Lithium-Ion Battery/Lithium-Ion Capacitor Hybrid Energy Storage Device in UUV Applications

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Abstract

The technique of pairing a battery and supercapacitor has been accomplished electronically through the development of a hybrid power management unit. The device uses power electronics, closed loop control, and power management algorithms to facilitate the combination of an energy dense battery and a power dense super capacitor. The combination has been demonstrated to significantly improve battery performance in pulsed power applications in terms of energy density, peak power capability, battery lifetime, and total energy delivered over the lifetime of the paired battery. The approach is applied to an unmanned underwater vehicle (UUV) through station keeping and obstacle avoidance applications which experience pulsed loading under these conditions. The hybrid UUV battery shows regulated operation within a defined envelope using the supercapacitor element to support the peak pulse requirements of the thrusters used to maneuver the UUV. Operation of the UUV battery in this manner projects to provide improved performance over the battery lifetime with higher endurance and dynamic response for the UUV.

Keywords

Supercapacitor; Battery; Hybrid; Power; Energy; Power Management; Lithium Ion; Autonomous Vehicles; Underwater Unmanned Vehicles; UUV; Marine; Pulse Power; Marine Energy; Power At Sea

Introduction

The work presented expands on previous results detailing the hybrid power unit [1]. The unit features a lithium-ion battery/lithium-ion capacitor system directed at managing bidirectional pulsed power that improves battery performance. For primary type batteries, pulse power loads draw down voltage proportional to the internal impedance reducing energy availability. During pulsed voltage drawdown, the minimum voltage is reached before the battery's energy is depleted in terms of state of charge. This is due to the fundamental property of batteries as being an energy dense storage device with relatively high impedance. Pairing the battery with a low impedance power dense device such as a lithium-ion capacitor in support of load pulsing allows the battery to operate at a lower constant power and deliver a greater portion of its energy. ESL has developed a hybrid power system consisting of a power dense supercapacitor and power electronics along with management circuitry and algorithms to facilitate hybrid operation. The system pairs with energy sources whose performance degrades under pulsed loading or are current limited in a particular application.

Motivation

Meassured performance of the hybrid power management unit demonstrates the motivation for pursuing hybrid power system development and integration into a wide range of applications. Figure 1 compares a standard BA5790 battery system (blue) and hybrid system (red) pairing a BA5790 with a 1000F hybrid system for primary type batteries. A SATCOM load defined as 1 minute @ 100W, 9 minutes @ 12W is applied to each system. The resulting energy densities achieved by each system are shown in Table 1. There is an 83% improvement in effective energy density when utilizing the hybrid technology For the BA5790 battery system. Note the voltage drawdown is significantly reduced under hybrid control.

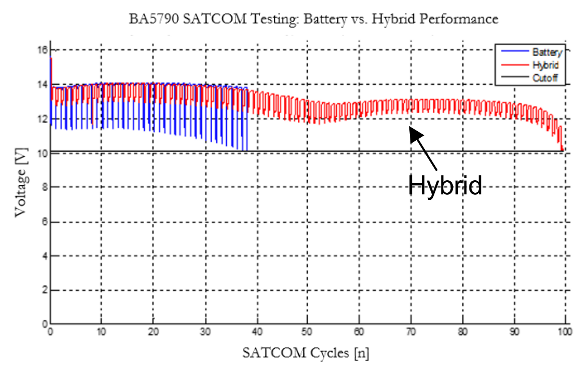

Figure 1: Primary SATCOM Performance: Battery System vs. Hybrid System

Table I: Primary Battery System Performance vs. Primary Hybrid System Performance

Primary System SATCOM Performance		
System	SATCOM Cycles	Energy Density
BA5790	38	113.44 Wh/kg
BA5790 + Hybrid	99	207.71 Wh/kg
Improvement	~160%	~83%

For secondary type batteries, a similar demonstration was conducted with cell equivalent testing, the result is provided in Figure 2. A cell equivalent SATCOM pulsed profile was applied to an INR18650MJ1 rechargeable cell assuming a battery approach (blue) and to another INR18650MJ1 cell assuming a hybrid approach (red) which operates the battery at a low constant current. The result is two points of improvement providing greater overall energy delivery from the hybrid approach. The hybrid approach showed greater single cycle capacity delivery as well as greater cycle life. The single cycle capacity improvement, measured by the difference in capacity retention each cycle, averaged ~10% until 375 cycles where the battery approach cell failed below the 80% capacity cutoff. The total cycle life of the hybrid approach was extended beyond 1100 cycles an improvement of 193%. The results are summarized in Table II.

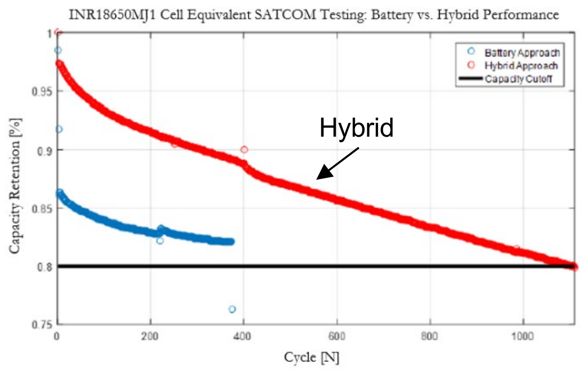

Figure 2: Secondary SATCOM Performance: Battery Approach vs. Hybrid Approach

Table II: SATCOM Performance: Secondary Battery System vs. Secondary Hybrid System

Secondary System SATCOM Performance (Cell Equivalent Testing)		
System	Avg Cycle Capacity	Cycles
INR18650MJ1	83.3%	375
INR18650MJ1+Hybrid	92.2%	1100
Improvement	~10%	~193%

Hybrid Architecture and Operation

Hybridization of a battery or energy dense device is achieved according to Figure 3. An energy dense storage device such as a lithium-ion battery is connected to a hybrid bus. Connected to the hybrid bus in parallel is a power dense device such as a supercapacitor. Between the supercapacitor and the physical bus connection are power electronics which facilitate the interfacing while also actuating closed loop control of the power system. The hybrid power management unit based on this hybrid architecture automatically fuses the benefits of energy dense devices and power dense devices.

Figure 4 captures the basic operating principle of the hybrid power system. The top plot shows the system currents, the middle plot shows the load and battery voltages, and the bottom plot shows the supercapacitor voltage. Negative batter current is out of the battery, negative load current is into the load and the hybrid regulates battery current to maximum of one amp. The sequence follows: 1. The battery supports the baseline load and recharges the supercapacitor, 2. The load pulses beyond the battery operating envelope and the supercapacitor discharges to support the difference, 3. The load becomes regenerative beyond the operating envelope of the battery and the supercapacitor absorbs the difference, 4. The baseline regenerative load falls within the battery operating envelope and the supercapacitor provides the difference to charge the battery. The plots demonstrate the basic operating states of the hybrid system. The system sinks and sources power capable of handling power pulses in either direction. Maintaining the battery to operate within a defined envelope is key to providing the energy performance improvement.

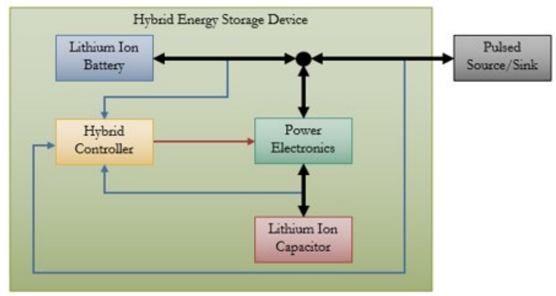

Figure 3: Hybridization Architecture

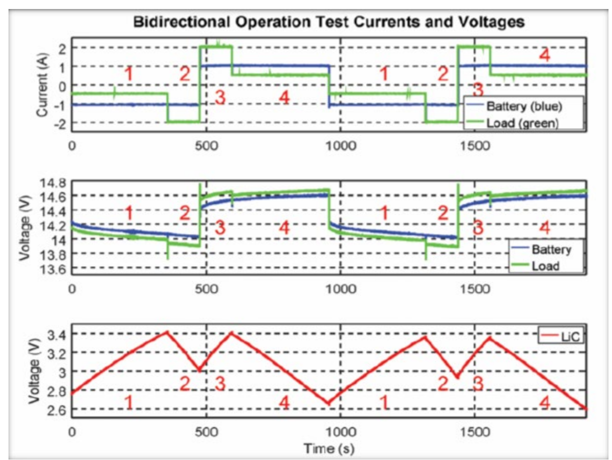

Figure 4: Hybrid Operation

Unmanned Underwater Vehicle Integration

Unmanned underwater vehicles (UUV) are suitable for hybridization as evidenced by their operation. The UUV power source experiences pulsed loading from a variety of sources including propulsion, positioning, actuation of robotic armatures, and various payload technologies such as communications. Advances in UUV controls and geometry are being made to improve mission performance but often do not account for the resultant electrical stress degradation of the battery [2]. This work focuses specifically on hybridizing the operation of the thrusters used to maintain station and depth. Rough conditions, underwater currents, stiction lifting off a muddy sea floor, and obstacles create the need to provide pulsed power to the vehicle's thrusters.

The test platform used to demonstrate hybridization was a Blue Robotics BlueROV2, a flexible UUV development platform. For this work, the power to the four vertical thrusters is disconnected from the main battery and connected to the hybrid system contained within the cylindrical watertight enclosure located in the payload area. The hybrid power system consisted of a BB2557/U lithium-ion rechargeable battery and ESL's hybrid power management unit comprised of ESL power management circuit board and a 1500F lithium-ion supercapacitor (LiC) as shown in Figure 5. Its dimensions are approximately 4.9"X4.3"X1.4". The prototype unit was not optimized for this application but was sufficient for testing. The power management circuity board contains power electronics for interfacing the battery and supercapacitor, closed loop power electronics control, and processing power for intelligent power management algorithms.

Figure 5: ESL Hybrid Power Management Board and Lithium-Ion Supercapacitor

The pairing of the power management unit and the battery is achieved through cabling that forms the hybrid bus. To integrate into the UUV, the power distribution of the UUV is modified such that the supply for the thrusters is connected to the load interface of the hybrid bus. Communications and power exit the tube via penetrators in the end cap. Figure 6 shows the fully integrated UUV. The vertical thrusters are located on each corner at the top of the vehicle. The hybrid power management unit is contained within the watertight acrylic enclosure fixed to the payload frame as the bottom of the UUV.

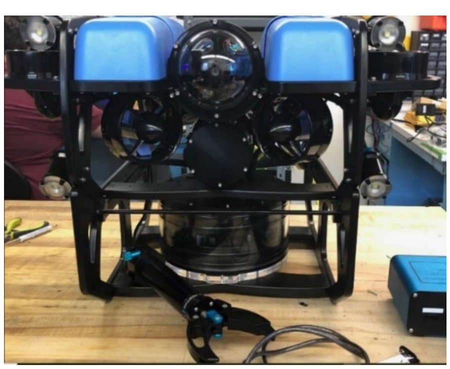

Figure 6: Hybridized UUV

Hybrid UUV Testing

The hybrid system used in testing was sized to accommodate pulsing on the order of 100W to 200W for durations under 1 minute. The hybrid power management circuit board contains on board measurement conditioning, data logging and storage capabilities for post processing and analysis, ideal for testing in the field and limiting cabling. The UUV system of ROV type is controlled remotely through the connected tether. The hybrid system is evaluated under station keeping and obstacle avoidance test cases.

Station Keeping: Station keeping refers to the ability of the UUV to maintain a particular orientation at depth and is important for performing various tasks such as underwater maintenance. To maintain position, the UUV is required to quickly respond to disturbances through the use of vehicle thrusters. In this experiment, a wave tank is used to generate a periodic disturbance. The vehicle thrusters must provide a pulsed profile to quickly regulate positional errors induced by the waves.

The UUV was commanded to maintain a 20cm depth at level orientation while being subjected to a 7cm wave with a roughly 1 second period. Figure 7 (top) shows the results from station keeping testing. The power flow between the battery (blue), supercapacitor (green), and the load (red) is captured in the data. The load is the sum of the four vertical thruster power requirements. Power pulsing due to the periodic wave disturbance were observed to peak around 150W for a duration on the order of milliseconds. Negative power indicates discharging of the battery and supercapacitor and utilization by the load. A positive power indicates charging of the battery and supercapacitor and regeneration by the load. The battery operating envelope for this application was defined to be between +/- 25W. The battery is allowed to operate anywhere within this envelope and is capped once the limit is reached. The difference in power required by the load is then provided by the supercapacitor.

The station keeping power cycle includes a power pulse towards 150W, the battery discharge is limited to 25W by the hybrid power management unit control, the supercapacitor provides the 125W difference plus some additional power to offset losses due to power conversion efficiencies. The pulsed load returns towards baseline as the wave disturbance subsides. As the load power draw falls within the battery operating envelope the difference is then used to restore charge to the supercapacitor in anticipation of future pulsing. Note just before 27s and 28s the battery is seen sinking power as the load becomes regenerative demonstrating the bidirectional capabilities of the hybrid system.

Obstacle Avoidance: The second experiment evaluated the hybridized thrusters assuming a nonperiodic pulsing profile such as would occur in obstacle avoidance operation. In this

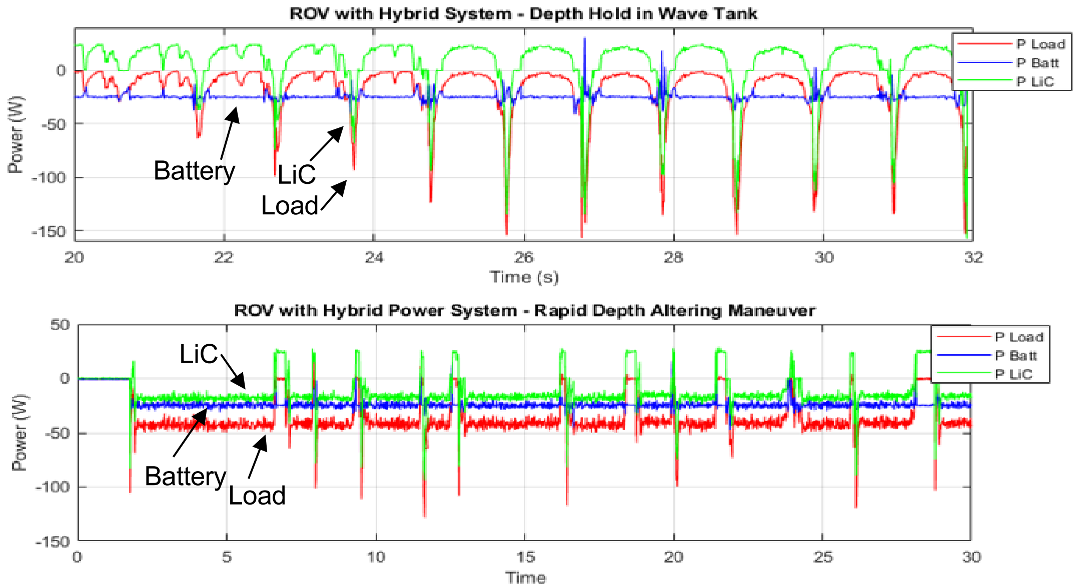

Figure 7: Hybrid UUV Testing: Station Keeping (top), Obstacle Avoidance (Bottom)

situation the UUV was aggressively commanded to change depth with random magnitude and pattern. The resulting waveforms are shown in Figure 7 (bottom).

The load profile (red) shows a baseline load around 45W with discharge pulsing around 100W magnitude and periods where the load rests around 0W. The supercapacitor profile (green) is shown to provide the difference between the load requirement and the battery discharge limit during pulsing. During periods where the load falls below the baseline towards zero, the battery then provides power to the supercapacitor to restore charge. The battery profile (blue) shows operation within a +/-25W envelope indicating the hybrid controller is tightly regulating battery operation. Operation within the envelope provides performance improvement via single cycle life and total cycle life as demonstrated in the above sections.

Conclusion

The hybrid system demonstrated the ability to limit battery operation to within a predefined current envelope to ensure that the battery operates within its highest efficiency operating region. The energy device and power device must be sized according to the application's peak power and duration requirements. The hybrid architecture is effective when seeking to minimize weight and volume while improving endurance and dynamic performance such as the UUV. To achieve minimal form factor, power density and energy density must be achieved simultaneously. The hybrid architecture addresses this through integration of a power dense device in the supercapacitor and an energy dense device in the battery made interoperable through use of the hybrid power management board.

Future Development

Future work in the UUV area includes integrated learning algorithms for adaptability in the field. Dynamic battery operating envelopes based on measured performance and environmental conditions can further enhance performance. Dynamic hybrid state based on load usage looks to adapt the hybrid unit autonomously to perform optimally in both sourcing and sinking applications. This would allow the UUV's to incorporate more aggressive optimal control algorithms to handle a wide range of sea and mission conditions without degrading its batteries. In addition, scalability in terms of power and energy are being explored to address higher and lower power applications.

Acknowledgements

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References

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