

High Power Electrochemical Energy Storage for Directed Energy Applications

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ABSTRACT

The desire of the US Department of Defense (DoD) to field new directed energy systems for a variety of applications increases daily. This desire stems from recent advances in energy storage and solid-state switch technologies, which enable researchers to make systems more compact and energy dense than ever before. While some systems can draw power from the mobile platform on which they are mounted, other systems need to operate independent of a platform and must be completely self-sufficient. The transient and repetitive operation of these directed energy systems requires that the prime energy source provide high power to intermediate energy storage devices. The ability of electrochemical energy storage devices, such as lithium-ion batteries, to source high power quickly has previously been limited. However, battery manufacturers have recently produced cells that are more power dense than previously available. In addition to lithium-ion batteries (LIBs), researchers have greatly improved the capabilities of electric-double-layer capacitors (EDLCs) and lithium-ion capacitors (LICs) increasing their application space further as well. In order to experimentally validate the pulsed current cycling limitations of some of the newest electrochemical cells, a novel low impedance test stand has been developed. The total impedance of the stand, less than 1 milli-Ohm, is such that in most cases, the impedance of the cell dominates the charge/discharge current. A description of the test stand will be given and experimental results will be presented to demonstrate the capabilities of those new power dense electrochemical energy storage technologies

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INTRODUCTION

Research and development of directed energy systems (DESS) has accelerated at a rapid pace in recent decades as a result of the vast reduction in the size of intermediate energy storage and solid state switching components. This reduction in size and the DoD's desire to reduce its dependency on oil and increase the use of electrically driven vehicles has significantly increased the need for electrochemical energy storage devices for use as a portable prime power source. Electrochemical energy storage technologies have also increased at a dramatic pace since the early 1980's, enabling portable electronic devices to be used for a vast number of applications in most everyone's daily lives. Electrochemical energy storage technologies are usually placed into two categories, cells that have a high energy density and cells that have a high power density. Traditionally, rechargeable batteries have fallen into the energy dense category due to their ability to source their rated current in a stable and continuous fashion for a considerable amount of time. Their high equivalent series resistance (ESR), typically 10's of mΩ, has historically prevented them from sourcing high currents

in a transient or pulsed nature to a fast changing load. Electric-Double-Layer-Capacitors (EDLCs), also known as supercapacitors or ultracapacitors, typically have a higher power density due to their ability to source high currents in a pulsed fashion. However, EDLCs are not able to store a considerable amount of energy. A vast number of applications, such as DESS and electric vehicles, require their power source to be both energy and power dense. The lack of having one electrochemical energy storage technology that falls into both categories has prevented the development and deployment of these critical applications from occurring at a rate faster than it has been.

Electric vehicles and directed energy systems such as high power microwave sources, electromagnetic launchers, and pulsed lasers are all prime examples of high power systems in need of a portable prime power source. Several vehicle manufactures, such as Chevrolet, Nissan, Ford, Honda, and Tesla have all commercially produced their own form of vehicle that uses electricity as one means of power. The number of vehicles and the range or percentage of electricity they use versus standard combustion is limited presently by

the stored energy density available in the batteries. The DoD has spent much time and effort trying to make their vehicles more electrically driven as well. The US Army has supported development of a hybrid Humvee for over a decade [1]. The F-35 Lightning II Joint Strike Fighter's Electrical Power Management System uses Saft 28 V and 270 V modules to provide start-up power for the auxiliary power unit and back-up power to operate the flight control surfaces respectively [2]. The US Navy started the Electric Ship Research and Development Consortium (ESRDC), a team made up of seven U.S. universities, in 2002 to develop near term and far term research solutions for ship power systems on an all-electric ship [3]. Several researchers have developed laboratory based directed energy weapon systems using batteries as their prime power source. A few include Sitzman [4] and Allen [5] who have each demonstrated small scale electromagnetic launchers which use lithium-ion and lead acid batteries respectively to draw their prime power. Nunnally [6], Dragt [7], and Cadilhon [8] have each documented their respective development of a battery driven pulsed power system capable of driving a high power microwave source. All of these different vehicle and weapons systems are in need of one technology that is both power dense and energy dense to make them more viable in the field.

Recently, researchers and manufacturers of lithium-ion batteries have made significant breakthroughs, enabling them to decrease a cell's ESR and significantly increase their power density. The increase in the power density comes with a cost of reduced energy density; however, the hit is not significant enough to prevent them from being useful in directed energy and vehicular applications. Additionally, a hybrid technology known as a lithium-ion capacitor has been developed that combines the features of lithium-ion batteries and EDLCs to form a device which has a power density similar to that of an EDLC with roughly four times the energy density of EDLCs [9]. While some of these new technologies are commercially available, all of them are still in their infant stages of use. Consequently, considerable testing must occur before their full capabilities and limitations are known. With the support of the US Office of Naval Research (ONR), researchers at the University of Texas at Arlington (UTA) are working with many different cell manufacturers to experimentally validate the cells' ability to source high pulsed power loads. This paper will focus on some recent experiments performed on a high power GAIA 18 Ah LiFePO₄ battery and provide some insight on how new energy storage devices will work for driving future directed energy systems.

EXPERIMENTAL SETUP AND RESULTS

In the spring of 2011, researchers at UTA began a research study to understand the fundamental energy and power limitations of new electrochemical energy storage technologies when they are recharged using high pulsed

currents and used to source high pulsed power to a load. An additional research area of interest involves trying to fundamentally understand how the aging of these new devices changes when they are recharged using high currents applied in a pulsed fashion and when they are used to source high power in a pulsed mode of operation. These two modes of operation are representative of the manner in which the cells will be used in directed energy and vehicular applications.

In order to understand the power delivery capabilities of these new high power cells, a switchable load whose impedance is less than or equal to the impedance of the device under test (DUT) is needed. If the impedance of the load is higher than the impedance of the cell, then the load acts as a current limiter. The new high power cells have internal impedances less than 1 mΩ, making the design of such a load a non-trivial task. With support from the US Office of Naval Research (ONR), UTA developed a novel low impedance test stand capable of discharging and recharging electrochemical energy storage cells at pulsed and continuous currents essentially as high as the cells will allow up to roughly 10 kA. The test stand has been thoroughly documented in both configurations in [10,11,12,13] and the reader is encouraged to refer to those publications for a greater knowledge of the system.

Until recently, the elevated charge and discharge procedures have been isolated. Recently, researchers have added the capability to recharge the cell during breaks when the load is not drawing power from the source [12]. When the cell undergoes discharge, the stand remains essentially unchanged from its original configuration where high current bus bars, 60 high power MOSFETs connected in parallel, and a variable series resistance controls the discharge C rate, are connected in series across the positive and negative terminal of the cell. To recharge the cell without reconfiguring the stand, a high capacity lithium-ion battery module, whose cell configuration is easily adjustable to obtain different voltage and capacity settings, sources current through two 2400 A Insulated-Gate-Bipolar-Junction-Transistors (IGBTs) connected in series into the cell under test. The number of variable components enables researchers to modify the stand's parameters and limitations easily as needed for different experiments. A photograph of the stand in the configuration just discussed is shown in [Figure 1](#) and a schematic diagram is given in [Figure 2](#). Numerous voltage, current, and temperature measurements are collected during each test using a high sampling rate / high resolution data acquisition system.

Most DESs are made up of a number of components. A prime power source stores the initial source of energy. A power electronic device conditions the energy from the prime power source into a form that is usable by the intermediate storage device. Most power electronic converters consist of a switched mode power supply that draws energy from the primary storage in a pulse width modulated (PWM) fashion and outputs an averaged constant voltage or current to the

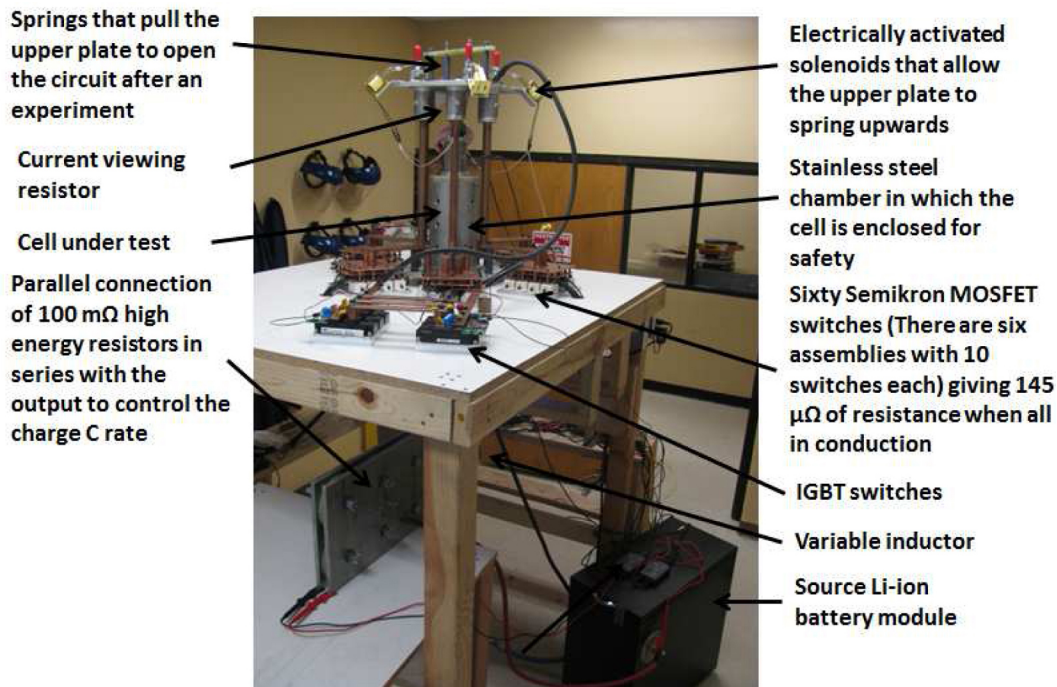


Figure 1. Constructed photograph of the experimental test stand in the hybrid charge/discharge configuration.

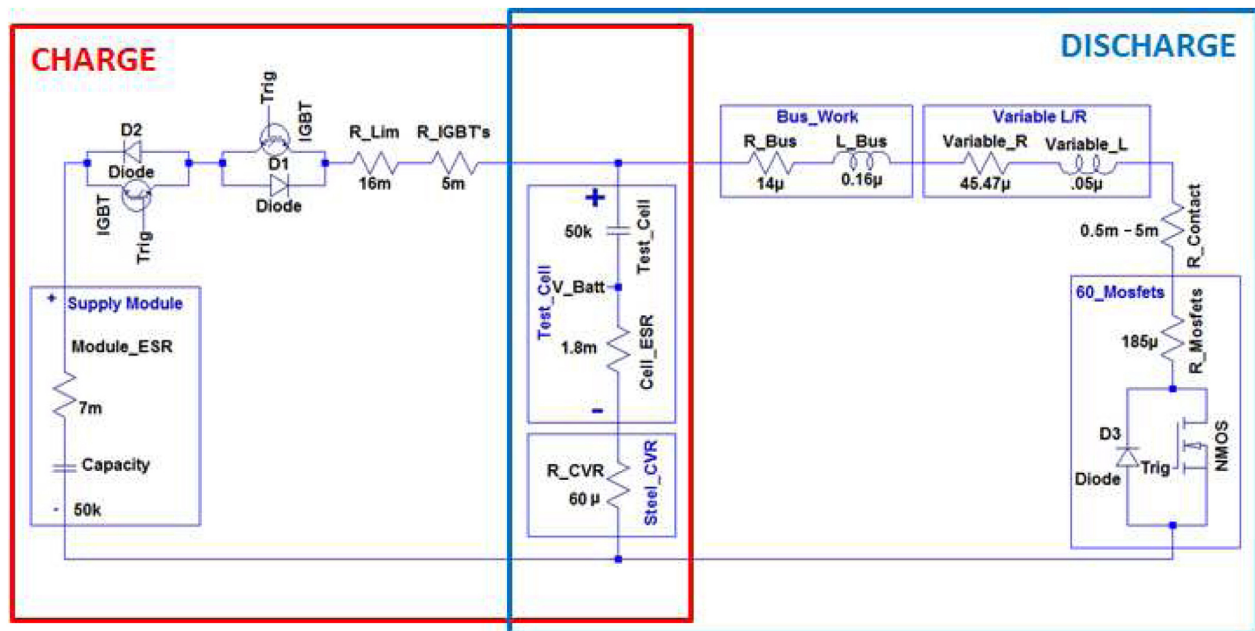


Figure 2. LTSpice circuit schematic and simulation model of the stand in the hybrid charge/discharge configuration.

intermediate storage. In most pulsed power systems, the intermediate storage is some form of capacitive, inductive, or rotating energy storage. Independent of the method of storing energy, the intermediate storage discharges into the load through a high energy switch. Almost all DESs are repeatedly cycled many times per minute. UTA is mimicking this type of load profile on many different types of electrochemical energy storage devices. In the work presented here, a GAIA

18 Ah lithium-iron-phosphate (LiFePO_4) battery is used. The battery, which has an internal equivalent series resistance of $0.8 \text{ m}\Omega$, was pulsed discharged at roughly 60 C in a pulsed fashion representative of how it may be used to charge up a six shot per/minute DES. The results of the experiment are shown in [Figure 3](#), [Figure 4](#), [Figure 5](#), [Figure 6](#), [Figure 7](#) [13].