Ultracapacitors for Pulsed Power Systems

ULTRACAPACITORS IMPROVE SAFETY, REDUCE COST, AND ENHANCE DATA INTEGRITY FOR MUD PULSE MWD

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INTRODUCTION

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In this paper, we'll introduce the concepts of hybrid power supply design using mud pulse telemetry as an example. Mud pulse telemetry is a common method of transmitting digital information to the surface during Measurement While Drilling (MWD) and Logging While Drilling (LWD) operations. These systems rapidly modulate the flow of drilling fluid to create pressure waves that travel through the drill pipe. The resulting pressure waves are then decoded by a transducer on the surface. These systems, inherently, require an energy storage solution that can provide high power in short bursts. Batteries are typically used for this application because they provide point-of-load power and mitigate the complexity associated with wireline and generator operations. However, to satisfy the energy and power requirements of a mud pulse telemetry system, a volatile and potentially hazardous battery chemistry is generally utilized.

Lithium-thionyl chloride (Li-$SOCl_2$) is popular for its particularly high energy density of greater than 1000 Wh/L. This high energy density enables long duration operations while keeping the battery pack small enough to accommodate the space restrictions associated with the MWD environment. Despite this chemistry's high energy density, its power density is quite low, approximately 70 W/L[1]. The incorporation of the Li-$SOCl_2$ battery in the oil and gas industry has inspired technological advances in power handling capability in the form of high-rate cells. The incorporation of ultracapacitors will address the need for enhanced energy and power density in MWD systems by leveraging the characteristic inverse relationship between power and energy density typically pertaining to battery design. Preferential selection of a Li-$SOCl_2$ construction in favor of a higher energy density often results in a battery pack with diminished power handling capability.

To overcome this power deficit, the Li-$SOCl_2$ battery must increase in both weight and size to sufficiently sustain the peak power demands of a high powered load. A similar situation is encountered when preferentially choosing a Li-$SOCl_2$ construction for its high power density only to subsequently increase the weight and size of the battery to accommodate the energy demands of the load. Coupling ultracapacitors to batteries can greatly extend runtimes by enabling the use of these energy dense chemistries. The technological trade-off between energy and power density is illustrated in **Figure 1**. In this discussion, we will explore the limitations of using a Li-$SOCl_2$ battery as the sole power source for mud pulse telemetry and present an ultracapacitor-based solution that can improve safety, reduce costs, and enhance data integrity.

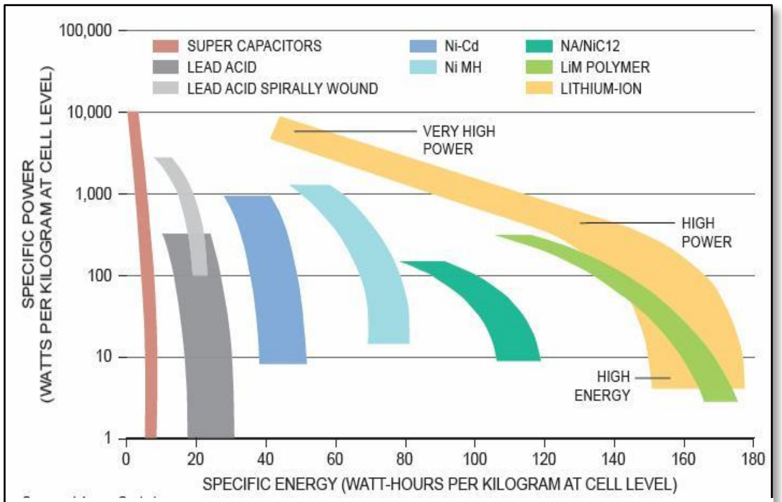

Figure 1 Ragone plot of battery chemistries

BATTERY PACK DESIGN

Using a Li-$SOCl_2$ cell, we can design a battery pack to drive a mud pulse telemetry system. First, we must establish the design constraints. The system requirements for our proposed MWD system are collected in **Table 1**. The maximum operating temperature requirement is initially the most difficult requirement to meet and limits our options to only a few battery chemistries. In choosing a cell for the proposed battery pack, we need to also ensure it satisfies our dimensional and electrical requirements.
For this design, we will try to meet all our system requirements with Electrochem's Li-$SOCl_2$ MWD150[1] cell.

[1] http://www.electrochemsolutions.com/energy/high.aspx

Parameter	Value	Unit
Maximum Output Voltage	32	V
Minimum Output Voltage	24	V
Maximum Current (100 ms)	2	A
Chassis OD	1.5	in.
Maximum Operating Temperature	150	C

Table 1 System requirements

CELL MODELING

For the purposes of analyzing the electrical performance of the cell during relatively narrow time windows, we can construct a lumped element model consisting of an ideal voltage source with series resistors that capture the cell's effective series resistance[2] (ESR) and any additional aggregate resistance due to wiring and connectors as shown in **Figure 2**. Since this model is intended only for transient analysis, we can ignore the effects of State of Charge (SoC) on the cell's ESR. A cell's SoC is a measure of stored energy. For a Li-$SOCl_2$ cell, ESR is inversely proportional to the cell's SoC and tends to increase as the cell discharges. Since this effect generally dominates when the cell is nearly depleted, we have ignored this behavior to simplify the model.

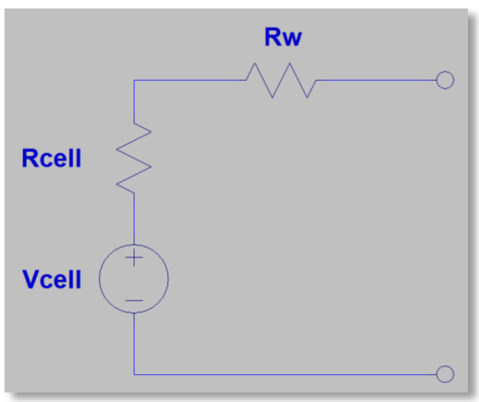

Figure 2 A simplified lumped element model of a Lithium-thionyl chloride cell with external wiring resistance

MINIMUM OUTPUT VOLTAGE

To satisfy the minimum output voltage requirement, we need to arrange the cells in series. During the **100 ms** discharge event, there will be a drop in voltage proportional to the battery pack's ESR. Using our model of the Li-$SOCl_2$ cell, we can calculate the minimum number of cells needed to support the load,

$$n(V_{\text{cell}} - iR_{\text{cell}} - iR_{\text{w}}) > V_{\text{min}}$$

Where,

- n, represents the number of cells
- V_{oc}, represents the open-circuit cell voltage
- i, represents the output current
- R_{cell}, represents the cell's internal resistance
- R_{w}, represents the aggregate resistance attributed to wiring and connectors[3]

[2] Also known as "internal resistance," this resistance is an aggregate of mechanical and electrochemical cell features.
[3] For this analysis, we will approximate wiring resistance to be nominally 10 mΩ/cell length.

- V_{min}, represents the minimum output voltage

Re-arranging,

$$n > \frac{V_{\mathrm{min}}}{V_{\mathrm{cell}} - iR_{\mathrm{cell}} - iR_{\mathrm{w}}}$$

$$n > \frac{24\ \mathrm{V}}{3.67\ \mathrm{V} - (2\ \mathrm{A})(0.4\ \Omega) - (2\ \mathrm{A})(0.01\ \Omega)}$$

$$n > 8.42$$

So, we can meet both the minimum output voltage and maximum current requirements with **9 cells** in series.

MAXIMUM OUTPUT VOLTAGE

Now that we have determined the minimum number of cells needed to support the load, we must ensure this design also satisfies the maximum output voltage requirement. With **9 cells,** we will have a maximum output voltage of,

$$V_{\mathrm{max}} = nV_{\mathrm{cell}} = (9)(3.67\ \mathrm{V}) = \mathbf{33.03\ V}$$

Since the maximum output voltage for this pack exceeds the required 32 V, we need to adjust our approach. For this, we have at least two options.

1. Choose a higher-rate cell with a lower ESR.
2. Add cells in parallel to increase current handling capability.

There are a few disadvantages associated with the first option. As mentioned before, a cell with a relatively higher power density tends to have a relatively lower energy density. So, even though the higher-rate cell may initially meet the power specification, it will likely suffer from shorter service times and would need to be replaced more frequently. In addition, high-rate Li-$SOCl_2$ cells are more volatile than their moderate-rate counterparts and pose a significantly increased risk of failure during operation that may compromise safety. As an alternative to this approach, we can instead add cells in parallel. Calculating the maximum number of series cells, we have

$$nV_{\mathrm{cell}} < V_{\mathrm{max}}$$

Re-arranging,

$$n < \frac{V_{\mathrm{max}}}{V_{\mathrm{cell}}}$$

$$n < \frac{32\ \mathrm{V}}{3.67\ \mathrm{V}}$$

$$n < 8.72$$

From this, we can utilize a maximum of **8 cell** in series. This gives us an open-circuit[4] voltage of

$$V_{\mathrm{oc}} = nV_{\mathrm{cell}} = (8)(3.67\ \mathrm{V}) = \mathbf{29.36\ V}$$

Now, we can iterate the design and satisfy the minimum output voltage requirement.

[4] The open-circuit voltage is equal to the output voltage measured at zero output current.

MINIMUM OUTPUT VOLTAGE – SECOND PASS

First, we will verify that **8 cells** are insufficient with regard to satisfying the minimum output voltage requirement. Expanding on our model of the cell, we can construct a lumped element model for the battery pack. The battery pack's effective series resistance due to cell ESR and external wiring is,

$$R_{\text{ESR}} = n(R_{\text{cell}} + R_{\text{w}}) = (8)(0.4\ \Omega + 0.01\ \Omega) = \mathbf{3.28\ \Omega}$$

Calculating for the minimum output voltage[5], we have

$$V_{\text{min}} = V_{\text{oc}} - iR_{\text{ESR}} = 29.36\ \text{V} - (2\ \text{A})(3.28\ \Omega) = \mathbf{22.8\ V}$$

We can also confirm this result through simulation shown in **Figure 3.**

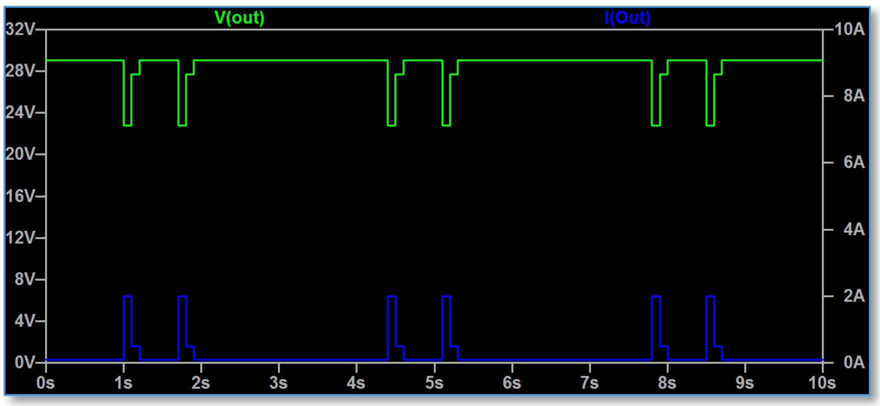

Figure 3 Simulated battery pack performance

To simplify the manufacturing logistics associated with paralleling cells in a single structure, we can instead analyze the performance of two discrete battery packs installed in a quasi-parallel configuration as depicted in **Figure 4**. In order to accurately capture the effects of wiring resistance on electrical performance, we need to decouple the wiring resistance contribution from the battery pack ESR. There is a logistical consequence to connecting multiple battery packs in a quasi-parallel configuration. Since the current delivered from auxiliary battery packs must travel through the wiring of subsequent battery packs on its way to the load, the resulting network resembles more of a series-parallel configuration. **Figure 5** depicts an electrical model for this quasi-parallel configuration.

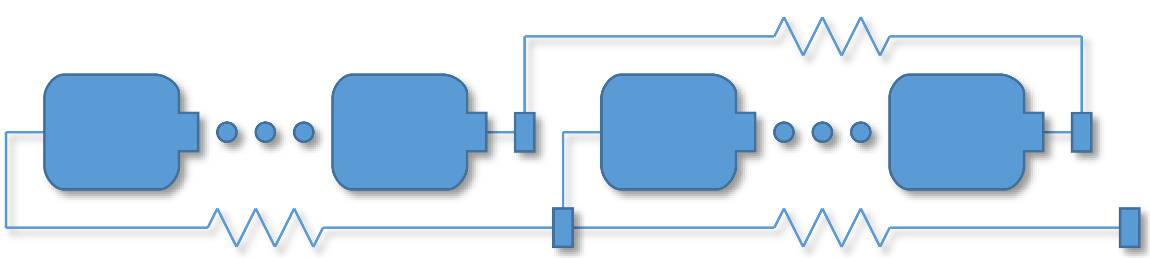

Figure 4 Quasi-parallel connection with wiring resistance

[5] Li-SOCl₂ battery packs generally have output protection diodes as well as fuses that would contribute to the voltage drop during discharge. To simplify the analysis, we are ignoring the effects of those components.

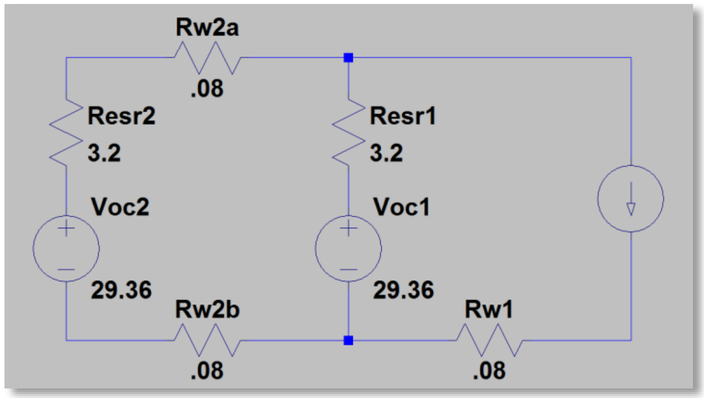

Figure 5 Parallel battery model with wiring resistance

Using this new electrical model, we can adjust our lumped element model for the quasi-parallel configuration.

Assuming,

$$R_{\mathrm{ESR1}} = R_{\mathrm{ESR2}} = R_{\mathrm{ESR}},\ R_{\mathrm{w1a}} = R_{\mathrm{w1b}} = R_{\mathrm{w2}} = R_{\mathrm{w}}$$

We have a configuration ESR of,

$$R_{\mathrm{TOT}} = R_{\mathrm{w}} + R_{\mathrm{ESR}}//(R_{\mathrm{ESR}} + 2R_{\mathrm{w}})$$

$$R_{\mathrm{TOT}} = (0.08\ \Omega) + (3.2\ \Omega)\ //\big(3.2\ \Omega + (2)(0.08\ \Omega)\big)$$

$$R_{\mathrm{TOT}} = \mathbf{1.7\ \Omega}$$

We can now calculate the minimum voltage,

$$V_{\mathrm{min}} = 29.36\ \mathrm{V} - (2\ \mathrm{A})(1.7\ \Omega) \approx \mathbf{26\ V}$$

We can also verify this new design meets our system requirements through simulation. The simulation data in **Figure 6** confirms that 2x 8-cell battery packs connected in a quasi-parallel configuration can satisfy the minimum voltage requirement. It's import to note that,

$$R_{\mathrm{TOT}} > \frac{3.28}{2}\ \Omega = 1.64\ \Omega$$

If the two identical battery packs were truly in a parallel configuration, we would expect the configuration's ESR to be half that of an individual battery pack. In fact, this is an inherent disadvantage to paralleling battery packs in such a fashion. The diminishing return in ESR reduction comes as a result of the wiring resistance of the pass-through conductors built into the battery packs.

SYSTEM SUMMARY

Our final design for powering a mud pulse telemetry system with a Li-$SOCl_2$ energy storage solution consists of 2x 8-cell battery packs connected in a quasi-parallel configuration. There are a few things to note about this design. Due to the series-parallel connection of the cells, the battery pack closest to the load delivers more power than the auxiliary battery pack. As such, the battery packs will discharge at different rates. The gradual divergence in the SoC between the two battery packs necessitates the use of forward protection diodes to avoid reverse current events. These diodes will further increase the drop in voltage during loading and may encourage the use of higher-rate cells or more battery packs extending the quasi-parallel configuration.

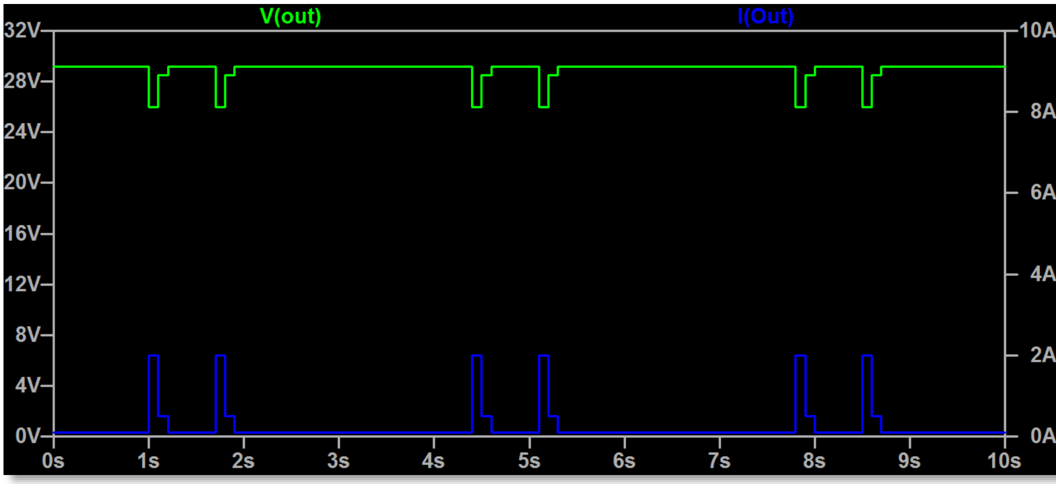

Figure 6 Simulation data of 2x batteries in a quasi-parallel configuration

As previously mentioned, a diminishing SoC causes the cell ESR to increase. This minimum voltage specification would only be valid for a relatively new battery pack and, as a result, this design would have an actual capacity less than the full rated capacity[6]. The system specifications are collected in **Table 2**.

Parameter	Value	Unit
Maximum Output Voltage	29.36	V
Minimum Output Voltage	25.76	V
Maximum Current (100 ms)	2	A
Chassis OD	1.5	in.
Maximum Operating Temperature	150	C

Table 2 $Li\text{-}SOCl_2$ system specifications

HYBRID DESIGN

As an alternative approach to satisfying the load requirements for this mud pulse telemetry system, we can utilize ultracapacitors to enhance the power handling capability of the single $Li\text{-}SOCl_2$ battery pack designed in the previous discussion without adding any auxiliary battery packs. First, we need to select an ultracapacitor that will satisfy the system requirements. **Table 3** contains specifications for several ultracapacitor manufacturers. For this analysis, we will use FastCAP's EE150-350[7] cell since it is the only commercially available capacitor that can operate at temperatures up to 150 °C.

Parameter	FastCAP	Ioxus	Maxwell
Maximum Operating Temperature (C)	150	85	70
Maximum Cell Voltage (V)	1	2.7	2.5
Cell ESR (mΩ)	8	2.5	3.2
Cell Capacitance (F)	340	400	350

Table 3 Ultracapacitor specifications

[6] A cell's rated capacity is a measure of time elapsed at a constant discharge current prior to reaching a specified output voltage. Generally, this is 2 V for a $Li\text{-}SOCl_2$ chemistry. At 2 V per cell, our output voltage would decrease to 16 V, violating the minimum voltage requirement.
[7] http://www.fastcapsystems.com/products/ultracaps/

CELL MODELING

Similar to the Li-$SOCl_2$, we can construct a lumped element model consisting of an ideal capacitor with series resistors that capture the cell's ESR and any additional aggregate resistance due to wiring and connectors as shown in **Figure 7**.

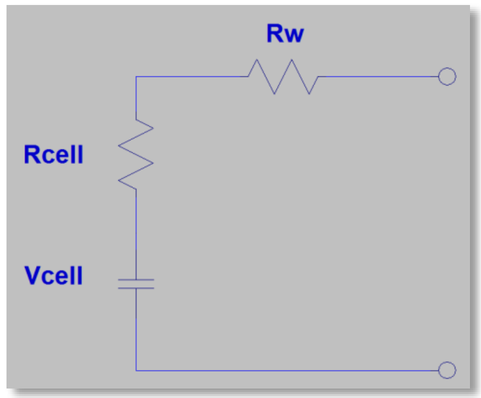

Figure 7 A simplified lumped element model of an ultracapacitor cell with external wiring resistance

MINIMUM OUTPUT VOLTAGE

Although we could satisfy the minimum voltage requirement with a 7-cell battery pack when integrating ultracapacitors, the popularity of the 8-cell battery pack will make an 8-cell analysis more applicable to current MWD energy storage solutions. Since ultracapacitors are rechargeable, we need to ensure that their voltages are kept below the specified maximums. To satisfy the minimum output voltage requirement, we need to arrange the ultracapacitor cells in series.

$$V_{\text{cell,max}} > \frac{V_{\text{out,max}}}{n}$$

Where,

- n, represents the number of ultracapacitor cells
- $V_{\text{cell,max}}$, represents the maximum ultracapacitor cell voltage
- $V_{\text{out,max}}$, represents the maximum battery pack voltage

Re-arranging,

$$n > \frac{V_{\text{out,max}}}{V_{\text{cell,max}}}$$

$$n > \frac{29.36\ \text{V}}{1\ \text{V}}$$

$$n > 29.36$$

So, we can satisfy the minimum output voltage requirement and maximum cell voltage constraint with **30 cells** in series. Similar to our battery pack analysis, we can construct a simplified lumped element model of our ultracapacitor pack. **Figure 8** shows our new model for our battery pack coupled with our ultracapacitor pack.

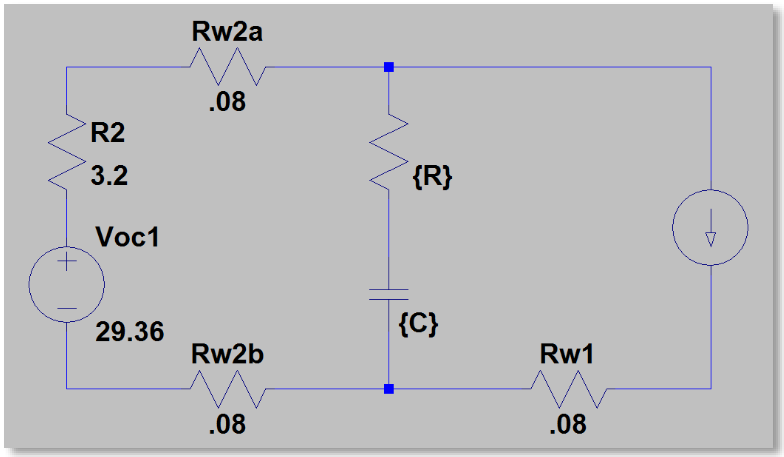

Figure 8 Battery-Ultracapacitor pack circuit model

For this model, we have made sure to include the wiring resistance in both the battery and ultracapacitor packs. Where,

- R_{w2a}, represents the resistance encountered by the battery current traveling through the ultracapacitor pack
- R_{w2b}, represents the resistance encountered by the battery current returning through the battery pack
- R_{w1}, represents the resistance encountered by both the battery and ultracapacitor return current

Through simulation, we find the minimum output voltage to be,

$$v_{\min} = \mathbf{28.2\ V}$$

This voltage drop is approximately 5.4 V less than what we would expect to see with a single Li-$SOCl_2$ battery pack. This correlates to a power savings of approximately,

$$P_{\text{saved}} = (5.4\ \mathrm{V})(2\ \mathrm{A}) = \mathbf{10.8\ W}$$

SYSTEM SUMMARY

We have seen that by adding ultracapacitors to existing 8-cell Li-$SOCl_2$ battery packs, we can reduce the amount of Li-$SOCl_2$ battery packs needed to power a mud pulse telemetry system. Also, since ultracapacitors are rechargeable, they can be reused for future MWD operations. FastCAP Systems has rigorously tested and qualified their patented ruggedized high temperature energy storage to ensure their ultracapacitors can be redeployed multiple times. The enabling of moderate-rate cells, extension of runtime, and reduction of battery pack purchases can reduce costs and simplify the logistics associated with the handling of high-rate cells and configuration of paralleled battery pack arrays. Completely eliminating high-rate cells significantly improves safety while stabilization of the output voltage can increase signal integrity. Enhanced signal integrity afforded through the integration of ultracapacitors can yield additional cost reductions by improving drilling time through higher confidence decoding on the surface. **Figure 9** shows the simulation results of the hybrid solution compared to the results of the previously discussed battery solution, shown in **Figure 10**.

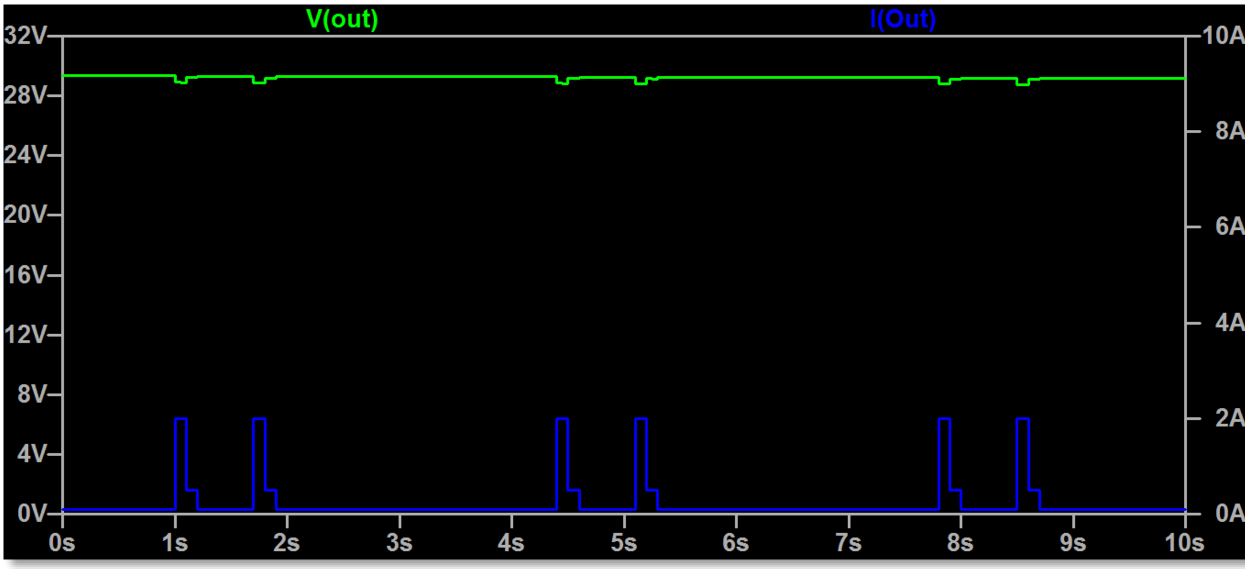

Figure 9 Hybrid system power performance

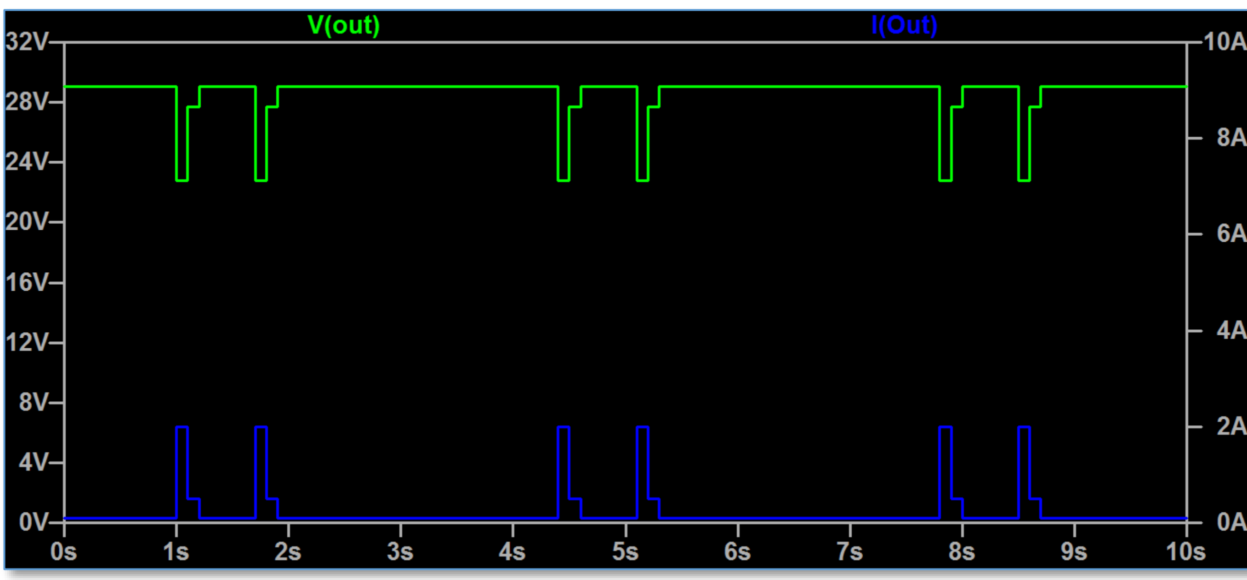

Figure 10 1x battery pack performance