Design of a Battery Intermediate Storage System for Rep-Rated Pulsed Power Loads

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***Abstract*—The U.S. Naval Research Laboratory (NRL) is developing a battery-powered, rep-rate charger for a 60-kJ capacitor bank. The capacitor will be charged with a bank of LiFePO4 batteries in conjunction with a DC-DC converter. During discharge, the batteries will generate heat from the internal resistance. If the heat is not addressed, damage to the cell may occur, leading to degraded cell lifetime and the potential for cell venting. NRL has developed an integrated cooling system for high power batteries that can limit the residual heat in the battery cells. Results from experiments will be presented, both at the cell and the module level.**

I. INTRODUCTION

The development of compact, portable pulsed power is of continuing interest at NRL, and recent technological developments such as 3.0 J/cc capacitors, the emergence of SiC high-power devices, and the availability of high power density electrochemical storage present an opportunity to apply these technologies to applications of interest to the Navy. Several challenges exist when attempting to integrate these emerging devices into the development of a compact rep-rated pulsed power system. These include but are not limited to the input power management, DC-DC converter efficiencies, and thermal management.

The Naval Research Laboratory is developing a rapid charger for a 60-kJ capacitor bank capable of charging a 4800-μF capacitor to 5-kV in roughly five seconds. This system needs to be rep-rated at 10 times a minute for five minutes, or 50 total shots. The system needs to be portable and self-sustaining; therefore it will not be able to use typical wall power. High power electrochemical cells will be used as the prime power source and emerging technologies such as LiFePO4 enable this level of performance to be achieved. As the US Navy transitions to a more electric fleet, Next Generation Integrated Power System (NGIPS), electrochemical prime power sources like the one being developed here will be needed to help source the intermediate storage of high pulsed power loads.

The design of a high-power battery module is not trivial, as advanced cell chemistries require active management to prevent overcharging, under-volting, over-discharge, and thermal damage. While the electrical conditions can be managed with a COTS Battery Management System (BMS), the thermal management of the battery cells in a module needs to be engineered to specifically address the application of the battery pack. This paper will discuss the design of the NRL battery module and testing that was performed to characterize and optimize the operation of the module.

II. BATTERY MODULE DESIGN

A battery module prototype was constructed to determine the engineering challenges to be faced in the assembly of a sixteen-cell pack. The module is of the same form factor and contains identical components to those used in the planned full-scale system. In the full system design, twelve 51.2V battery modules will be connected in series via high current relays to provide the approximately 600V necessary for the DC-DC converter to charge the capacitor to 5-kV.

As shown in Figure. 1, the NRL 52.1 V battery module is comprised of 16, 3.2V (nominal) K2 Energy LFP26650 LiFePO4 cells connected in series [1]. Each cell has a capacity of roughly 2.6Ah, has an approximate internal resistance of 9mΩ, and a mass of roughly 80 g.

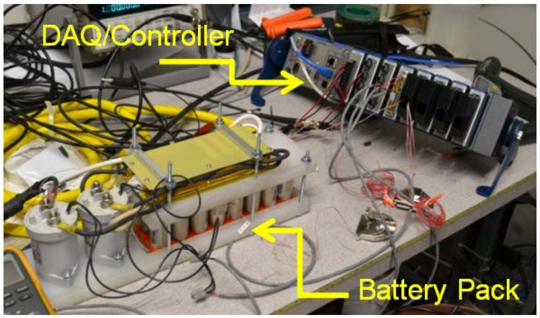

Figure 1: Assembled Battery Module with Data Acqusition (DAQ) Hardware

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14. ABSTRACT

The U.S. Naval Research Laboratory (NRL) is developing a battery-powered, rep-rate charger for a 60-kJ capacitor bank. The capacitor will be charged with a bank of LiFePO4 batteries in conjunction with a DC-DC converter. During discharge, the batteries will generate heat from the internal resistance. If the heat is not addressed, damage to the cell may occur, leading to degraded cell lifetime and the potential for cell venting. NRL has developed an integrated cooling system for high power batteries that can limit the residual heat in the battery cells. Results from experiments will be presented, both at the cell and the module level.

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For this application, instead of a continuous string of batteries the cells were split into two strings of eight batteries apiece, with a bridge link between the two strings. This enabled the design to be very compact, as the width of the two strings is very close to the width of the DC relays. The two parallel strings of battery cells also enables a single cold plate to be used.

Located above the batteries is the Battery Management System (BMS) which is needed to ensure proper and safe operation during both discharge and recharging procedures. For this application, PCM-L16S40-346 BMS from AA Portable Power Corp. was chosen. The BMS provides multiple levels of protection, such as over-charge protection, over-discharge protection, cell balancing, and low cell voltage shutoff protection. All of the BMS operations are passive with no user interaction.

One high-current, high voltage relay is used to connect each terminal of the module in series with the other modules adjacent to it. While the minimum requirements fort this application are 40 A and 600 V; the closest available design is rated at 500 A and 900 V. A separate relay is used to connect each module to a battery recharger. Even when it is disconnected, the recharger relay will see the full erected bank voltage, requiring it to have the same high voltage requirements. The one chosen to accomplish these needs was the Tyco LEV-200.

For benchtop testing, a dummy load has been constructed and is being used as a current sink to test the battery module performance. Six 1.6 Ω Ohmite PFE5K1R60E resistors were connected in three parallel pairs for an equivalent resistance of roughly 1.5 Ω. The design assumed a maximum of 3-kW of dissipation would be needed during discharge testing. The results of the benchtop testing will be presented in the next section.

III. INITIAL BATTERY MODULE TESTING

An iterative process was used develop a battery module that performed satisfactorily. Discharge testing into the dummy load was performed to simulate the pulsed nature of the capacitive load. The output relay was energized for four seconds, de-energized for two seconds, and then repeated for 40 total cycles. Thermocouples were attached to the cells at various points and used in the control software to stop cycling if any of the thermocouples reached 55°C, 5 degress below the recommended 60°C thermal limit of the K2 cells [1]. A full analysis of design performance is discussed in [2]. A diagram of the cell numbering system is shown in Figure 2. This system is used for all of the tests peformed.

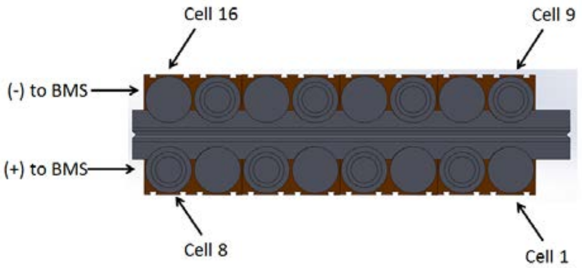

Figure 2: Cell Numbering System in Battery Module

A. Initial Module Design Test

The first design consisted of battery cells that relied exclusively on ambient air flow for any necessary cooling. All of the cells had their cases exposed without any tape or thermal material applied. As shown in Figure 3, the module was unable to reach the desired number of cycles, falling short by 58 seconds. This test shows conclusively that some sort of active cooling is necessary to enable full operation of the battery module.

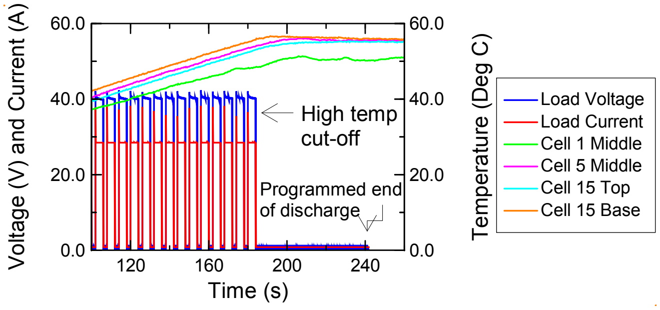

Figure 3: Uncooled battery module discharge measurements

B. COTS Cold Plate Modification Test

A second battery module was constructed which was designed specifically to include a Lytron C-CP10G19 cold plate between the two strings of battery cells. As shown in Figure 4, this design is less than optimal, but was built with COTS parts. The water lines were connected to a Miller Coolmate 4 water cooler, which is capable of removing 5-kW of heat energy.

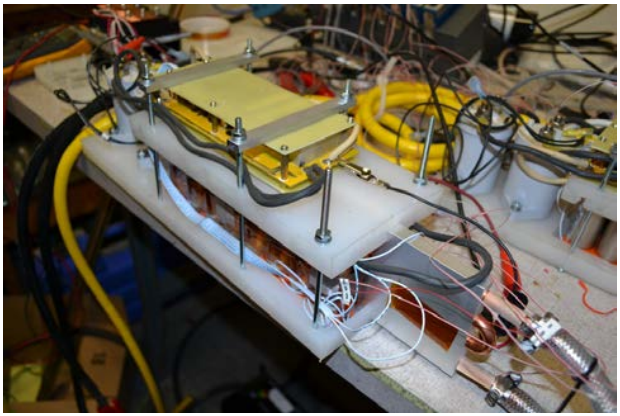

Figure 4: NRL cooled battery module with COTS cold plate

The second module was then subjected to the same discharge procedure discussed earlier, shown in Figure 5. It is worth noting that the thermocouples were placed in approximately the same position as they were in the previous test. The addition of the cold plate enabled several more cycles, but the system still shut down roughly 22 seconds prior to the desired time.

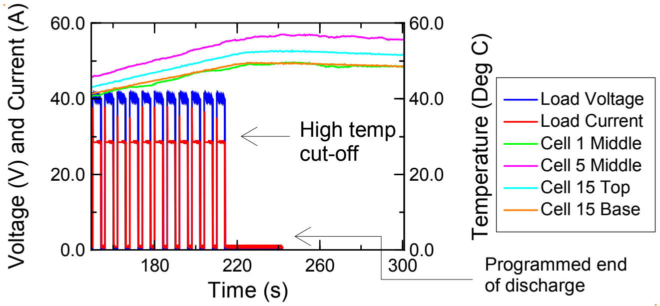

Figure 5: Results of cooled battery module with COTS cold plate

C. NRL Custom Cold Plate Test

The battery module test with the COTS cold plate demonstrated that the cold plate does have a measurable effect on the case temperatures of the battery cells. In that design, the curved surface of the cells is only in contact with the cold plate on a tangent line, in addition to the thermal barrier created by the use of Kapton tape which is used for voltage isolation. To address this issue, a custom cold plate was designed by NRL and manufactured by Thermavant Technologies.

As shown in Figure 6, the NRL two-pass cold plate is constructed of aluminum and has cuts specifically design to fit the 26650 form factor. Instead of a tangent, there is now a significant amount of surface area in contact with the cold plate.

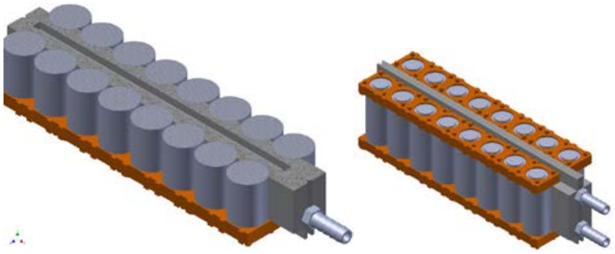

Figure 6: NRL optimized cold plate design

A 0.005” layer of Boron Nitride (BN) was applied to the surface of the aluminum cold plate to increase the thermal conductivity and reduce electrical conduction. BN is an ideal surface coating materials, as it has very high thermal conductivity (0.08 cal/(cm-sec-K)), high dielectric strength (≈1000 V/mil), and is completely inorganic and inert [3]. The water-based Zyp BN spray [4] is a hard coat that is difficult to scratch, unlike the aerosol application, and provides a slightly rough finish.

In place of the Kapton tape, The Bergquist Company’s Gap Pad 5000S35 material is used. The 5000S35 material is essentially a structured thermal interface compound, with a fiberglass reinforcement to conform to contoured surfaces and prevents rips or tears in the material. 5000S35 features a very high thermal conductivity (5.0 W/m·K) and very high dielectric strength (5000 V/mil) [5]. The gap pad material is able to fill in the gaps in the BN coating as well as eliminate air pockets in the interface to the battery cell. An additional thermal mass was added, in the form of aluminum side braces that are used to press the cells into the thermal interface material and the cold plate.

The assembled battery module with the enhancements was tested under the original 40-shot conditions, and was able to successfully discharge all 40 shots without a thermal cut-off. To test the limits of the module, the experiment was expanded to the full 50-shot design, and the results are shown in Figure 7. Though closer, 49 shots were achieved as only 1.52 Ah was able to be extracted during the experiment before a lower voltage cutoff was engaged.

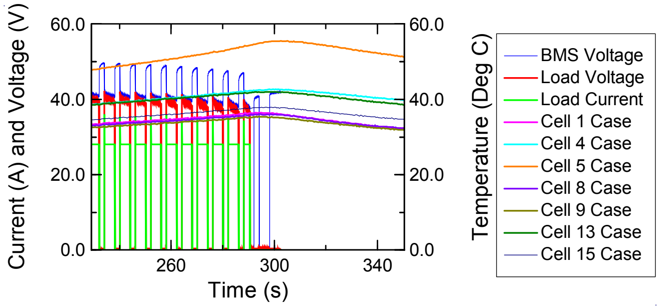

Figure 7: Cooled battery module discharge measurements with NRL cold plate

All of the cell cases monitored with thermocouples stayed well below the 55°C limit with one exception, and the temperatures were just above 40°C. The outlier is Cell 5, and while it did stay below the thermal limit during discharge, it was significantly higher than the other measurements during the test. Further investigation is necessary, but it is most likely that the cell has an abnormally high internal resistance resulting in additional heat accumulating in the cell.

As shown in Figure 7, the 49th cycle is shorter than normal. This is due to the BMS low-voltage cut-off engaging, indicating that one cell or more was in danger of being permanently damaged. The cause of the cut-off is being investigated, but it is most likely the result of unmatched cell capacities connected in series. The results show that the evolution of the battery pack enabled the development of a pack that is robust, reliable, safe, and more thermally efficient.

IV. BATTERY CELL CHARACTERIZATION

While cooling performance was drastically improved with the NRL cold plate design, it appears currently that the performance of the individual cells is limiting the operation of the battery module. As shown in Figure 7, the thermocouple on Cell 5 is reading significantly higher than the other cells. Hardware has been procured that will enable each individual cells’ 1C capacity and equivalent series resistance (ESR) to be characterized prior to being used in a pack. This will enable the maximum capacity to be extracted and distribute the heat losses uniformly in each cell.

Computerized Battery Analyzers (CBAs) were purchased from West Mountain Radio to evaluate the capacity, voltage, and temperature performance of all of the cells [6]. Eleven units were purchased, and the software will support up to 12 simultaneous tests. As shown in Figure 10, a battery pack structure was also constructed to enable rapid removal and installation of cells to be tested and recharged as a 16-cell unit. A single CBA as configured will support up to 150W of continous discharge from the pack, ideal for a 1C or less discharge of the pack for conditioning.

Figure 8: CBA units and rapid-deployment battery module

Sixteen K2 cells were tested in the CBA array. It was observed through testing that the batteries need to be conditioned before use, therefore each cell is being discharged at the 1C rate until it is discharged to 2V. Once the cells are recharged, each was tested with a CBA and discharged at 30A until the cell voltage reached 2V, as shown in Figure 9. Among the random cells selected for the test shown, there is a 0.15 V variation from the mean during discharge. Of particular concern are cells such as 122248, 122260, and 123080, where the voltage is not constant. It is likely these cells have internal resistance problems which may be corrected as the cell is cycled. All of the cells showed greater than 90% of the rated capacity during the discharge test after the 1C discharge and recharge .

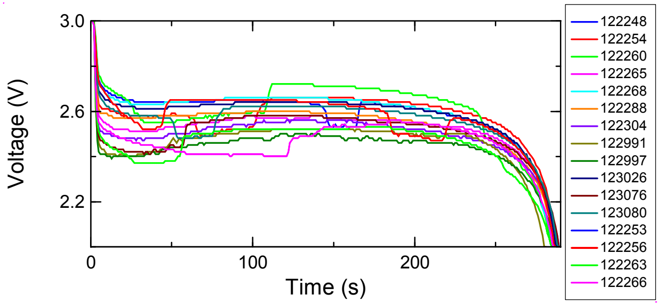

Figure 9: Cell voltages during 30A discharge into CBA array

The temperatures of the cells tested at 30A are shown in Figure 10. The thermocouples on two of the cells appear to have malfunctioned during a portion of the test; nevertheless they recovered during the second half of the discharge. The initial hypothesis was that the cells with the lowest voltages would have the highest temperatures, however that is not true. There is no obvious connection between cell voltages and the recorded temperature during high current discharge. A new battery pack was constructed using the cells with the lowest temperature data. Using the data shown in Figure 10, cells 122265 and 122266 were eliminated from consideration. Two cells from another test series which had low terminal temperatures were used in their place.

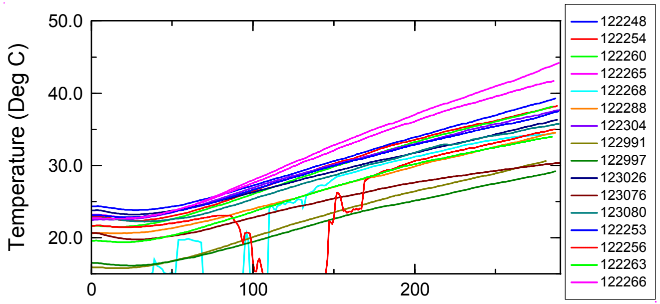

Figure 10: Cell temperatures during 30A discharge into CBA array

The newly constructed battery pack was tested under the same conditions as those used in Figure 7. As shown in Figure 11, the measured temperatures were all below 47°C when a BMS shutdown occurred. Unfortunately, the battery module was unable to complete the full 50 cycles, cutting off during the 45th cycle. Using the recorded current data, the battery pack discharged 1.41 Ah, which is well below the expected maximum of 2.6AH. It appears that even when preconditioning the cells, a capacity issue exists.

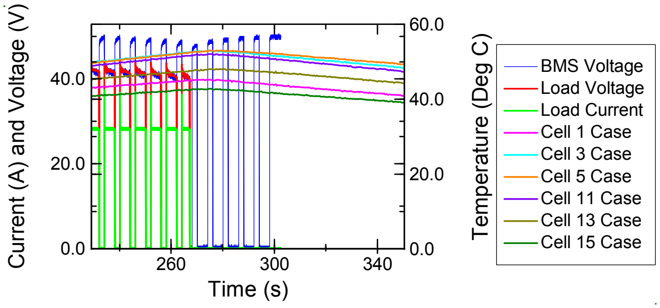

Figure 11: Test results from pre-qualified cells in a new battery pack

Since the previous test did not perform as expected, a final experiment was performed with the previously constructed battery pack shown in Figure 7. The pack was discharged at 2A and recharged four times to recondition the cells. After each recharge cycle, the maximum capacity was increased. The final cycle at 1C into the CBA showed 1.8 Ah of capacity, or 69% of theoretical maximum. The pack was recharged and discharged at 30A for 50 cycles, as previously discussed, and the recorded data is shown in Figure 12.

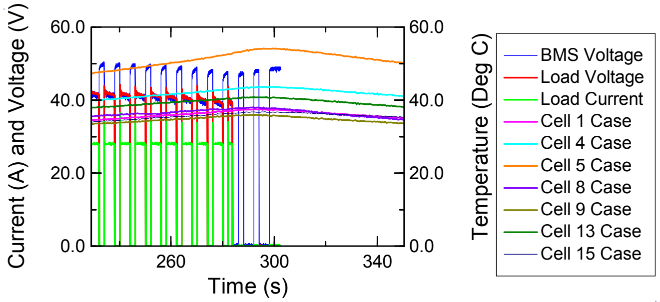

Figure 12: Test results from reconditioned battery pack

Surprisingly, the data indicates that conditioning of the pack resulted in a worse performance than previously shown. The measured energy discharged during this test was 1.49 Ah, less than the 1.52 Ah measured previously. The BMS cutoff was initiated during the 48th cycle instead of the 49th, indicating one or more cells reached a low voltage state earlier than previously shown. To address this issue, further testing will involve direct cell voltage measurements to isolate which cells are causing the BMS fault.

V. CONCLUSION

The Naval Research Laboratory has successfully designed and constructed a cooled battery pack capable of operating well below the maximum thermal limits of the K2 LFP26650 $LiFePO_4$ cells. Integrated cooling and the removal of thermal potential barriers is the key, as shown by testing of a variety of battery modules. While the thermal issue has been overcome, the capacity of the battery pack and balancing of the cells is an obstacle to full 50 shot operation of the pack.

The data indicates that selection of cells prior to pack construction is critical, as the K2 LFP26650 cells show variability in construction. It appears the majority of cells will operate within the datasheet parameters, but about 10% of the cells will have temperature anomalies. Filtering of these cells by the use of Computerized Battery Analyzers can ensure a battery pack with even thermal characteristics. As shown, however, preconditioning cells prior to pack installation does not appear to positively affect discharge performance. More testing is required to develop methodologies to ensure high quality battery pack construction.

Future work on this system will focus on the interaction between the BMS and the cells, as well as determining the actual amount of energy deposited into the pack during the recharge sequence. A pack will be tested on a MACCOR test unit at the University of Texas – Arlington to perform life cycle testing, and it is anticipated this testing will shed more light on the performance of these cells.

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