Lithium Ion Battery / Lithium Ion Capacitor Hybrid Portable Energy Storage Device for Pulsed Power Applications

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***Abstract* — a portable hybrid power system is presented that utilizes a lithium ion battery and lithium ion capacitor in a single solution. Integration is carried out through the use of a hybrid power management circuit board. The electronics allow for the system to act as both a portable power source and portable energy harvester. The hybrid system directly addresses pulse power applications characterized by peak power support where battery only solutions have exhibited reduced performance. Hybrid testing comparing battery and hybrid approaches have shown significant benefit when utilizing the hybridized system under pulsed power conditions.**

Keywords—hybrid, power, energy, conversion, lithium ion, battery, capacitor, bidirectional, feedback, controller, pulsed, sourcing, harvesting, benefit

I. Introduction

Pulsed power applications are defined by short durations at a peak power followed by long durations at a low power draw. Fig. 1 shows a typical repetitive pulsed power profile. An example of a pulsed profile that sources power is wireless radio communications, where transmissions require peak power support and channel monitoring requires a nominal low power draw. An example of a pulsed power application that sources power is wave energy harvesting, where a linear generator uses displacement to generate power. Peak power occurs at maximum displacement in the generator and nominal power draw occurs near minimum displacement. The peak power regions of a pulsed profile can be characterized as the power dense intervals of the profile, whereas the low power draw intervals may be described as the energy dense portions of the profile. Therefore, a pulsed power profile can be described as both an energy dense and power dense load, requiring an equally power dense and energy dense source for support.

Existing established power source solutions suffer from limitations when attempting to support pulsed power profiles. Typically, for portable electronic systems, the electrochemical battery is chosen as the energy storage device. Generally, batteries boast high energy density but possess relatively low power density. In applications whose profiles consist of a constant low power draw, batteries are the ideal solution because their high energy density allows them to support such profiles for long durations. In contrast, battery performance deteriorates when implemented in a system seeking to support pulsed power loads. Increasing peak power requirements necessitate additional battery packs to meet them. For relatively low power levels this is a suitable solution. However as the peak levels continue to increase, even more additional battery packs are required.

Additional battery packs quickly pose logistics issues, especially in the case of portable applications. There is an inherent increase in cost to maintain sufficient stock and storage of the additional battery packs, and this issue is exacerbated where non-rechargeable primary chemistries are used. Further, the size of the power source used to support the pulsed loads increases in both volume and weight. Each of these are fundamentally detrimental to portable type applications. Also, though the addition of battery packs is in response to the need to support peak power levels, significant additional energy is added to the system. This additional energy may be unnecessary and may stand to be wasted depending on the application parameters. An ideal power source for portable pulsed power applications is one that is both energy dense and power dense so as to meet the demands of the profile without over designing for power or energy. One such solution is a hybrid design that combines an energy dense device with a power dense device.

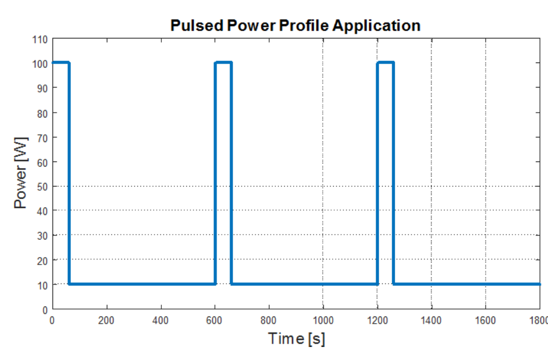

Fig 1: Pulsed Power Profile

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II. Hybrid Power System Design

An approach to a hybrid system design utilizes power electronics to integrate an energy device and a power device into a single power solution. A lithium ion battery (LiB) is used as the energy dense device in the system, and a lithium ion capacitor (LiC) is used as the power dense device in the system. At present, LiBs feature energy densities reaching towards 300 Wh/kg, while LiCs have been shown to produce power densities in the vicinity of 4000 W/kg. A solution that integrates both a LiB and LiC through electronics without significant weight serves to outperform a battery-only or super-capacitor only system to support a pulsed power application.

The basic principle of hybrid operation is to utilize the lithium ion capacitor when the load demands peak power levels, as the LiC is better suited to support these needs. The lithium ion battery is primarily used to support the baseline low power draw of the load. During these periods, the LiB also uses a portion of its power capability to direct energy to the LiC and fully recharge it in preparation for future peak pulse occurrences. In principle, the same amount of energy is moved between the power source and the load, but the hybrid allows the shape of the energy or power seen by each device to be manipulated to levels more favorable for each device's operation. This is an important concept, as the actual quantity of energy expended at the power source to do so differs for each approach.

A. Hybrid Power Management Circuit Board

To perform the hybridization through use of electronics, a circuit board was designed referred to as the hybrid power management circuit board. The circuit board features power electronics, signal conditioning circuitry, and an embedded processor. Fig. 2 shows the hybrid power management circuit board with the lithium ion capacitor mounted to the underside. The system is designed to conform to the BA5590, BA5790, BB2590, etc format such that the final power solution may be directly substituted with existing battery systems to operate with existing power equipment.

The power electronics feature a set of power switches that are strategically placed to route power through the system appropriately while also maintaining the ability to isolate the energy device, power device, and external equipment separately. The voltage of the main hybrid bus is held up by the battery voltage, which is nominally 12.5V. Since the nominal LiC voltage is 3.0V, a DC/DC converter is utilized to allow the LiC to participate in the system response. The converter boosts or bucks the voltage depending on the direction of energy flow. The signal conditioning circuitry allows for system measurements of voltages and currents of the energy and power devices as well as conditions present at the interface connecting to the external load. Temperature measurements are also available in the system for monitoring thermal conditions present. The embedded processor allows for complex functionality to be built into the hybrid system. The processor executes the advanced hybrid algorithm and the feedback controller, which facilitate power flow and regulation in the hybrid system.

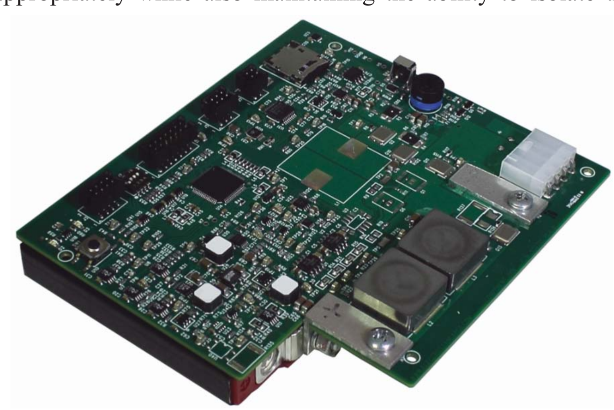

Fig 2: Hybrid Power Management Board with LiC Mounted

B. Hybrid System Overview

The diagram in Fig. 3 displays the interconnections and relationships between the critical components of the hybrid power system. It is worth noting that the design of the hybrid power management circuit board does not restrict the selection of the power and energy devices. The system is customizable such that many different devices may be used. For example, a power dense battery and an energy dense battery may be used. Alternatively, a two-capacitor system may also be implemented. The external sink/source device is dependent on the particular application.

The hybrid bus is identified as the node in the hybrid circuit where the lithium ion battery and lithium ion capacitor branches join. The hybrid interface is defined as the point in the hybrid circuit where the output of the hybrid system interacts with the external sink or source. The hybrid bus is routed through the power electronics to the hybrid interface under standard operation. The hybrid interface is a critical point of interest in the circuit and a key component in driving the advanced hybrid algorithm. As mentioned previously the system measurements read in currents and voltages throughout the circuit including those of the LiB, LiC, and at the hybrid interface. Power electronics are located between the hybrid bus and hybrid interface and between the hybrid bus and lithium ion capacitor. The power electronics between the interface and bus include circuitry operated by the embedded processors peripheral control. The circuitry is manipulated to direct the flow of power through the interface appropriately depending on the conditions present. The hybrid may be configured to

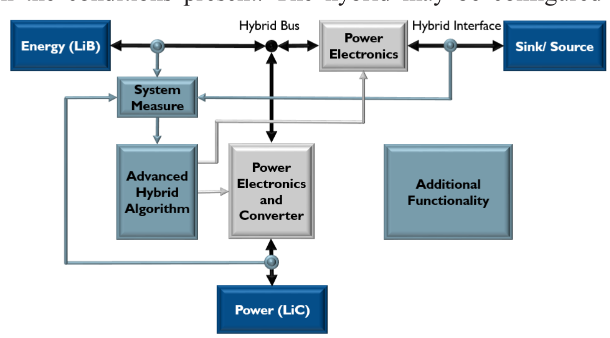

Fig 3: Hybrid Power System Overview

facilitate the flow of power between any of the elements of the system. This creates a flexible portable power source or energy harvester capable of supporting a wide variety of applications.

III. Advanced Hybrid Algorithm

A. Principles of Hybrid Operation

The advanced hybrid algorithm works to control the flow of power throughout the hybrid system in order to regulate the operation of the battery in the system. Regulation of the battery operating conditions is critical to achieving superior performance over battery-only power source systems. In a battery-only system, the battery is directly coupled to the external sink or source. Therefore, the load dictates the conditions placed on the battery which for a high-power load deteriorates battery performance and reduces realizable energy delivery. It is known that battery performance, in terms of capacity delivered, decreases in response to increasing load demand. To improve performance, the battery must be operated in its region of high efficiency as much as possible. Otherwise, its full energy potential may not be realized. These effects are in part due to battery cell power limitations. Power delivery is ultimately limited by the battery's impedance. The impedance acts to reduce the battery voltage as load demands increase. For safety purposes, batteries have defined cutoff voltages above which normal behavior can be expected. At the cutoff voltage, the battery's capacity for supplying energy is considered depleted. Under peak load conditions, the current in the battery increases, forcing a larger and larger drop in voltage such that the cutoff may be triggered prematurely. Any remaining energy in the battery cannot be delivered due to its power limitation

Fig. 4 contains a plot that illustrates this concept more clearly. The plot contains a mapping of a LiCFxMnO2 cell battery operating efficiency as a function of ambient temperature and discharge current. The mapping was created using data obtained through cell characterization testing. Regions outside of the mapping may be considered to have zero percent efficiency as they reside outside of the battery's prescribed operating range. The cold colored regions suggest low efficiency, while the warm colored regions suggest higher efficiency. To promote efficient operation, the battery should be operated in the warmer regions as much as possible. As mentioned before, in a battery-only power source, the load dictates the conditions on the battery. In the hybrid approach, the conditions on the battery are able to be maintained within the regions of efficiency improving performance. The hybridized solution eliminates the effects of battery power limitation by decoupling the battery from the load and utilizing the LiC, as it is better suited to support peak pulse levels. To regulate battery operation while managing power flow into and out of the hybrid system, an algorithm was developed and executed by the system's embedded processor.

B. Algorithm Development

The advanced hybrid algorithm works to regulate battery operation while managing power throughout the system described in Fig. 3. The algorithm structure is shown in Fig. 5. The system measurements module comprised of

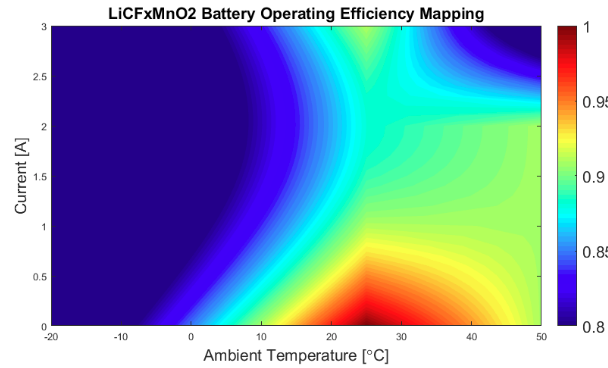

Fig. 4: Battery Capacity Efficiency Mapping

voltages, currents, and temperatures of the battery, capacitor, and hybrid interface are inputs to the algorithm. The management structure module includes dedicated software components for the energy, power, and hardware aspects of the system. The energy management system houses information pertinent to the energy dense device of the system. Since the hybrid design presented here uses the lithium ion battery as the energy dense device, the management structure monitors the health and state of the lithium ion battery and ensures the battery is operating within its limitations. The power management system monitors the health and state of the lithium ion capacitor and ensures it is operating within its limitations. The hardware management system works to monitor key points in the power electronics circuitry to ensure the conditions present are within the limitations of the design.

The condition detection and evaluation component of the algorithm is critical for determining the operating mode of the system and the regulation of the battery within its operating envelope. The hybrid system is able to operate as either a portable power source, portable energy harvester, or in an idle mode. The mode is determined by detecting and processing the conditions present at the point of the hybrid interface described in Fig. 3. In addition to the mode, the conditions present are evaluated against the battery operating envelope to determine if battery regulation is required. The battery operating enveloped is defined by the zero point and max efficient discharge rate for a primary chemistry type cell and by a max efficient charge rate and max efficient discharge rate for a secondary type chemistry. The charge bounds and discharge bounds are based on cell characterization data such as the set shown in Fig. 4. The envelope should be chosen to maintain the battery within its regions of efficiency.

The management system information as well as the mode and condition evaluation provides input to the hybrid state decision machine. The sequence of inputs provide information that determines which one of the defined system states in which the hybrid should operate. The set of states is based on the storage devices and power flow present in the system. The system state provides input to the hardware configuration and command generator. The hardware configuration sets the power electronics in the particular manner as associated with the present hybrid state of the system. The power electronics

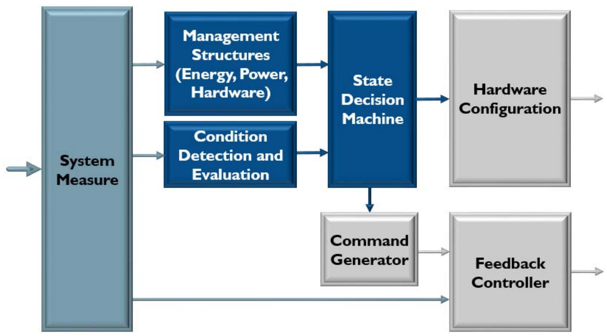

Fig. 5: ESL Advanced Hybrid Algorithm

route the power flow appropriately to support the requirements present at the hybrid interface. The command generator processes the hybrid state and determines where in the defined operating envelope the battery should be regulated. The command generator provides the reference point for the feedback controller. The hybrid controller takes as input the envelope command reference and the feedback measurement. The feedback controller produces a command for controlling the power electronics in a manner that carries out the controller regulation.

C. *Algorithm Evaluation*

The algorithm is designed to allow for bidirectional power flow through the system. For the hybrid as a portable power source, the lithium ion capacitor acts to support the peak power requirements of the load allowing the battery operating point to remain in an efficient region. For the hybrid as a portable energy harvester, the peak power pulses enter the hybrid through the interface are absorbed by the lithium ion capacitor while the controller regulates the battery to operate within an efficient range. The capacitor acts to level the incoming pulses initially then pass the energy absorbed to the battery at power levels within the battery envelope. As previously mentioned, in each of these cases, a battery only approach would be unable to handle pulses outside of the battery specifications, while the hybrid system is able to do so. Adding additional battery packs to the battery-only approach would improve the power support capability however the cost, weight, and volume of the solution would continue to increase as peak requirements increase. Conversely, the hybrid solution is capable of supporting these peak pulses with an advantage in cost, weight, and volume. The algorithm developed demonstrates the pulse support capabilities, battery regulation, and power flow routing of the hybrid system.

Pulsed discharge testing was conducted to verify the advanced hybrid algorithm's ability to operate the hybrid as a source. The pulsed discharge profile consisted of the an Arbin cycler sinking a 1 minute -2A pulse followed by a 6 minute -0.5A draw period. The test was designed to allow the hybrid to enter a discharge state that utilized both the LiC and the LiB to support the pulsed load demand. The controller was programmed to regulate the battery current to -1A such that the remaining power would be provided by the LiC. During the low power draw the hybrid enters a state in which the battery supports both the load and the recharge of the LiC in preparation of future peak pulses. The power management algorithm maintains the battery within its optimal discharging current range by utilizing the LiC to supply outgoing pulsed power. Fig. 4 shows results from this testing. The behavior of the hybrid system during this test can be characterized by three distinct regions. In region 1, the load demands -2A, which is greater in magnitude than the LiB's -1A regulation point. The LiC provides the remaining -1A to the load. This is shown in that the LiB and LiC voltages both steadily decrease as they provide energy to the load. In region 2, the load demands -0.5A. Since the LiC is below its charge limit, and the load draw is lower than the LiB's regulation point, the LiB provides energy to both handle the load and recharge the LiC. This is shown in that the LiB voltage steadily decreases and the LiC voltage steadily increases. In region 3, the load is still demanding -0.5A, but the LiC has reached its charge limit, as shown by its voltage remaining constant. The LiC disconnects from the system, directly coupling the LiB to the load. The LiB provides -0.5A to the load. Note that the LiB current magnitude is always maintained within its commanded regulation point.

Pulsed charge testing utilizes the addition of bidirectional power flow capability. To demonstrate this mode of operation a pulsed charge test consisted of a 1 minute 2A pulse followed by a 6 minute 0.5A pull period. The test was designed to allow the hybrid to enter a charge state that utilized both the LiC and LiB to harvest the incoming peak pulse from the Arbin. The controller was programmed to regulate the battery current to 1A such that the remaining power would be absorbed by the super capacitor. During the low power pull portion, the hybrid enters a state in which the battery receives energy from both the external source and the LiC in order to drain the LiC in preparation of future incoming peak pulses. The power management algorithm maintains the battery within its optimal charging current range by utilizing the LiC to absorb incoming pulsed power. Fig. 5 shows results from this testing. The behavior of the hybrid system during this test can be characterized by three distinct regions. In region 1, the load provides 2A, which is greater than the LiB's 1A regulation point. The LiC absorbs the remaining 1A from the load. This is shown in that the LiB and LiC voltages both

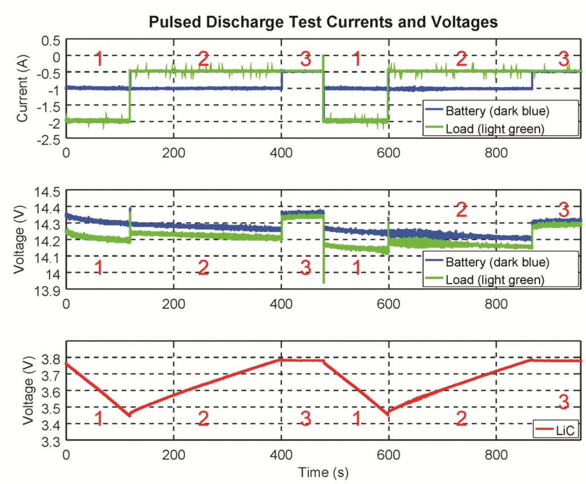

Fig. 6: Algorithm Evaluation Pulsed Discharge Testing

steadily increase as they absorb energy from the load. In region 2, the load provides 0.5A. Since the LiC is above its discharge limit, and the current provided by the load is lower than the LiB's regulation point, the LiB absorbs energy from both the load and the LiC. This is shown in that the LiB voltage steadily increases and the LiC voltage steadily decreases. In region 3, the load is still providing 0.5A but the LiC has reached its discharge limit, as shown by its voltage remaining constant. The LiC disconnects from the system, directly coupling the LiB to the load. The LiB absorbs 0.5A from the load. Note that the LiB current is always maintained within its commanded regulation point.

To evaluate the advanced hybrid algorithm for continuous bidirectional operation, the pulsed discharge and pulsed charge test conditions were combined to create an alternating profile. The profile forces the algorithm to actively and correctly determine the appropriate operating state and configure the hardware properly. The discharge and charge conditions followed the same levels and time durations as described in the previous sections in the following order: low draw discharge, pulsed discharge, pulsed charge, low pull charge. This testing demonstrates the ability of the hybrid system to both source and harvest energy. The power management algorithm maintains the battery within its optimal charging and discharging current range creating an operating envelope by utilizing the LiC to absorb and source pulsed power from the load. Fig. 6 shows results from this testing. The behavior of the hybrid system during this test can be characterized by four distinct regions. In region 1, the load demands -0.5A. Like in the pulsed discharge test, the LiB provides its regulation point current of -1A which both supports the load and recharges the LiC. In region 2, the load demands -2A. Like in the pulsed discharge test, the LiB provides -1A and the capacitor makes up the remaining -1A to support the load. In region 3, the load provides 2A. Like in the pulsed charge test, the LiB absorbs 1A and the capacitor absorbs the remaining 1A. In region 4, the load provides 0.5A. Like in the pulsed charge test, the LiB absorbs 0.5A from the load and 0.5A from the discharging LiC. Note how during the test the LiB is always within its regulation point of 1A magnitude.

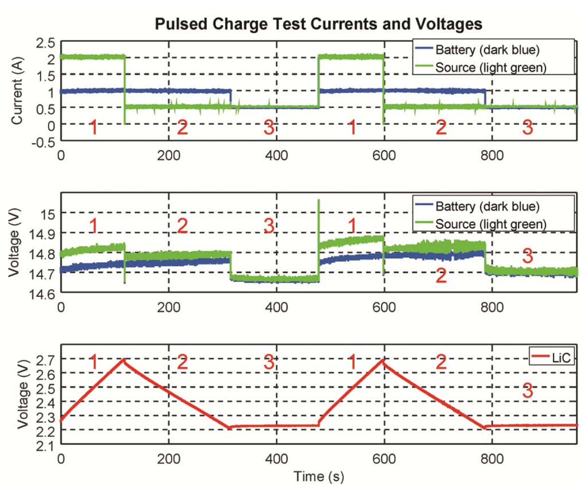

Fig. 7: Algorithm Evaluation Pulsed Charge Testing

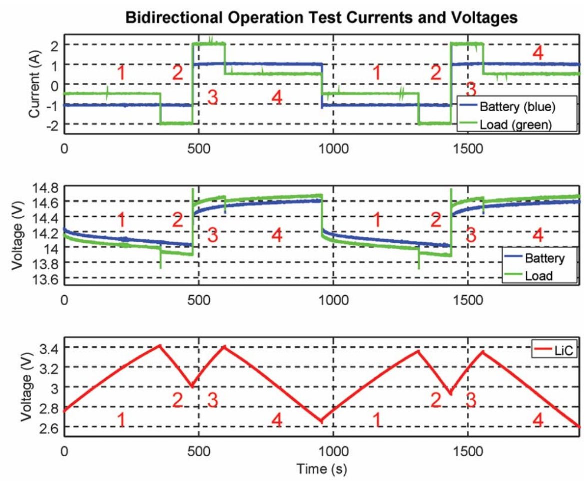

Fig. 8: Algorithm Evaluation Bidirectional Operation Testing

An additional condition was tested to evaluate an operating state that allows for continued automated operation for unknown or unpredictable conditions at the hybrid interface. In this scenario a constant load greater than the battery operating point is continuously applied to the hybrid system. Given the conditions the LiC will eventually run out of charge to support the power requirements above the battery threshold. This forces the hybrid to periodically disconnect from the load and recharge the LiC internally before reconnecting to the load to continue operation. The mode eliminates need for user input and allows for tuning to minimize system downtime. Hybrid overloaded charge not shown here is the dual of this operating state. Fig. 7 shows results from this testing. The behavior of the hybrid system during this test can be characterized by two distinct regions. In region 1, the load demands -2A, which is greater in magnitude than the LiB's -1A regulation point. Since the LiC is above its discharge limit, it provides the remaining -1A to the load. This is shown in that the both LiB and LiC voltages steadily decrease as they provide energy to the load. In region 2, the load still demands -2A, but the LiC has reached its discharge limit. Since the load is demanding a higher magnitude current than the LiB's regulation point, and

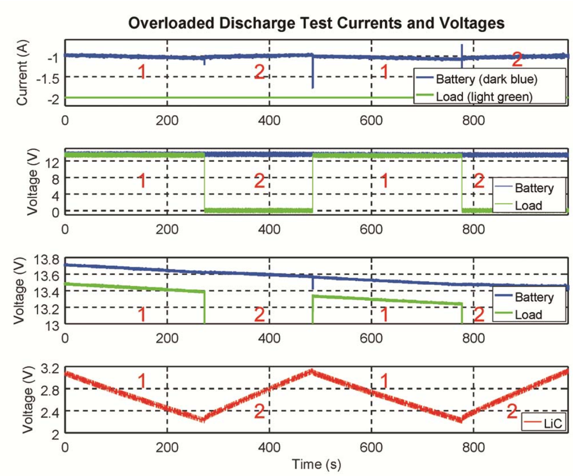

Fig. 9: Algorithm Evaluation Overloaded Discharge Testing

the LiC can discharge no further, the hybrid system disconnects from the load. During this time, the LiB provides -1A to charge the LiC. This is shown by the LiB voltage decreasing as the LiC voltage is increasing. Once the LiC absorbs a significant amount of power for the application, the load is reconnected and the system provides power from the LiB and LiC to the load as in region 1. Note that during this test, the LiB current is always -1A.

IV. Hybrid System Testing

Algorithm evaluations verified proper operation of the hybrid algorithm and controller. Successful evaluations prompted full testing of power source systems to demonstrate benefit in hybridization. To do so testing focused on benefit obtained through hybridization of primary chemistry type batteries and secondary chemistry type batteries. Primary type batteries are single use and so benefit is shown over a single discharge cycle. Secondary type cells are rechargeable over many cycles and so benefit may be cumulative over the lifetime of the cells. The following testing demonstrates the benefits seen through hybridization.

A. Primary Chemistry Hybrid Testing

Primary chemistry testing was carried out using high energy LiCFxMnO2 chemistry cells. The cells operate nominally at 3.0V with capacity of 16Ah. The maximum current of each cell per manufacturer specification is 3.0A. The cells were tested under battery approach and hybrid approach for several configurations at cold, room, and warm temperatures.

The data present in Fig 10 shows the comparison between a battery approach utilizing a five series three parallel configuration of the LiCFxMnO2 cells and a hybrid approach composed of a five series two parallel configuration. The test was conducted at -20C ambient temperature through use of a temperature chamber. The hybrid system in primary cell testing, used the first revision of the hybrid power management board which supported unidirectional power flow. The hybrid system was restricted to act solely as a portable power source and was therefore suited for primary cell support. The lithium ion capacitor used was the JSR 1000F capacitor operating between 3.8V and 2.2V. The load profile applied to each power system consisted of a 60 second peak pulse at 100W followed by a 540 second draw phase at 12W. The battery approach voltage is shown by the blue curve while the hybrid approach voltage is shown by the red curve. The battery voltage is shown to support approximately 3 cycles of profile support while the hybrid approach support more than 80 cycles of the profile. The batteries under the battery approach suffer from power limitations exacerbated by cold temperatures such that the high current demand forces the voltage swings to be large. The battery approach voltage trips the 10V cutoff point prematurely while the hybrid approach system is able to operate significantly longer due to increase power capability of the system. The battery approach achieves approximately 1.6% system efficiency in terms of energy delivered while the hybrid approach yields 66% efficiency, a significant improvement.

Fig 11 shows the results from testing conducted on the battery-only and hybrid approaches at room temperature. In this case, both the battery-only and hybrid approaches use a 5S2P configuration of the LiCFxMnO2 cells. The same load profile is used as described in the first primary type testing. The hybrid voltage is shown to be maintained above the 10V cutoff until approximately 100 cycles of pulsed profile support, while the battery-only approach voltage fails around 40 cycles of profile support, which demonstrates an improvement of 250%. The battery approach shows approximately 33.4% system efficiency, while the hybrid approach shows 81.5% system efficiency. The hybrid sacrifices some nominal energy density to improve power density which ultimately allows for improved overall system energy efficiency.

The final primary type testing demonstrates hybrid benefit for when the systems are exposed to warm temperatures of 50^{0}C ambient. Fig. 12 and Fig 13. show the results from the described testing. The plot in Fig. 12 shows the battery approach voltage in blue and hybrid approach voltage in red. The plot in Fig. 13 shows the external pack temperature of the battery system in each approach. Both the battery approach and hybrid approach used a 5S3P. The battery approach voltage reaches the cutoff at 138 profile cycles, while the hybrid approach achieves 157 pulse profile cycles. The system efficiencies are 75% and 85% respectively. Note the substantial voltage dips occurring in the battery approach at approximately 100 cycles and 110 cycles. These dips are due to thermal fuse disconnect occurring on one of the battery packs from significant elevated internal temperature. Fig. 13 shows the battery approach maintaining higher external pack temperature throughout the majority of testing with a max difference of 15^{0}C. The hybrid demonstrates improved thermal energy performance.

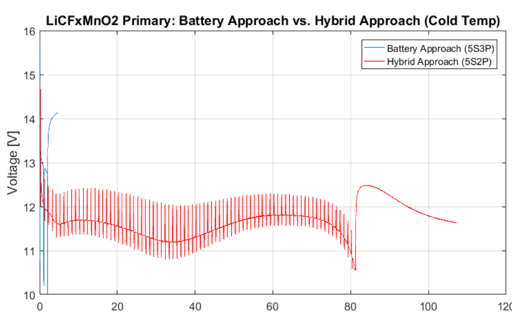

Fig. 10: LiCFxMnO2 Primary System Testing: Cold Temp

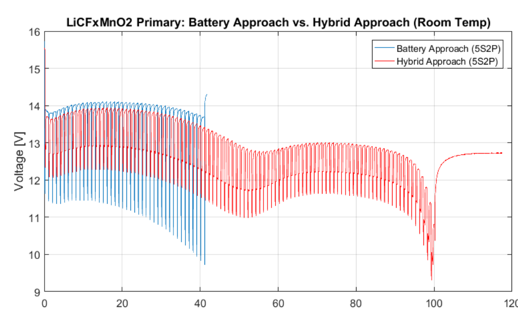

Fig. 11: LiCFxMnO2 Primary System Testing: Room Temp

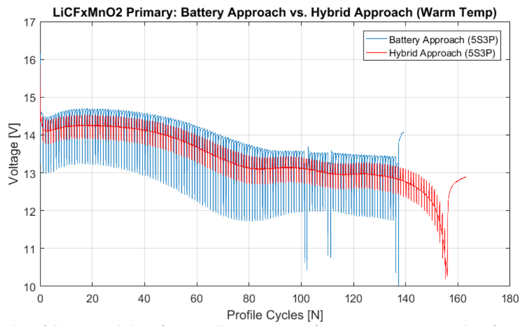

Fig. 12: LiCFxMnO2 Primary System Testing: Warm Temp (Voltages)

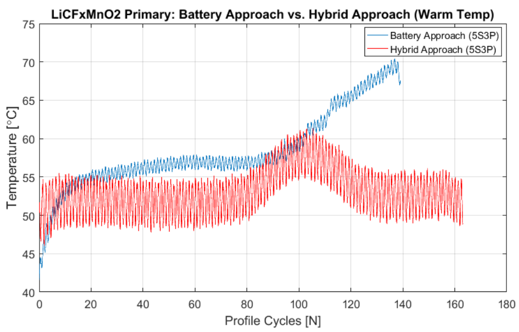

Fig. 13: LiCFxMnO2 Primary System Testing: Warm Temp (Temps)

Primary type testing demonstrates hybrid benefit in several ways over a wide range of temperatures. System efficiency is shown to be improved through the mechanism of increased power capability in order to make available more energy than would be possible under a battery only approach. Thermal performance is also improved under hybridization as battery temperature is maintained within a more acceptable range reducing risk of thermal runaway and thus improving safety.

B. Rechargeable Chemistry Hybrid Testing

Secondary chemistry testing was then investigated to evaluate long term hybrid effects over the lifetime of the rechargeable cells. Secondary chemistries are affected by both charging and discharging. Since many cycles are achievable, the degradation of the internal mechanisms of the cells may differ depending on the conditions applied to the cells. It stands to reason that lower stress on the cells would result in reduced rate of degradation. This concept is investigated initially through cell level testing. To carry out testing, high energy LG18650MJ1 rechargeable cells are cycled under two load profiles at room temperature. The first profile, called the battery-only approach, applies repeated profile cycles of 60 seconds at 10A followed by 540 seconds at 1.2A. The peak pulse current values are within the manufacturer specified limitations of the cell. The second profile, referred to as the hybrid profile, simulates hybridization at the cell level by regulating the current on the battery to 2.08A constant. Each profile requires the same amount of charge; however the rate at which the charge is transferred differs, placing different levels of stress on the cells.

Fig. 14 and Fig. 15 show the discharge and charge efficiency achieved as a function of cell cycle. The charge and discharge efficiency are the ratio of capacity delivered versus the nominal capacity expected. Two cells were cycled for each approach. The blue and orange data points represent the battery approach cells and the yellow and purple data points show results for the hybrid approach. Note the outliers in the data points are attributed to a facility power outage which occurred during testing which stalled testing temporarily. The hybrid maintains a margin of benefit throughout testing which ranges between 6% and 10% per cycle in each the discharge and charge comparisons. In addition, there is some interesting behavior in the efficiency curve of the battery approach. Early on, there is a shelf which forms around 90% which experiences a significant drop off down to 84% between cycles. This occurs again later in cycle life around the 370 cycle mark. This drop-off is attributed to a reduction in the number load cycles supported due to the power limitation of the cells. The battery voltage trips the low cutoff voltage one load cycle earlier than the previous cell cycle, therefore showing an immediate drop in delivered capacity. The hybrid does not suffer from this issue since the current is regulated to a constant value, reducing the effects on battery power limitation. The battery approach also shows it has reached the standard 80% capacity retention failure point around 350 cycles whereas the hybrid approach at the time of this writing achieved 400 cycles while still retaining 86% capacity retention. The hybrid projects to support many more cell cycles before reaching its 80% cutoff.

Fig. 16 shows the energy efficiency achieved between the two approaches. The energy efficiency is a metric that analyzes the energy delivered during discharge followed by the energy recaptured during the following charge cycle. This measurement incorporates changes in voltage behavior and capacity, acting a metric for degradation. The results continue to support the hybrid approach as a superior method for supporting the pulsed power loads. The hybrid approach boasts approximately a 3% advantage in energy efficiency at beginning of cycling and this grows to greater than 4% at the 400 cycle mark. The trend present suggests the gap in performance would increase with additional cycling, further testing will investigate. Note the benefit shown here is under conditions within these particular cells' operating limits. Therefore, it is understood that for power or current conditions outside of the cells limits, the hybrid would be necessary as the battery approach should not be operated at those conditions.

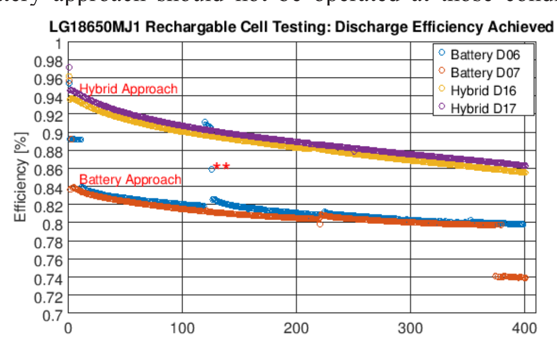

Fig. 14: LG18650MJ1 Secondary System: Discharge Capacity Efficiency

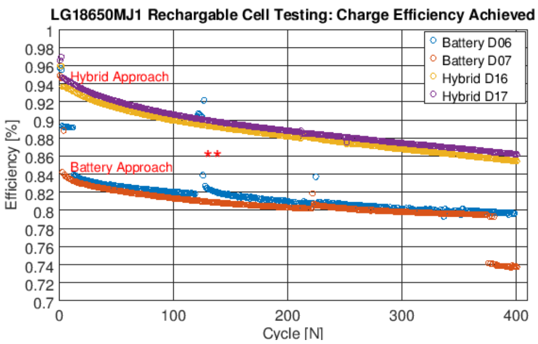

Fig. 15: LG18650MJ1 Secondary System: Charge Capacity Efficiency

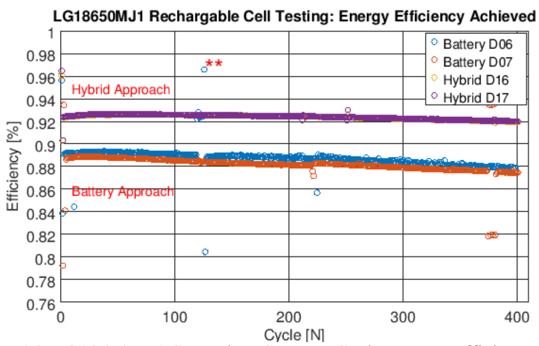

Fig. 16: LG18650MJ1 Secondary System: Cycle Energy Efficiency

V. CONCLUSIONS

The concepts and results presented here lend reason to continue further development in the area of portable hybrid power systems. The hybrid is ideal for pulsed power load support as the profiles are both energy dense and power dense in nature. The hybrid features the high energy density of the electrochemical battery and the high power density of the lithium ion capacitor. The system integration is performed through the use of power electronics and an embedded processor. These afford flexibility in hybrid operation, as the system is able to delegate power tasks to the LiC and energy tasks to the battery. A typical battery solution is directly coupled to the load so its operation is directly dependent upon that load. For high power applications, this has demonstrated deterioration in performance for battery only solutions where the hybrid system has thrived. Battery solutions feature greater nominal energy density however the energy is not accessible under high power pulsed loads. The hybrid solution reduces burden on the battery allowing this energy to be accessed, providing greater realized energy density through improved power density. This was demonstrated in primary battery testing, where benefit was seen over a wide range of temperatures and was also seen in rechargeable chemistries at the cell level. Hybridization showed benefit even under conditions within the battery specifications. As power demands increase beyond the battery capabilities the hybrid benefit will continue to grow.

VI. FUTURE HYBRID DEVELOPMENT

To demonstrate the additional benefit described above, higher power hybrid electronics are under development to take full advantage of the lithium ion capacitor's power capability. The current system power level is suitable for demonstrating benefit for primary type lithium ion battery chemistries, as they are generally lower in power than rechargeable types. Higher power electronics will further improve the benefit seen in the primary cells and allow for full system testing of hybridized secondary chemistries. In addition, hybridization through electronics and the use of an embedded processor allows for complex algorithms and controls to be implemented into the system. Through the use of these algorithms and controls, the hybrid system can employ learning techniques and optimized control methods to promote system performance.

VII. REFERENCES

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