ANALYSIS

### A. Nominal System

The load for the nominal system under study is a 2-MJ muzzle energy railgun with a 4-m-long circular bore propelling a 1-kg launch package to a muzzle velocity of 2 km/s. For simplicity, no energy recovery or muzzle shunt is used, and the launcher is assumed to operate at 50% efficiency. The battery pack is composed of Saft VL5U lithium-ion batteries with each cell starting at 3.8 V, which is slightly less than its published peak open circuit voltage of 4 V, and a resistance of 350 μΩ at room temperature [4]. The inductor is constructed of aluminum alloy conductors starting at room temperature and operating at a peak magnetic flux density B of 10 T, with a current multiplication factor γ of around five. The geometry of the toroid is such that the outer radius of the air core is three times that of the air-core inner radius, giving a nearly circular core cross section. The amount of energy stored in the capacitor is primarily determined by the initial inductance in the load, which is taken at 0.1 μH and is nominally around 10% of the peak energy stored in the primary inductor. A peak capacitor voltage of 20 kV is used, which is within practical limits of current technology. It should be noted that the transformer will increase the back emf of the railgun by the current multiplication factor. The capacitor is subjected to this increased voltage, giving practical limits on the multiplication factor so as to not overvoltage the capacitor.

**B. Parameter Variation**

The nominal system will be varied in the following fashion, with all parameters remaining at nominal values unless

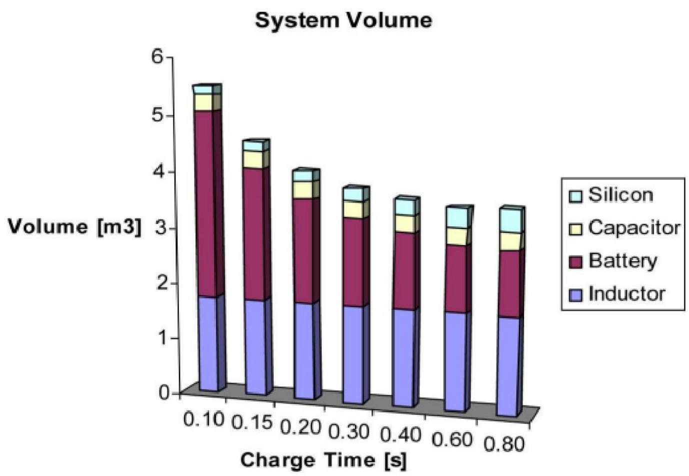


Fig2 System volume with increasing charge time

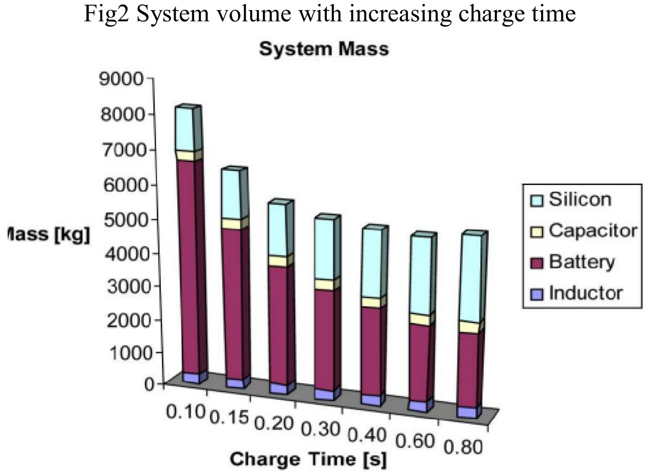


Fig3 System mass with increasing charge time

otherwise noted. First, the charge time of the inductor is varied to establish an appropriate charge time baseline for the examination of other parameters. Second, the battery cell voltage and resistance are varied, followed by the inductor resistivity. This paper is completed with the variation of the peak magnetic flux density in the inductor. To explore the changes in the system volume, mass, and efficiency with inductor charge time, the charge times were varied to 100, 150, 200, 300, 400, 600, and 800 ms. Of these, the time of 200 ms was found to give the best trade of low volume and mass with high efficiency, as shown in Figs. 2–4. In general, we see that, as the inductor charge time increases relative to the time constant (increasing α), the number of series batteries required decreases (14), but the transfer efficiency also decreases (23)—because of increased resistive losses—while the cell current increases. At the same time, the inductor and battery temperatures rise due to ohmic heating, and the number of switches increases to handle the increasing action. In this paper, the sizing of a cooling system to extract the heat from the inductor and batteries, and possibly the switches as needed, has not been included but is predicted to increase in volume and mass with charge time. As longer charge times remove more energy from the cells at lower efficiency, we see that the number of shots stored decreases, as shown in Fig. 5. In the end, the mission at hand determines the number of shots needed and the amount of time allowed for recharging, which then greatly influence the rest of the system, so these values should be taken in context. One important aspect of a battery–inductor system is that low efficiency is offset by the increased number of shots stored before recharge is necessary, due to energy-rich batteries. Looking at the aforementioned system volume and mass, it is obvious that the battery pack dominates in both and should therefore be the area of focus for the most improvement. Currently, the maximum open circuit voltage of lithium-ion cells is just above 4 V, but present research in academia and industry on improved battery cathode materials shows potential for a terminal voltage increase to 5 V. In addition, battery manufacturers have made significant progress in reducing the internal resistance of lithium-ion cells over the past decade. To obtain an idea of the system performance if some of these advances were achieved, a variation of these battery parameters was performed with the values in Table I, where the actual voltage used in the calculations was 3.8 and 4.8 V, respectively. It should be noted that the reductions in the cell resistance are chosen to explore the system performance and are not based upon predicted future values. In Figs. 6–8, we can see that the performance trend is the same for 4- and 5-V batteries for cell count, volume, and mass, as expected. An interesting point is highlighted by the relatively unchanged efficiencies (see Fig. 9), which point out that the resistive losses in the inductor dominate the losses of the system.

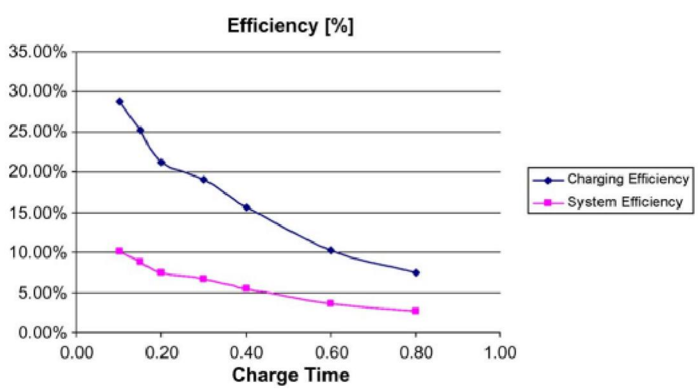


Fig4 Charge and system efficiencies with increasing charge time. The “bumps” around 0.20 s are believed to result from rounding in the optimization algorithm to minimize the number of battery cells for each charge time.

**Advantages**

- ♣ Its ability to reduce the time and cost.
- ♣ The goal of drug design is the chemical entities with desirable pharmacological properties.
- ♣ Structure based drug design played a large role in the discovery.

## IV. CONCLUSION

This paper has presented the equations governing the performance and sizing of a 2-MJ muzzle energy battery–inductor system, along with the variations of the performance and size with changing charge time, battery voltage and resistance, inductor resistivity, and inductor peak magnetic flux density. In each case, only one parameter was varied at a time, giving the effects of that parameter. Future work could include the combination of these variations to achieve an optimal system in the future. As these calculations are fixed points, a detailed simulation would be the next step to complement this paper. Other possible work could include varying the semiconductor material to silicon carbide, sizing of the cooling systems, and inclusion of energy recovery. In review, we have seen that the most benefit would come from work to decrease the internal resistance of lithium-ion batteries and a compact liquid nitrogen cooling system for an aluminium alloy inductor.

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