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Modern High Power Li+ Batteries for Efficient Load Levelling in Combat Vehicles

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Abstract

Recent advances in Li+ battery cells have been focused on increasing energy density for longer duration use in cell phones, laptop computers, and other portable consumer electronics. At the same time, new emphasis is being given to battery development and manufacture for advanced electric and hybrid-electric vehicles of all types. While cost has been a major deterrent to more widespread use of Li+ technology in the automotive industry, new research and manufacturing methods are attacking this hurtle well. As these developments unfold, and as high-power military applications mature, some new Li+ cells are being produced with significantly reduced internal impedance. This attribute not only increases the efficiency of charge and discharge processes, but is enhancing the opportunity for use in pulsed power applications. Because combat vehicle applications are typically higher power level duty profiles, new interest in load levelling for these platforms with pulsed electrical loads is being found. This paper provides a look at the new power performance of some sample battery cells and outlines potential utility for combat vehicle load levelling.

Keywords: lithium battery, fast charge, HEV, military

1 Introduction

Dramatically increasing interest in electric, hybrid-electric, and plug-in hybrid vehicles has opened new markets for commercial vehicles and spawned increasing investment in large-scale high-energy and power density batteries such as A123's series 32 cell and Saft's VL and HP series cells [1]. This growth in potential commercial automotive application is also stimulating US interest in growing on-shore advanced battery manufacturing capabilities [2,3]. Looking ahead to successful transitions of both automotive and battery industries in the US, the Army is interested in how military vehicles will evolve as well. This paper examines, in particular, the role that high-power and energy-density batteries could play in advanced ground combat vehicles utilizing pulsed power and hybrid drive systems. In these cases, advanced batteries for load levelling both the drive system (well understood) and pulsed power (less well understood) will be discussed.

2 Load Levelling Basics

Well known in the use of hybrid electric drive systems for ground vehicles is the need for compensation during acceleration (when power consumption is high) and braking energy recovery (to minimize vehicle kinetic energy loss). The use of energy storage devices such as batteries, flywheels, and other less common devices is critical for maintaining the power levels needed in the platform while minimizing the size and fuel consumption of an onboard prime power source. These same concepts apply for plug-in hybrids and electric vehicles (EVs) as well, though in the latter, the energy storage device must be sized not only for the load-levelling function, but for the overall energy consumption between opportunities to charge from a (typically stationary) infrastructure source. For combat vehicles (other than very small robotic systems), the overall energy consumption can be on the order of 1000 kWh. This and the often unpredictable availability of "infrastructure charging sources," dictate that hybrid electric architectures are preferred over EV-based systems for these medium to heavy combat vehicles, since fuel and a combustion engine are more volume efficient for very large energy levels.

Load levelling the engine then typically involves understanding the peak to mean power needs for the vehicle (where the mean power is provided by the engine) as well as estimating the duration of representative power fluctuations about this mean for the particular platform being developed. This latter characteristic is often very difficult to estimate for combat vehicles compared with vehicles such as busses and delivery vehicles with relatively fixed routes and schedules. Nevertheless, simulation based studies have shown significant benefit in sizing load-levelling energy storage systems for mobility in concept combat vehicles, and along with appropriate driver interfaces and training can result in practical approaches even for somewhat unpredictable conditions expected in combat.

3 Advanced Battery High Power Properties

In an effort to understand the potential for batteries in the pulsed power regime associated with electrical powered weapons and protection systems, the IAT has conducted characterization experiments for several very high power Li+ cells. In these experiments, the cells are exposed to very low impedance loads for brief periods to quantify the cell effective internal impedance when being pulsed. The cells tested are listed in Table 1.

Table 1. Cells tested

	Mass (g)	Volume (cc)
Saft VL12V	600	271
Saft VL5U	320	142
A123 M1	70	35

The load impedance for these experiments was ranged from 0.25–3.5 mΩ. A picture of the test fixture is shown in Figure 1.

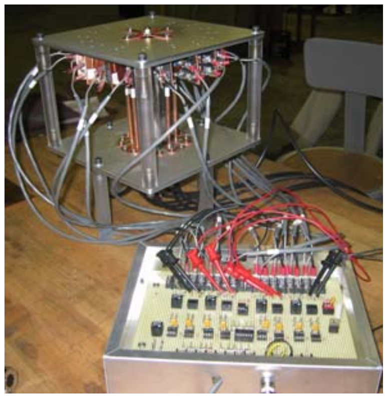

Figure 1: Battery cell test fixture

The associated power density and derived internal impedance for each cell when pulsed over a 0.1 second period are shown in Table 2.

Table 2: Energy, power, and derived impedance (R) (0.1 second pulse, 25 ^{o}C)

	Power (kW/kg)	R (mΩ)	Energy (W-hr/kg)
Saft VL12V	14	0.5	75.8
Saft VL5U	30.5	0.4	62.5
A123 M1	4.7	10	108

Figure 2 and Figure 3 show the sample current and power from VL12V and VL5U cells under 0.5 mΩ and 0.4 mΩ resistive loads, respectively.

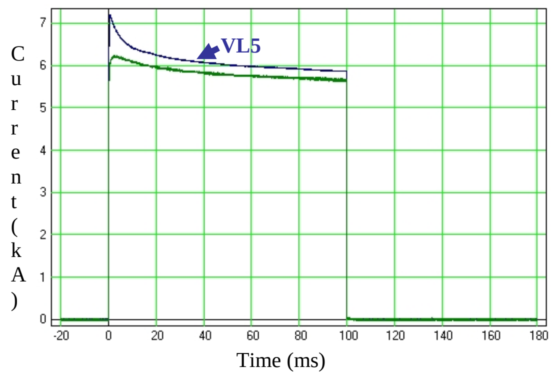

Figure 2: Current outputs of VL5U and VL12V

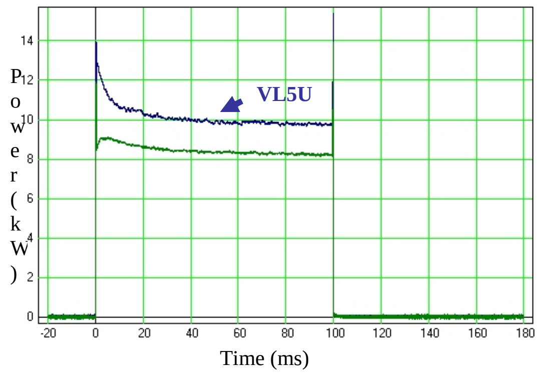

Figure 3. Power outputs of VL12V and VL5U

These values are up to 15 times the typical high power limitations normally reported for high power cells of this type and are only realizable when coupled to low impedance loads as might be envisioned for pulsed systems described in the next section. For the remainder of this paper, our analysis utilizes the Saft VL12V, which we have the most experience with at this time. Note however, that the newer, limited availability, VL5U cell provides better performance, indicating a continuing trend towards improved integration opportunities in the future.

4 Battery Based Pulsed Power

Pulsed combat loads considered here are associated with low impedance systems which require significant current over short periods of time to either exert an electromagnetic force, or control the combustion of a chemical propellant. Some examples of these applications are described below along with estimates for the battery size required, based on simulations where an intermediate pulse compression inductor is used to amplify and shorten the pulse to match the load. The inductor is charged from the battery over a period of anywhere from 0.25 to 1 s. Once charged, the battery is switched out of the circuit and the load switched in. The load side output of the inductor is at a different turns ratio than the input, which results in a transformer effect on the output current. For this paper, we assume a current amplification factor of approximately 6 between the input and output of this pulsed inductor. The simulation utilizes the measured battery properties described previously for the VL12V and the inductor is iteratively sized to meet the pulse output conditions required. The simulation is coupled with an optimization algorithm within Matlab/Simulink [4] to estimate the minimum number of battery cells (both in parallel and in series) to provide the inductor with needed energy in the allocated charge time. The capacity of this battery is then examined to determine its relevance for use in mobility load levelling for hybrid electric combat vehicles.

4.1 Electro-Thermal-Chemical Guns

In an Electro-Thermal-Chemical (ETC) gun, a current pulse is used to heat an electrical fuse, which is integrated with a cartridge propellant to more closely control the burn rate and resulting pressure profile, and in some cases obtain increased pressure from the propellant. A figure showing this system is shown in Figure 4.

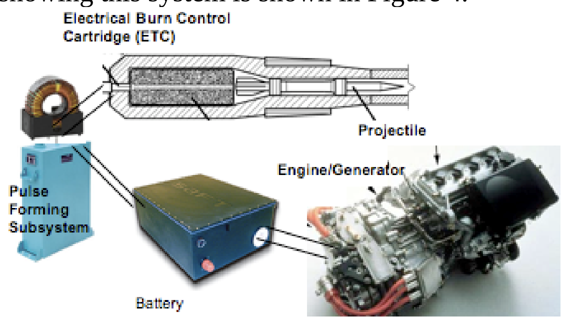

Figure 4. ETC gun concept

For a tank gun, the electrical pulse needed is on the order of 50 kA for 2.5 ms against a load voltage of approximately 1 kV [5]. Using the inductive pulsed power approach, an inductor storing 450 kJ is sized for this load. The resulting minimum sized VL12V battery pack needed to charge this inductor over 0.5 seconds utilizes 3 strings of 88 cells in series for a total of 264 cells. It is assumed for all of the candidate battery packs that they are arranged into appropriate modular groups of between 8 and 12 cells per module following existing SAFT practice. In this case, the resulting battery pack capacity is decreased by ~3% for a single shot. This suggests that 16 shots can easily be powered with this battery without dropping below 50% state of charge (SOC).

If one assumes that 70% of the nominal pack capacity is available (approximately 100 kJ from each battery cell) we find the pack can provide 28 MJ for non-pulsed loads. For a mobility load at 400 kW average and +/-20% variation, we'd expect such a battery to provide the 80 kW fluctuation for 5.8 minutes without using the weapon. Note that we assume the 400 kW average mobility power is provided by a separate prime power unit.

4.2 Elecromagnetic Armor

In electromagnetic (EM) armor applications, EM induction is used to propel plates, which fly into incoming projectiles and disrupt their penetrating performance, as shown in Figure 5.

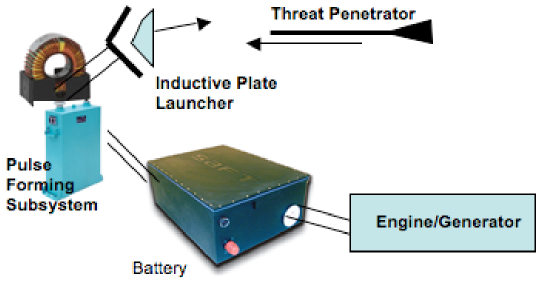

Figure 5: EM armor concept

EM armor pulse profiles depend heavily on the size and velocity of plates desired, but a notional kinetic energy of 84 kJ is scaled up by a factor of 10 from laboratory experiments by Li etal. [6]. Using inductance vs. plate separation distance from Deng etal. [7], a battery-inductor based pulsed power supply is sized for 0.13 second inductor charge time with a resultant battery pack composed of 12 strings of 60 cells in series for a total VL12V cell count of 720. The resulting battery system stores 76 MJ with a 70% depth of discharge limitation. Over 20 pulses of this type can be taken within the top 25% of total battery energy storage. For an 80 kW load levelling draw, the battery can provide 10 minutes of power while maintaining the energy margin needed for the armor system.

4.3 EM Guns

The use of EM guns in the form of railguns uses the Lorenze force in a conducting armature to propel a launch package at very high velocities. Figure 6 shows the concept for this launch mechanism. Here we consider a launcher similar to that described by Crawford etal. [7] capable of launching 13 kg to a velocity of 420 m/s. The circuit simulation for this 2.44 m launcher length gives a required inductor energy of 3 MJ. In charging this inductor over a period of 0.134 s, one needs 39 strings of 192 cells in series. The resulting battery pack is significantly larger (~2.8 m^3) than those currently considered for hybrid electric combat vehicle mobility. A platform designed for this would likely capitalize on this available energy and power to reduce volume elsewhere in the power and propulsion system without loss in mobility performance.

The weapon has only used 1.5% of the battery capacity in a single shot. The full pack capacity (again assuming only 70% depth of discharge allowed) in this case is 792 MJ, which would provide over 2.5 hours of 80 kW mobility load augmentation or other auxiliary field boost utility power using the same assumptions outlined previously for a 400 kW average mobility load. In this case, one might envision utilizing such a battery capacity for significant engine off operations and reducing acoustic signature.

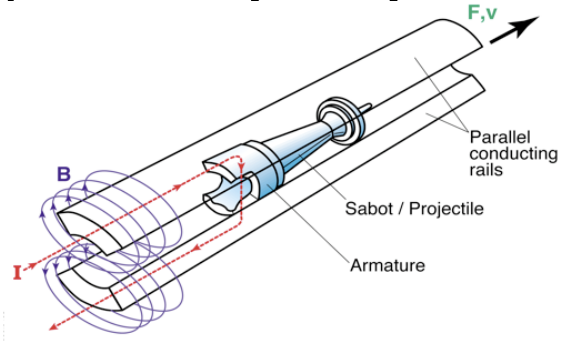

Figure 6: EM railgun concept

5 Summary

The advent of high power advanced batteries and the expectation that additional performance will be realized from the aggressive investments being made in this area, suggest that batteries may be a promising solution for load levelling combat vehicles even when pulsed power loads are considered. In the past, batteries were not practical for pulsed load levelling due to their excessive internal impedance, but recent measurements suggest that this may be mitigated by developments being made to improve the overall cell efficiency for automotive propulsion applications. If this trend continues, batteries maybe used to share load levelling function for both propulsion and pulsed loads, thus providing a lower cost and more weight and volume efficient solution for future combat vehicle designs.

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