A Modular High Power Battery System for Pulsed Power Applications

Eric Cordero[1], Shad Holt[1], James Dickens[1], Andres Neuber[1], John Mankowski[1], Steve Calico[2] and Mike Scott[2]

[1]Texas Tech University, Center for Pulsed Power and Power Electronics, Department of Electrical and Computer Engineering, Lubbock, TX 79415, USA

[2]Lockheed Martin Corporation Missiles and Fire Control, Grand Prairie, TX 75051, USA

ABSTRACT

This paper presents the design of a scalable, high power battery system for pulsed power operations. The battery system is modular in design, with each module containing four Lithium Ion Polymer (LiPo) cells and a custom designed cell management board that actively monitors the voltage and temperature of each cell and also provides cell balancing functionality. The system is designed to be scalable by adding up to 25 modules in a series configuration. While the battery management system should be compatible with any lithium ion cells, this implementation uses 8 Ah capacity dual-core LiPo cells, rated for a 150 C discharge rate; allowing for a peak current output of 1,200 A. With 25 modules (96 LiPo cells) the system would have an open circuit voltage of 385 V and be capable of providing up to 1,200 A at 355 V for a peak output power of 420 kW. Special attention has been placed on safety features including overvoltage, undervoltage and temperature monitoring of every cell in the system. The charging/balancing system is capable of automatically shutting down if any of the voltages or temperatures exceeds established limits. The management circuitry is designed to have a low off-state power draw in order to maximize battery life when the system is not in use.

Index Terms — **LiPo, Lithium Ion Polymer, Battery Management System, Rapid Capacitor Charger, Power Electronics, Buck-Boost Balancing, ECAN**

1 INTRODUCTION

The design objective for this project is to create a high power battery system to supply an 80 kW H-bridge power electronics converter for operation in locations without a high power mains connection [1]. The battery system consists of 25, 4-cell LiPo batteries complete with a battery management system capable of real-time monitoring of cell temperature, voltage and current. These parameters enable assessing cell health as well as estimating cell lifetime.

As a major design requirement, the user interface needed to be intuitive and flexible, which was accomplished by providing an LCD readout and keypad to select various operating ranges. A ProTerm hand terminal as well as a computer serial link provides this functionality.

2 OVERALL SYSTEM

Figure 1 depicts the layout for the battery system and attached H-bridge power electronics converter. As indicated, the hand terminal communicates over RS-232 with the main board while the main board is linked to the battery management module (BMM) and the power electronics controller (PEC) via asynchronous fiber optic links. The battery management module is responsible for collecting data from each of the cell management modules (CMMs) via an isolated Enhanced Controller Area Network (ECAN) bus. With all the cell management boards daisy chained together over the ECAN bus, the battery management module is able to address each individual cell management module and request data or give commands.

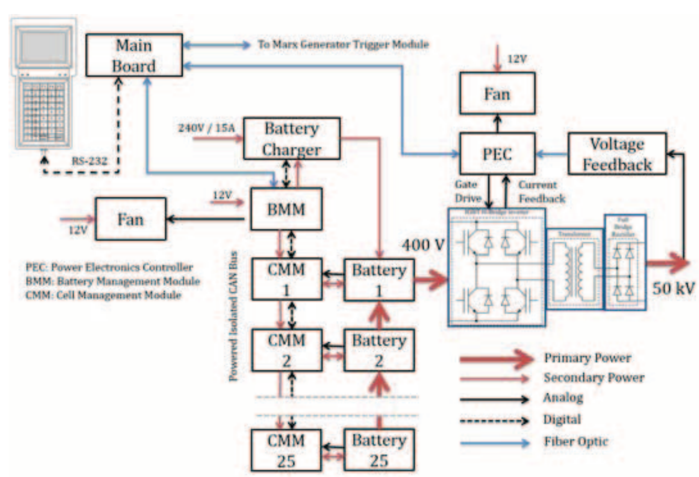

Figure 1. Battery System Layout.

Distribution Statement A: Approved for Public Release-Distribution is Unlimited

978-1-4799-4047-9/14/$31.00 ©2014 IEEE

The battery charger is a remotely controlled 6 kW DC power supply capable of outputting at least 400 V and 8 A. When activated by the battery management module, the power supply operates in a constant current mode to charge the LiPo cells in series at a constant C-rate. Once the first cell reaches cutoff voltage the CMM balancing circuits are activated to top off the remainder of the cells by diverting current from the fully charged cells.

3 BATTERY SELECTION AND PACKAGING

A parametric comparison of battery chemistries revealed that LiPo batteries have one of the highest specific power to specific energy ratios, making it the best available chemistry for this application. MaxAmps was selected as the battery manufacturer; their dual core (2 cells connected in parallel) offer a 150 C-rate discharge rating, and prior testing has demonstrated the manufacturers amperage ratings to be accurate [2-3]. A custom 8 Ah battery pack with 2 cells in parallel, 4 cells in series and a flat form factor was designed for this project. Twenty-four of these packs connected in series are capable of providing a peak discharge current of 1.2 kA at 355 V corresponding to a peak output power of 420 kW. All of the system components are packed in two different aluminum housings. One housing is for the battery cells and the CMMs while the other holds an auxiliary 12 V lead acid battery for relay and fan operation and the BMM. The mechanical design of the battery system is shown in Figure 2. The position of the smaller box containing the auxiliary battery and BMM may be relocated in relation to the larger box.

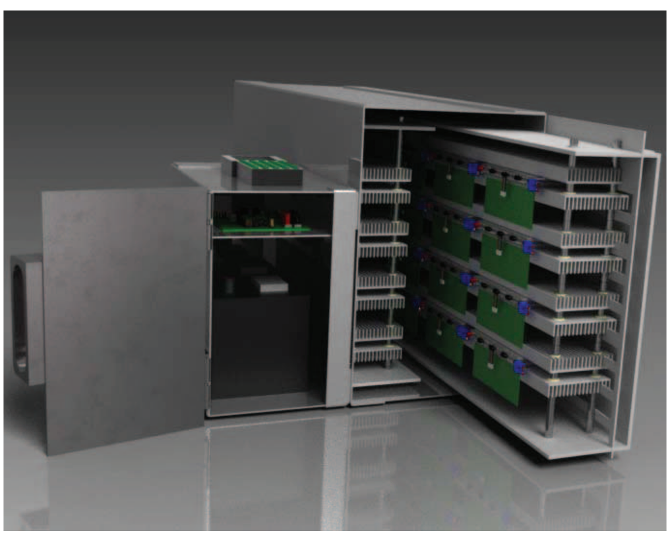

Figure 2. Battery Cage Design.

The batteries are designed to be flat so that they can be inserted between heat sinks such that each cell has significant heat sink contact area. The heat sink and battery assemblies are stacked into an aluminum housing such that six 120 mm case fans on the back panel pull air evenly across each heat sink.

To estimate the maximum battery temperature swing in a realistic operational scenario, a 1-D heat-flow numerical analysis was performed using the heat-flow circuit analogy method. A comparison of battery thermal dissipation for different heat sink profiles and airflows is shown in Figure 3. The operational scenario for this analysis was a 5 s, 80 kW average power discharge followed by 5 minutes of 10 CFM airflow over the heat sink. Figure 4 shows that in this scenario a steady state temperature of approximately 22 °C above ambient is reached after around 6 cycles. To avoid thermal runaway and a self-oxidizing fire, LiPo cells cannot be allowed to exceed 60 °C. This simulation indicates that the batteries could be theoretically operated at this duty cycle in an ambient temperature of 38 °C before reaching cutoff temperature.

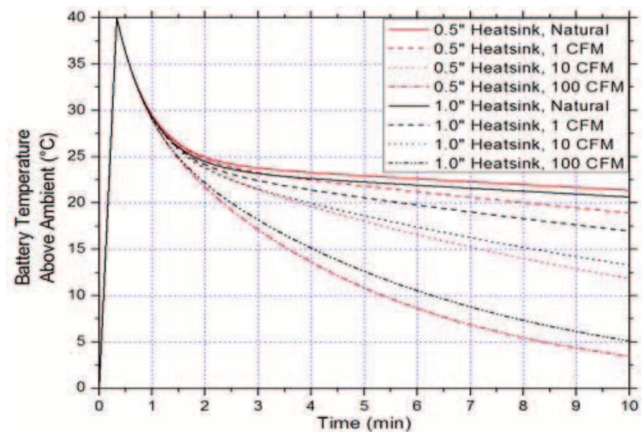

Figure 3. Heat Sink Performance.

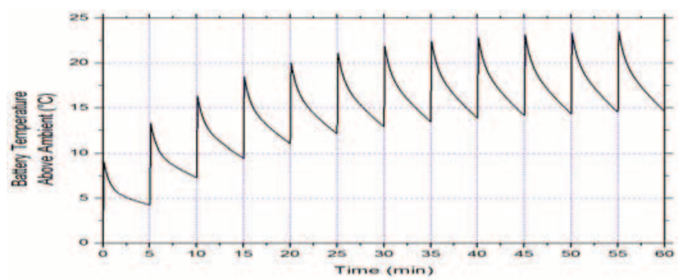

Figure 4. Estimated Thermal Performance/ 5 Seconds ON, 5 Minutes OFF, 10 CFM airflow.

4 SAFETY FEATURES

A significant hazard imposed by the high voltage and high short circuit current of the battery system is electrical arc flash. In the event of an arc flash, the electrical energy is capable of vaporizing metal which can result in explosive force as the metal expands from solid state to a gas vapor. Prevention of arc flash is thus a primary priority in the design of the battery system. To minimize this risk, when the system is not being charged or discharged the battery will be separated into four ~100 V stacks by three KILOVAC LEV200 relays. These relays are rated for 500 A at 900 Vdc continuous operation, with a 2 kA single cycle break current. Additionally, ultra-fast action semiconductor fuses rated for 600 A and 500 V are placed in series with each 100 V stack to limit any damage due to short circuit current.

5 BATTERY MANAGEMENT SYSTEM

The BMM module depicted in Figure 5 has multiple communication capabilities. The RJ45 ports on the upper right allow for connection to two powered, isolated ECAN buses as either a master or slave device. Three fiber-optic isolated asynchronous serial links are provided on the bottom right and an RS-232 connection is available through the RJ11 on the left hand side. Additionally, the BMM also includes an SD card slot for storage of battery operation logs.

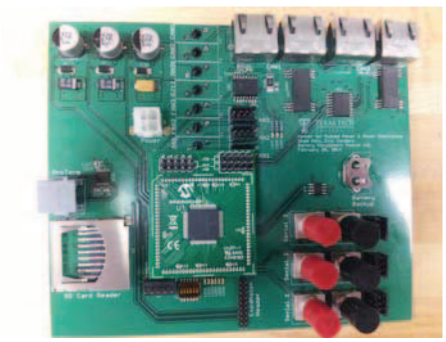

Figure 5. Battery Management Module.

The ProTerm hand terminal depicted in Figure 6 allows a user to interface with the battery management system and read cell currents, voltages and/or temperatures while also enabling the user to control the operation of the power electronics converter.

Figure 6. ProTerm Hand Terminal.

The software flowchart in Figure 7 shows the cell balancing algorithm. The BMM polls the cell voltages via the CMMs, calculates the necessary bypass current for each cell, and then reduces the main battery charger current to keep all currents within hardware limits.

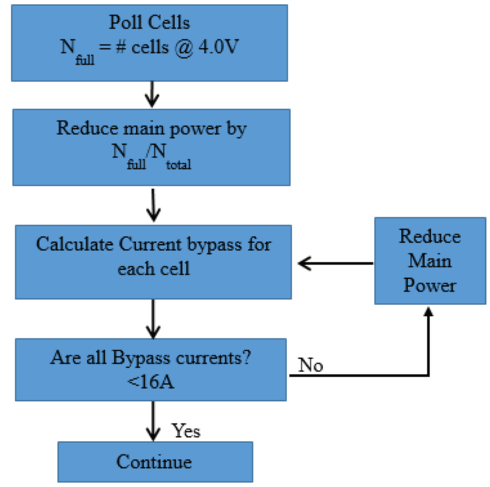

Figure 7. Balance Charging Algorithm.

Four cell balancing circuits, each consisting of a buck-boost converter and associated hardware, are integrated into each CMM. These buck-boost converters actively balance the cells with a non-dissipative method [4]. This strategy avoids losing excess energy into resistors which is the method typically used in smaller battery management systems. The operation of this circuit is shown in Figure 8. The blue arrow shows the flow of the current supplied by the main charging supply. During balance charging, energy is diverted from the top LiPo cell by using switch Q1 to charge the inductor L1 as indicated by the yellow arrow. When switch Q1 closes, the energy stored in L1 is deposited in LiPo cell 2.

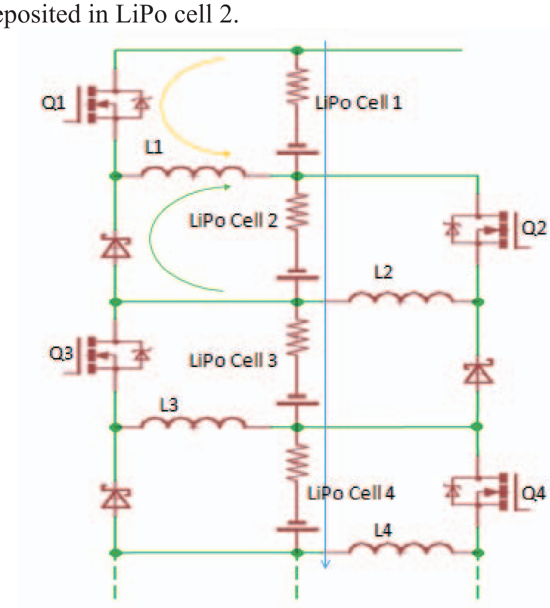

Figure 8. Battery Balancing Circuit.

Figure 9 shows a successful demonstration of balancing two cells with a buck-boost converter. Two intentionally unbalanced cells are connected in series and then charged. When the first cell reaches 4 V the balancing circuit activates diverting current from that cell into the next cell until they

Distribution Statement A: Approved for Public Release-Distribution is Unlimited both reach 4.0 V. The noise spikes in the waveforms are where the charging current was momentarily turned off to eliminate the ohmic drop across the battery terminals and acquire an accurate cell voltage.

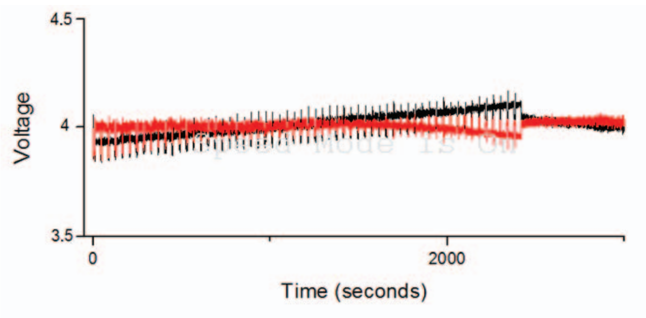

Figure 9. Charging Battery Cell.

The CMM, shown in Figure 10, is used to actively monitor each individual cell's voltage and temperature and control the feed-forward current of the buck-boost converters. Quad differential analog voltage comparators and serially connected semiconductor junction temperature sensors are read by a dsPIC microcontroller and communicated on demand to the BMM via the isolated ECAN bus. The buck-boost current limits are controlled via a serial programmable resistor.

A unique feature of the CMM is that it is powered over the CAN bus rather than the connected battery, providing several benefits. As each CMM must measure and balance four cells, isolation components are required to provide the ground reference shift. These isolation components have rather high power consumption and would significantly limit battery standby life. By supplying most of the components via the powered CAN bus the cell current draw is reduced to less than 800 μA allowing an estimated standby lifetime of almost one year. Additionally, powering the CMM's via the CAN bus allows all components to be operated in a fail-safe slave mode where the balancing circuits cannot operate without direct control from the BMM.

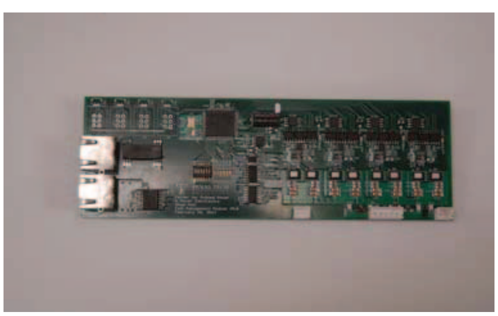

Figure 10. Cell Management Module.

6 CONCLUSION

Analysis of the individual components of the battery system has shown that the creation of a high power battery system is indeed feasible. Selection of optimal components for each individual task reassures that the fully integrated system will perform safely and as required. The remaining steps to be taken in this project are the integration of the individual components to demonstrate a complete battery system.

ACKNOWLEDGMENT

This material is based upon work supported by the Test Resource Management Center (TRMC) Test and Evaluation/Science & Technology (T&E/S&T) Program. This project is funded by the T&E/S&T Program through the U.S. Army Program Executive Office for Simulation, Training and Instrumentation (PEO STRI) under contract number W900KK-12-C-0053.

DISCLAIMER

Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the TRMC T&E/S&T Program and/or PEO STRI.

REFERENCES

[1] S.L. Holt, E. Cordero, J. Mankowski, J.C. Dickens, J.C., A.A. Neuber, S. Calico, M. Scott, "A Battery Powered 80 kVA Capacitor Charger," Proc. 2012 IEEE Int. Power Modulator and High Voltage Conf., Santa Fe NM, June 2014, To be published.

[2] S.L. Holt, M.A. Elsayed, B. Gaston, J.C. Dickens, A.A. Neuber, M. Kristiansen, "Rapid charging seed source with integrated fire set for flux compression generator applications," Power Modulator and High Voltage Conference (IPMHVC), 2010 IEEE Int., pp.133,136, 23-27 May 2010.

[3] S.L. Holt, J.C. Dickens, J.L. McKinney, M. Kristiansen, "A compact 5kV battery-capacitor seed source with rapid capacitor charger," Pulsed Power Conference, 2009. PPC '09. IEEE, vol., no., pp.897-901, June 28 2009-July 2 2009.

[4] S. Moore and P. Schneider, "A Review of Cell Equalization Method for Lithium Ion and Lithium Polymer Battery Systems", Sae Technical Paper Series, 5-8 March 2001.