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A CHEMISTRY-AGNOSTIC BATTERY MANAGEMENT AND CONTROL SYSTEM FOR THE PARALLEL INTERMIXING OF LITHIUM-ION 6T BATTERY PACKS

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ABSTRACT

This paper presents results that quantify how the homogenous and heterogeneous parallel interconnection of lithium-ion battery packs affect adversely their cycle-life, and how this problem can be corrected. Laboratory tests and modeling/simulation of two different lithium-ion battery packs are presented that highlight the importance of monitoring and controlling battery packs in parallel. A solution to this problem was designed and a prototype implemented that has the potential to fit within the available space of a commercially available lithium-ion 6T battery pack [1], [2]. This solution controls the sharing of load among heterogeneous and homogeneous lithium-ion 6T batteries with an efficiency of 95% or better, which is anticipated via simulations, to provide an improvement of cycle life of at least 3% for homogeneous and 10% for heterogeneous interconnections. This solution provides additional benefits including terminal voltage regulation and the flexibility to work as an active balancer in series interconnections of 6T battery packs without additional power paths.

INTRODUCTION

The U.S Army is looking for solutions that allow for parallel intermixing of lithium-ion 6T batteries with the same or dissimilar chemistries without impacting battery life or safety and while providing improved performance. There are a wide variety of dissimilar lithium-ion chemistries that could be used in lithium-ion 6T's, such as $LiFePO_4$ (LFP) or $LiNiCoAlO_2$ (NCA), among others [1]. Using lithium-ion 6T's with dissimilar chemistries from different vendors in parallel is desired to allow for increased competition, lowered cost, and greater compatibility and availability. However, such parallel intermixing poses challenges given each chemistry's unique voltage, capacity, and power characteristics. Innovative solutions must be developed and demonstrated which will allow for parallel intermixing of lithium-ion 6T batteries with dissimilar chemistries (such as lithium-ion 6T batteries from different vendors) without impacting battery life or safety relative to a baseline homogeneous 6T pack and while providing improved performance of the parallel 6T battery pack as a whole. The technology developed should also improve the performance of homogeneous parallel-connected lithium-ion 6T's. Emphasis will be on solutions and technologies which can be implemented within the interior of a Li-ion 6T battery and within existing Li-ion 6T battery management system topologies, including embedded hardware and software solutions as well as battery-to-battery CAN communication and coordination.

Few authors have worked on the effects of parallel interconnection of lithium-ion batteries. Their work is limited to small batteries composed of two or four cells, see [3], [4], and [5], and their findings hint at the degradation of cycle-life via internal impedance and temperature rise over time due to unequal currents. To the best of our knowledge there is lack of published results on the consequences of performing parallel interconnection of similar or dissimilar lithium-ion batteries with dimensions comparable to 6T batteries, as well as lack of feasible solutions to any performance degradations other than using batteries that are matched in chemistry, age, and manufacturing origin. Battery pack specifications, such as [2] for lithium-ion 6T batteries, are agnostic to specific lithium-ion variants; battery packs can, and in fact are, of different lithium-based chemistries. This promotes product differentiation. However, at the same time these battery packs are required by the Army to operate in parallel with one another. The Army requires the freedom to select any of the battery packs regardless of origin and chemistry specifics. For instance, it is possible that, by choice or by force, users of these batteries would want to interconnect battery packs using combinations of different manufacturers, or battery packs of different age. The intermixing of battery packs is a reality, and in fact one of the benefits, of modularizing batteries in standard form factors and with standard specifications. The parallel interconnection must be accomplished with lithium-ion battery packs having same or different chemistry within the lithium-ion family and complying with the same specification, such as [2]. In what follows the interconnection of battery packs having the same chemistry is referred to as homogenous and having different chemistry as heterogeneous interconnection.

We present results that quantify how the homogenous and heterogeneous interconnection of lithium-ion 6T battery packs in parallel affect adversely the overall cycle-life of the constituent battery packs, and how this problem can be corrected. The cycle-life degradation is attributed to the presence of inter-battery currents, also known as circulating currents, and also to the transitory and uneven share of the load among the batteries in parallel. Both effects increase internal Root-Mean-Square (RMS) losses within the batteries affecting their health and life performance. Our initial estimates based on analysis and simulations indicate that cycle life degradation reaches 10% for the heterogeneous case, and 3% for the homogeneous case. These results were obtained under room temperature conditions and may be optimistic when considering other more extreme scenarios. The inter-battery currents and transitory uneven load sharing result from differences among the batteries' internal parameters, such as internal impedance and Open Circuit Voltage (OCV) as a function of State of Charge (SOC). As expected, these differences are more pronounced when batteries of dissimilar chemistries are used, but they are also present, to a lesser degree, in batteries having the same chemistry, and possibly, originating from the same manufacturer as shown in our laboratory tests. The latter may be the consequence of small manufacturing differences, within tolerance, or because of the interconnection of battery packs with dissimilar age. In either case, the effects observed in our tests and simulations point to a degradation of cycle life and the possibility of tripping protection mechanisms within the batteries if the load current is sufficiently high, or during the charging process if the batteries are charged in parallel.

We start the paper by describing the modeling and simulation of 6T battery packs and their parallel intermixing. We then describe parallel intermixing tests results performed with two commercially available 6T battery packs originating from two different manufacturers and analyze the effect of paralleling on cycle life via analysis and simulation. We finalize the paper by presenting laboratory tests results that show how our first generation electronic prototype solution is able to control the individual battery currents between two dissimilar 6T batteries in parallel, and therefore show the potential to improve the life, safety, and controllability of lithium-ion 6T batteries in parallel intermixing scenarios. The results presented in this paper are carefully gathered, but they must be seen as initial, rather than rigorous and definitive, as a larger population of batteries and scenarios must still be tested. Our goal was to provide initial quantification of the problem and guidance toward possible solutions.

PARALLEL INTERMIXING MODELING AND SIMULATION

Modeling and simulation is considered an important tool for analysis and design considering the cost and time necessary to perform actual tests with 6T battery packs in parallel. For instance, modeling and simulation can estimate to a certain degree of approximation the effects of paralleling more than two batteries, such as four, ten, twelve, etc., prior to performing the tests. This also enables us to estimate, and properly size, the protection components necessary to perform a safe and reliable test. This becomes more important as 6T battery packs from different manufacturers are paralleled since there are no publicly available data we could refer to prior to our work. First we performed modeling of the two types of lithium-ion 6T pack batteries, and then we validated the models by comparing simulation results with laboratory tests. The dissimilar 6T lithium-ion batteries we used are developed by two different manufacturers that use different lithium-ion chemistries. We refer in this paper to these as manufacturers A and B. A 6T battery pack belonging to manufacturer A (B) is referred to as 6T battery A (B) hereafter. We had several battery packs from each manufacturer in our possession. If important within the context we refer to a specific instance of a battery by using the manufacturer letter and a number. For instance A-1 is battery pack 1 of manufacturer A, and B-2 is battery pack 2 of manufacturer B.

The battery pack modeling is based on the work in [6]. These models are equivalent circuit models as shown in Figure 1, where the OCV(SOC) voltage source is the Open Circuit Voltage (OCV) as a function of State of Charge (SOC), which was obtained at room temperature. This OCV(SOC) relationship is obtained for each 6T battery type using a charge and discharge profile similar to the one in [6]. The experimental OCV(SOC) for each battery type are shown in Figure 2. This was obtained using a single battery of each type due to limited time and resources. The parameters in the circuit equivalent model are found using a Sequential Quadratic Programming method.

We simulate the equivalent circuit models in LTspice®. The model and parameter values of the 6T battery A are shown in Figure 3. OCV(SOC) is modeled as a dependent voltage source using the .func A(x) Spice directive and it is a 7^{th} order polynomial fit to the OCV(SOC) relationships. Note that the 6T batteries modeled and tested have a nominal capacity of 60Ah and have different lithium-based chemistries. We connect and simulate multiple of these circuits in parallel to simulate batteries in parallel.

The simulation of a 6T battery A in parallel with a 6T battery B under a constant current load of 60 Amps is shown in Figure 4. This figure shows the

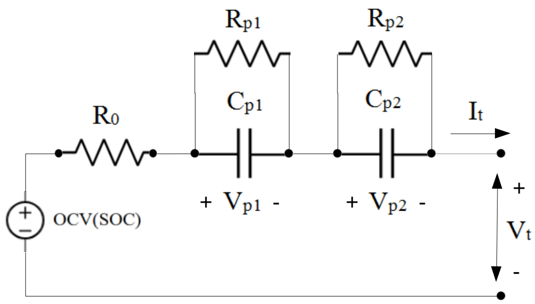

Figure 1: Circuit Equivalent Model of a lithium-ion 6T battery pack

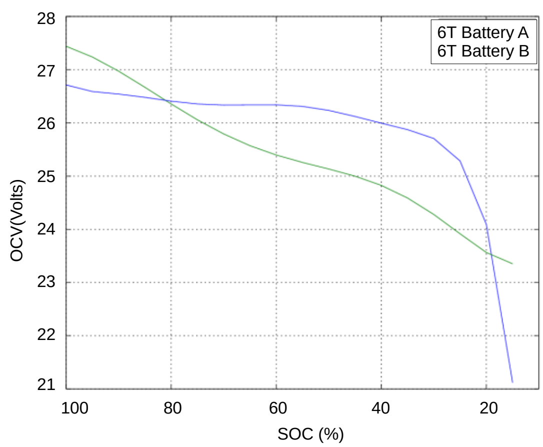

Figure 2: OCV(SOC) of lithium-ion 6T battery packs A and B. Battery packs are of dissimilar chemistry

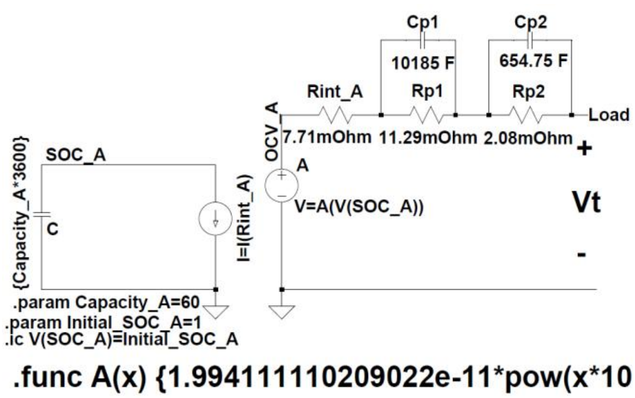

Figure 3. Equivalent Circuit model of 6T Battery A

current in each battery and the terminal voltage. This is compared with the actual test of the same batteries in the laboratory as a demonstration of the model accuracy. The batteries discharge from a SOC of close to 100% to approximately 5%. First, there is good agreement between the

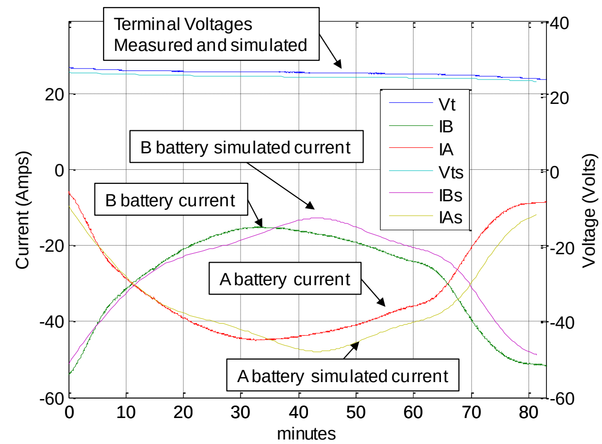

Figure 4. Simulation and test of 6T Batteries A and B in parallel: A||B with a constant current discharge load of 60 Amps

simulated and tested results, both in terminal voltage and currents. Second, the paralleling of these two dissimilar batteries results in current swings in which batteries take turns delivering most of the constant current load. Initially, 6T battery B delivers most of the load current down to the 12th minute. After the 12th minute roles reverse and 6T battery A delivers most of the current until the 68th minute, where roles reverse again afterwards. At their respective peaks the 6T battery B delivers up to approximately 85% of the load at the beginning and end of discharge, while the 6T battery of manufacturer A delivers also close to 85% of the load during the middle of the discharge (approx. at the 40th minute). These current swings may have several consequences. First, protection mechanisms, such as integrated battery circuit breakers, could be tripped in one or both batteries if the load current is sufficiently large and more than what a single battery can safely handle (not the case in Figure 4). Both batteries will not share the load equally even when the load can be safely handled by both batteries. The uneven share of the load, although momentary, is long enough to be a concern. Second, by intuition, and analogous to mechanical and natural systems, the continuous variation in load sharing is deemed detrimental for the long-term life of the batteries. To verify the latter statement rigorously, however, requires numerous and long tests, including relevant load profiles, and more than two batteries in different scenarios. However, we are certain that the increase in current swings increases the internal losses of the battery because the current Root-Mean-Square (RMS) in each battery increases, which implies an internal battery temperature increase, and battery temperature increases have been correlated to life degradation and aging in batteries before, see for instance [7].

As will be seen in the simulation results, SOC in both batteries will also swing and eventually converge. Therefore, it is inaccurate to state that SOC of batteries in parallel is the same. As expected the reason for all these observed variations in load sharing and SOC is the difference between the battery parameters (i.e., resistance and capacitance), and the OCV(SOC) differences among the paralleled batteries. As the batteries are better matched in parameters and OCV(SOC), the current swings are less pronounced. Also note that 6T battery packs have more than cells as internal components. They have circuit breakers and wire/bus interconnections that also differ from manufacturer to manufacturer and within the same manufacturer. These also affect the load and SOC balance among parallel batteries.

Modeling and simulation lets us explore few alternatives that are more difficult, lengthy and costly to test. In what follows we evaluate few scenarios using the models previously described.

Simulated A||B under High Load Currents

We simulated the parallel connection of batteries from manufacturers A and B (i.e., A||B) under high load currents. Figure 5 shows the voltage and currents for a 120A constant current load. The A battery swings between 75A and 10A, whereas the B battery swings between 110A and 45A. These current swings represent an increase in RMS current, which translates into an increase in losses.

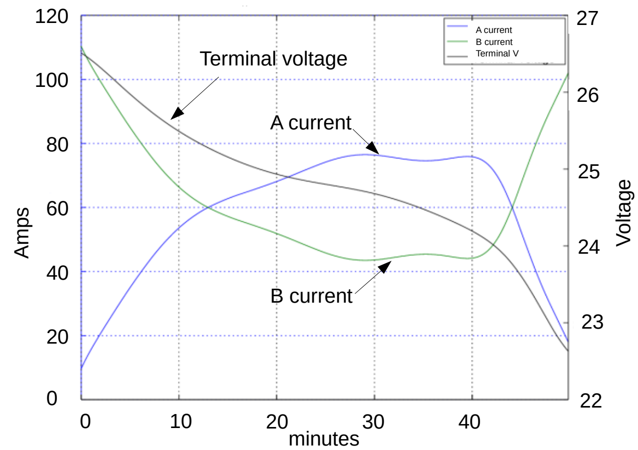

Figure 5.Battery type A in parallel with Battery type B (denoted A||B). Simulated currents and terminal voltages with a 120 Amps constant current load

The A battery RMS current is 63.1A and the B Battery RMS current is 66.7A, this is an increase of 5.2% and 11.1% over the case where each battery would deliver an equal current of 60A (for a total load of 120A). Power loss of each battery is shown in Figure 6 and the SOC of each battery in Figure 7. In all cases simulated and tested the final SOC of both batteries converged at the expense of large current swings. Note that two batteries in parallel do not have the same SOC while

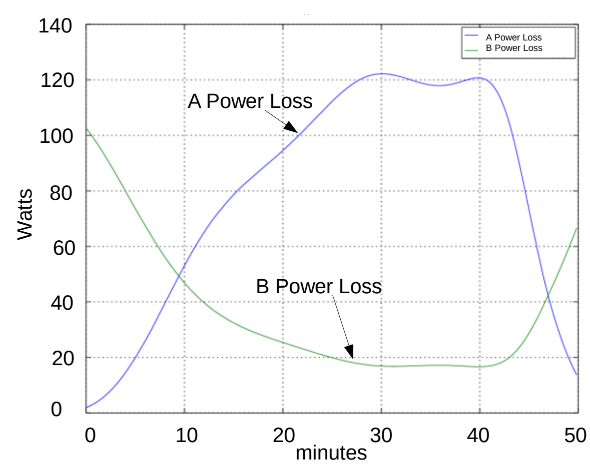

Figure 6.A||B simulated power losses with a 120 Amps constant current load

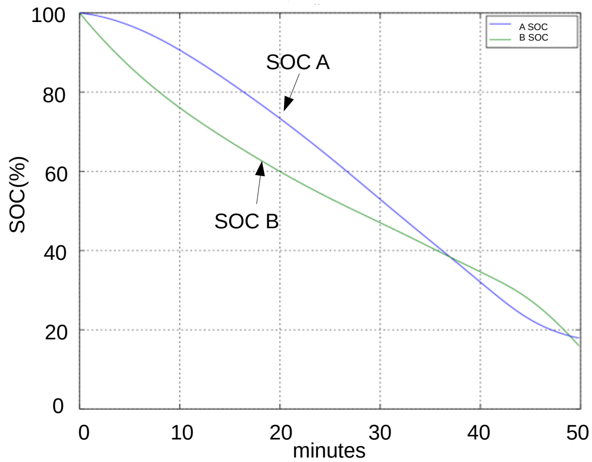

Figure 7. A||B simulated SOC for each battery with a 120Amps constant current load

discharging and therefore batteries in parallel are not strictly balanced in SOC. As the batteries are discharged, the batteries undergo different discharge dynamics which result in different SOCs for each battery over time as shown in Figure 7. If the load is turned off at points where the batteries have different SOCs, their SOCs can in fact diverge further via recirculating currents and due to their OCVs being different. For instance, if the load is turned off at the point in time where maximum difference in SOC happens, the result is shown in Figure 8 and Figure 9. The packs SOC's diverge while the load is off. At the point of reconnection (i.e., 97 min) the SOC of the A battery pack is 50% and the B battery SOC is 78%. During the disconnected interval the A battery charges the B battery. During this latter interval the battery is not doing any useful work even though currents are being generated. At reconnection time the currents peak, then swing again. At this point the B battery takes a larger share of the load and its RMS current during the time it delivers current to the load reaches 83.8A, this is an increase of approximately 40% over a balanced current of 60A, and it is expected to cause a large penalty in terms of long term life degradation of the battery.

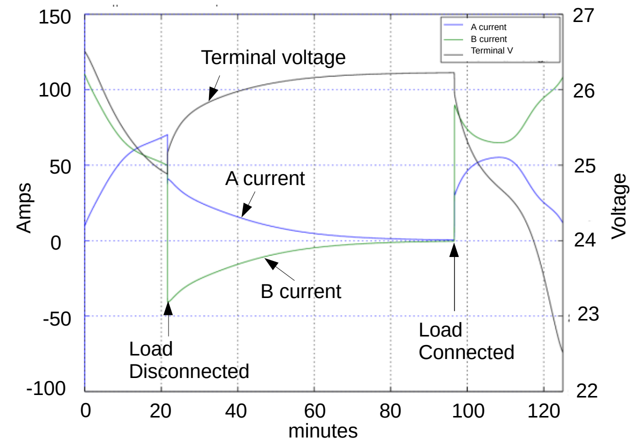

Figure 8. A||B simulated currents and terminal voltages with 120 Amps current load interrupted

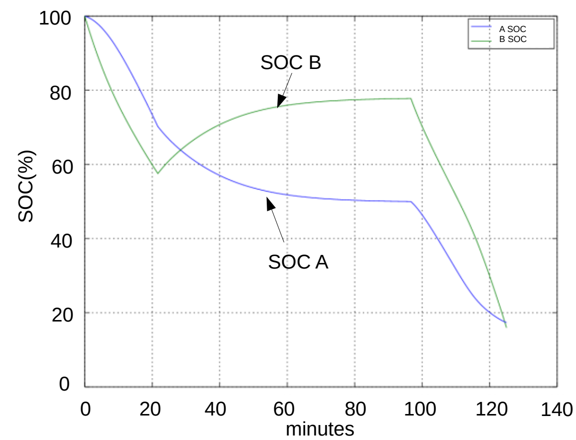

Figure 9. A||B simulated SOC with a 120 Amps constant current load interrupted

Simulated xA||yB

The Army specification in [2] calls for up to twelve 6T batteries in parallel. Therefore, we simulated scenarios in which we used more than two batteries. This is denoted as *x*A||*y*B, meaning *x* number of manufacturer's A batteries in parallel with *y* number of manufacturer's B batteries. For instance, Figure 10 shows voltages and currents when connecting one battery from manufacturer A with nine batteries from manufacturer B. The currents in all nine batteries are all equal - as their internal parameters are exactly the same - and quite uniform; however the current in battery A swings substantially making its load sharing unfair between 50 minutes and 150 minutes. Figure 11 shows the dynamics of the SOC of both battery types. Battery of manufacturer A (the minority battery) is overcharged at the beginning and its SOC changes rapidly due to the large current swing during the interval between 50 minutes and 150 minutes. Note that having nine B batteries in parallel is approximately equivalent to a single battery with nine times smaller internal resistance. Also note the OCV of the B battery is higher than the A battery at close to fully charged conditions as shown in Figure 2. This puts battery A at a disadvantage and explains the overcharging of battery A.

Table 1 summarizes the results of several simulations by paralleling dissimilar packs in multiple *x*A||*y*B combinations. The second and third columns show the RMS of the currents for battery A and battery B types respectively. The fourth column is the balanced current, which is the total load current divided by the total number of batteries in parallel, and the fifth column is the percentage of the minority battery current over the total load current. For instance, when paralleling nine A batteries with one B battery, the B battery shares 32.3% of the load, while the rest of the nine batteries the 67.7% of the load. Given the two batteries we modeled, the worst case of imbalance in the share of the load happens when a B battery is the minority battery. The B battery happens to have a smaller internal resistance than the A batteries, but more than two A batteries have not only a smaller internal resistance but also a higher OCV(SOC) during a large SOC interval in the middle of the OCV(SOC) curve (see Figure 2). This puts the B battery under disadvantage because several A batteries in parallel have less

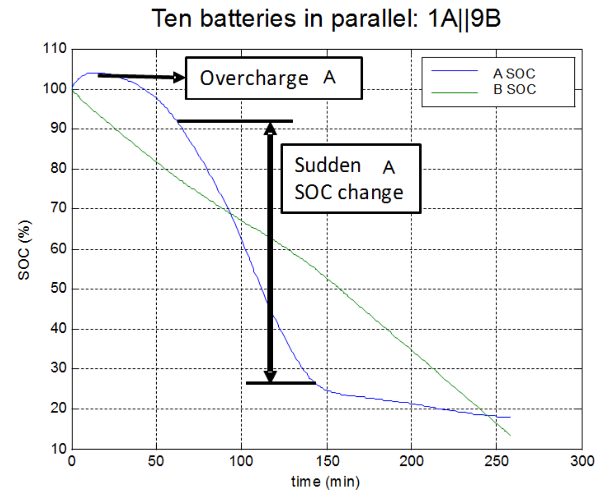

Figure 11. 1A||9B simulated SOC for each battery with a 120 Amps constant current load

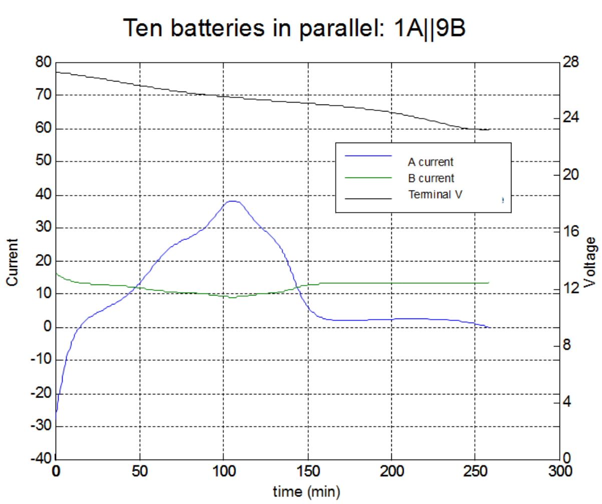

Figure 10. 1A||9B simulated currents and terminal voltages with a 120 Amps constant current load

Table 1. Simulation summary for some *x*A||*y*B cases

Case	A Bat. RMS current (A)	B Bat. RMS current (A)	Balanced current (A)	Minority battery current over total current
B majority; A minority				
A||9 B	18.50	12.70	12.00	13.9%
A||4B	30.05	26.02	24.00	22.4%
A||5 B	25.01	21.69	20.00	18.7%
A||2 B	42.42	45.61	40.00	31.7%
A||B	62.65	68.05	60.00	
A majority; B minority				
9A||B	10.46	44.83	12.00	32.3%
4A||B	19.58	62.83	24.00	44.5%
5A||B	16.24	58.77	20.00	42.0%
2A||B	37.83	62.09	40.00	45.1%

internal resistance and higher voltage, therefore the B battery must catch up in the only intervals where it has higher voltage which is at the beginning and end of charge. This can be seen for instance in Figure 5 where the currents of battery B peak at the beginning and end of discharge.

Discussion on Simulation Results

The swings in current represent a relatively small short-term efficiency problem for the two batteries tested, and under the conditions tested. At currents below 120 A the two specific battery types showed a good short-term (one-cycle) performance because of their low internal resistance. Larger load currents will decrease efficiency further due to even larger swings, which if left uncontrolled could damage the batteries, and are anticipated to degrade battery life, but this requires more testing for verification

Tests during charging (not shown) also showed swings in current which can degrade long-term battery life as well. Note that current swings also limit the speed at which the batteries in parallel are charged to a value below the minimum acceptable by any given battery.

As the number of batteries in parallel increase beyond two and there is a large imbalance in the number of battery types, the transient on the minority batteries (i.e., the fewer ones) becomes larger. This larger transient is due to the fact that the batteries in parallel will try to balance their SOC at the end of a discharge if their OCV(SOC) curves cross. The minority batteries will compensate for their segment of lower performance depending on their OCV(SOC) and internal resistance relationship to the majority batteries and a sudden change in current will be observed. This sudden change in current could stress the batteries and affect their cycle-life life. In some cases there could be overcharging. The latter has also been observed in tests performed in the laboratory when connecting A and B type batteries.

A way to balance or equalize the battery currents will minimize the possible stress incurred by the current swings, which in turn is expected to reduce the impact on battery cycle-life. Note that, for instance, an approach in which diodes are used to block circulating currents solve part of the problem, that is, the circulating current problem, and possible overcharge of some of the batteries, but cannot minimize the current swings on the batteries when power is delivered unevenly to the load.

PARALLEL INTERMIXING TESTS

In this section we present results of the direct parallel interconnection tests using two 6T batteries belonging to manufacturers A and B. We tested the following combinations: A||A, B||B, and A||B. The former two under constant current load, and the latter under constant current load and a silent watch profile.

A||A and B||B 60A Constant Current Load

Figure 12 shows currents and voltages for a parallel interconnection of two 6T battery types A, samples A-1 and A-2. The RMS currents are 31.2 A and 29.4 A, which are close to the balanced current of 30 A. The temperature rise under these

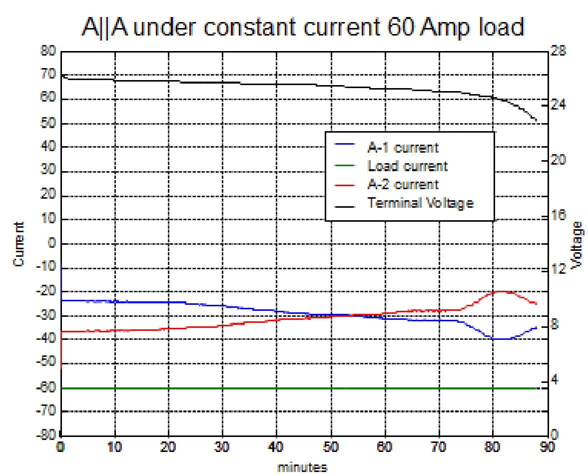

Figure 12. A||A current and voltages under a constant 60 Amps load

conditions was measured on the positive terminal and equaled 3.4°C over ambient of 27 °C. Figure 13 shows current and voltages for a parallel interconnection of two 6T battery of B type, samples B-1 and B-2. The RMS currents are 29.2 A and 30.9A, which are close to the balanced current of 30A. The temperature rise is only 1.3 °C. Paralleling these batteries demonstrated a good match, but further tests using batteries with perhaps a larger age difference or more extreme ambient temperatures and currents are necessary for a more comprehensive conclusion.

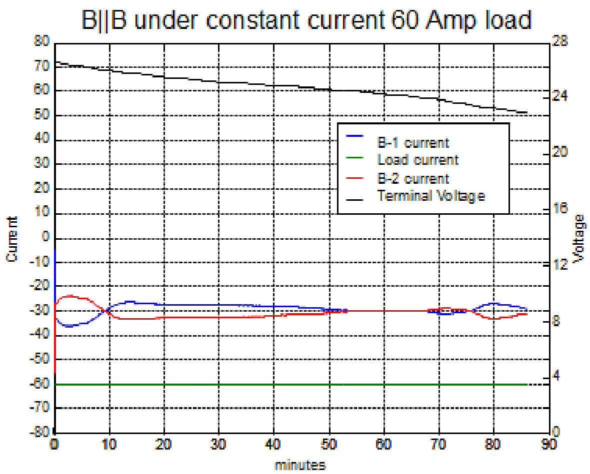

Figure 13. B||B current and voltages under a constant 60Amps load

A||B 80A Constant Current Load

Figure 14 shows currents and voltage for a parallel interconnection of dissimilar 6T battery types, samples A-1 and B-1. The RMS currents are 43.3A and 44.7A, which are 8.3% and 11.8% more than the balanced current of 40A. The temperature rise in this case is 3°C.

Table 2 summarizes some important parameters in all 60A constant current cases tested. The nomenclature used in this table reflects the type of batteries paralleled, and whether the current is controlled to be balanced or not. If the current is controlled the superscript c is added, such as in the second column of the table.

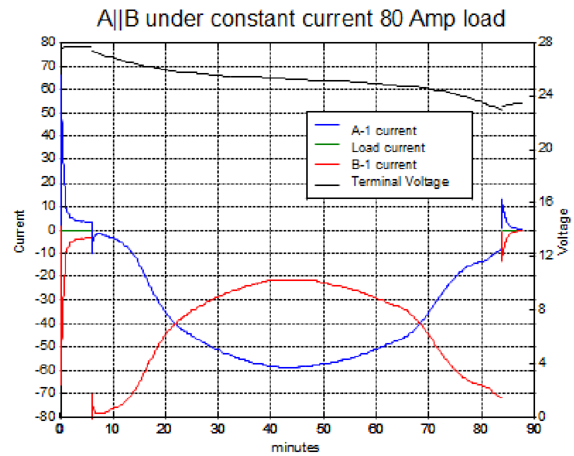

Figure 14. A||B current and voltages under constant load of 80 Amps

The control case in this table assumes batteries are discharged as if they were decoupled and current controlled. That is, currents in parallel controlled cases are 30A for each battery pack, and therefore performance is the same as a single discharge performance plus possible losses in the electronics used to make current balanced. The fourth column finds A||A^c - A||A to find the difference between direct paralleling the A batteries and controlling their currents, the 7th column does A||B^c - A||B, and the eight column A||A - A||B. The results in this table are consistent in that controlling currents to equalize, or balance the individual battery currents, is better, followed by the homogeneous direct interconnection cases, and finally the worse case is the direct heterogeneous case. This improvement is seen in

Table 2. Summary of test results at 60 A constant current load

Metric	A||A^C	A||A	A||A^C -A||A	A||B^C	A||B	A||B^C -A||B	A||A -A||B
Energy (Wh)	2,254	2,23 1	+23	2,274	2,173	+101	+58
Duration (min)	89	88	+1	90	87	+3	+1
Power (W)	1,528	1,52 2	+6	1,519	1,503	+16	+19
Temp. Rise (°C)	1.5	3.4	-1.9	1.5	3.5	-2.0	-0.1

all metrics captured: Energy extracted, delivered power, time discharging, and temperature rise.

At the tested conditions, including constant load of 60A, the specific battery packs tested (type A and B), and at the ambient temperature of close to 25°C, the differences in performance are deemed negligible for a one cycle discharge efficiency standpoint. However, note that this is the result obtained for the two specific batteries types tested and under the scenarios of room temperature and nominal constant current loads. Other cases that are important for future tests include: different battery packs (other than A and B), higher current levels, different ambient temperatures, dissimilar ages, and more than two battery packs in parallel.

The A and B batteries have compensating OCVs and internal resistances that make their parallel balancing possible. In particular, while the A OCV is larger in most of a discharge than a B battery, the B battery has substantially less internal resistance than the A battery. This will dampen the current swings in a parallel combination. Additionally, different ambient temperatures may also influence the results. This will be investigated in the future.

A||B Silent Watch Profile Load

We interconnected batteries A-1 and B-1 in parallel and applied an emulated constant current scaled silent watch profile load. The scaled silent watch profile is a series of periodic current pulses applied to the paralleled batteries as shown in Figure 15. Prior to this test we performed a simulation using the models of each battery type and obtained the result shown in Figure 16. Note that in this figure the load current is half the total current. There are three segments in the entire discharge cycle that are worth describing. During the first 30 minute segment battery B-1 delivers most of the peak load power, and during low load current conditions battery B-1 not only serves the load, but also recharges battery A-1. This could be particularly demanding for battery B-1 and can affect more drastically its cycle life when compared to the effort performed by battery A-1. During the second segment from minute 30 to minute 200 both batteries approximately share the peak load demands equally, although battery B-1 continues to have a slightly larger share of the load. During other than peak load demands battery A-1 is now serving all of the load, and even recharging battery B-1. This, however, is deemed more benign for battery A-1 as the load is actually less. During the third segment from minute 200 until the end battery B-1 goes back at sharing most of the load current and recharging battery A-1 during periods of low load. The presence of circulating currents among the batteries during period of low load condition is inefficient. These circulating currents are the result of voltage differences between the batteries, and perform no useful work. Battery B-1 sees larger peaks and a higher peak to average ratio in either direction (i.e., charging or discharging), which is unfair for this battery and may result in its poorer cycle-life.

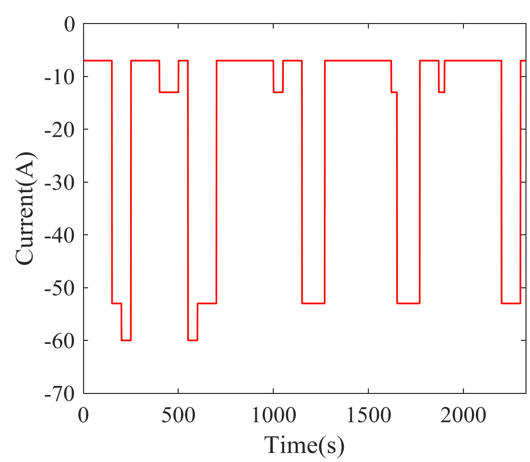

Figure 15. Constant current scaled silent watch profile used for A||B test. A single period is shown

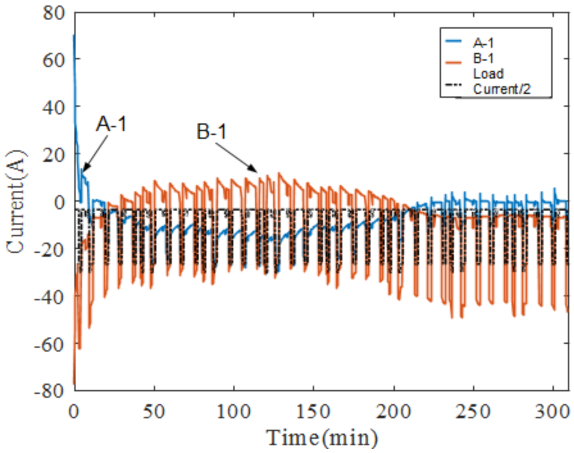

Figure 16. Simulated A||B under a constant current scaled silent watch profile

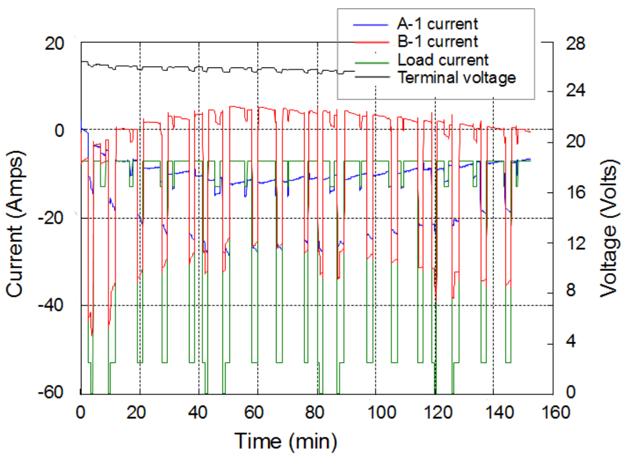

Figure 17. Test of A||B under a constant current scaled silent watch profile

The experimental test result is shown in Figure 17. The same conclusions can be drawn from these results. Battery B-1 sees more of the peak load demands at the beginning and end of discharge. In the middle section peak load demand is shared more equally, and during low load demands battery A-1 serves the load and recharges battery B-1. Overall, battery A-1 sees lower peak to average ratio demands. The time scales of the simulated result differs because the batteries under tests started from a point lower than 100% SOC to avoid overcharging, the test was also stopped before the batteries reached complete depletion, but other than that the simulation predicts similar results. These tests demonstrate unequal share of load as previous constant current tests, which, again, may affect the life of some batteries more than others. However, this must be demonstrated with long term tests.

Cycle Life Degradation

Due to equipment limitations we could only test up to 80A of load current. In all the direct parallel interconnections and tested scenarios the 6T batteries tested, either in homogenous or heterogeneous cases, resulted in few degrees of temperature rise and swinging currents that were within the limits of the tested battery performance and safety limits (i.e., there was never a protection trip event). Substantial short-term verification of performance degradation was also negligible. That is, we were able to parallel the batteries directly (with protection devices in between) up to 80A constant load with no major issues. However, as mentioned, the current swings observed are hypothesized to affect long-term life, which requires substantially more time to run, especially considering several ambient temperature conditions, different battery type permutations and higher load current levels. However, there is some evidence that the rate of discharge affects the long-term life of a battery as shown in [7]. There is less rigorous evidence on the effect the current swings observed in our tests have on the cycle-life batteries, which represent an interesting topic for further research. However, using previous data we can predict the potential effect of these current swings. Under these circumstances a model of capacity fade prediction is necessary to infer long-term performance degradation. We propose to use the model in [7]. This model of cycling induced capacity fade was performed for $LiFePO_4$ cells, which are a relevant chemistry used in 6T battery packs. The cells used for this study were 2.2 Ah 26650 cells. The importance of the results in [7] lies in the consideration of multiple factors in the prediction of capacity fade, including Depth of

Discharge (DOD), temperature, and rate of discharge. A model following the structure of the Arrhenius equation was found, where the specific parameters were fit to the measured data in a controlled laboratory environment. A model for low rates of discharge (i.e., C/2) and a model for high rates of discharge were obtained, and the most general model for capacity loss for capacities above C/2 is given by

$$Q_{loss} = B \cdot exp\left(\frac{-31700+370.3\times CRate}{R\cdot T}\right)(A_h)^{0.55} \qquad (1)$$

where B is the pre-exponential factor, R is the gas constant equal to 8.31446 $J\cdot mol^{-1}\cdot K^{-1}$, T is absolute temperature, Ah is the Amp-hour throughput, which is Ah = (Cycle Number) x (DOD) x (Full Cell Capacity), and CRate is the rate of discharge normalized to the full cell capacity (i.e., C/2, C, 10C, etc). The pre-exponential factor is taken as 15,560 in our simulations based on the average of the values in [7] for different C rates. The previous equation is used to obtain the capacity fade in % as a function of cycle number, DOD, temperature, and C rate. We realize the previous equation has been determined for a specific $LiFePO_4$ cell. Other cells and chemistries may have different results and must be validated for the particular cell used in the battery pack of interest. However, this is unimportant to illustrate the benefits of load balancing. Figure 18 shows the result of capacity fade versus cycle number for a Depth of Discharge (DOD) of DOD = 90% at 40°C, and C rates between 1C to 10C. Figure 19 shows the cycle number to end of life –defined as the 20% capacity fade– versus C rate. As the C rate increases the number of cycles to end of life- EOL decreases. That is, the battery reaches its EOL faster. This function is used to determine the life degradation of batteries in our parallel interconnection problem. To use this function we find an equivalent C rate delivered by a battery in a single cycle. We find this equivalent C rate by computing the RMS current delivered by a battery in a single discharged cycle. This is then used along with the curve in Figure 19 to determine the predicted life degradation. This represents a reasonable prediction that must be interpreted in relative terms rather than absolute terms, which implies we are more confident in the simulation results when interpreted as life degradation imbalances or relative differences as opposed to the absolute interpretation of the results, which

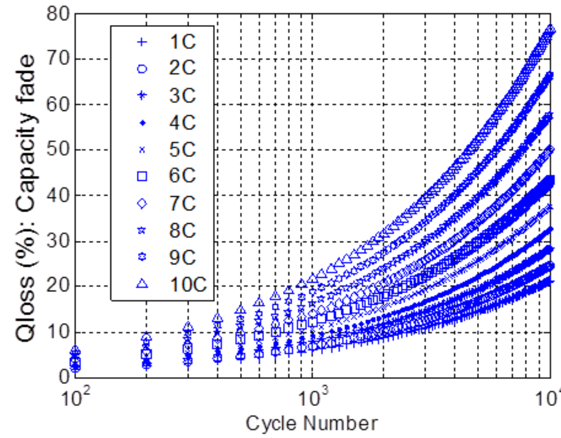

Figure 18. Capacity fade in a $LiFePO_4$ battery pack at different C rates. Temperature 40°C and DOD = 90%

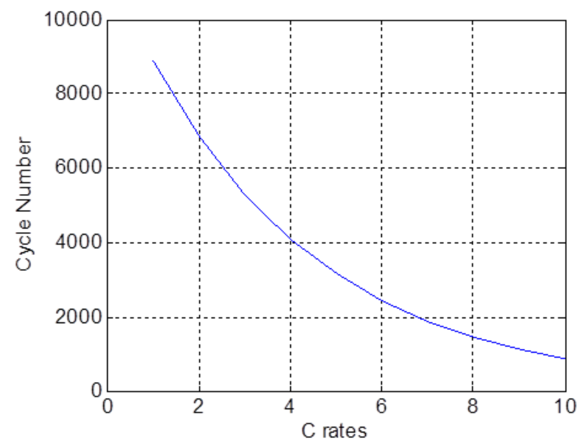

Figure 19. Capacity fade in a $LiFePO_4$ battery pack at different C rates. Temperature 40°C and DOD = 90%

must be obtained with actual tests. Using this approach Table 3 shows the life degradation expected for 6T packs in parallel as a function of the increase in RMS current and compared to the case where currents are balanced with an active electronic method. For instance, if RMS current is 20% higher than the balanced current then life degradation is expected to be 4.56% more than if currents are balanced. The results are consistent independent of the starting C rate used in Figure 19 and show a linear response. That is, whether the battery delivers, say, 1C or 2C the RMS current increase over that value results in the same % of cycle life degradation. We have seen that % of RMS current increases in our tests and simulations are between 5% and 10% for homogeneous cases in the batteries tested. We assume this same increase happens in this cycle life simulation. This increase represents between 1.14% and 2.29% decrease in cycle life when compared to the case were currents are balanced. The dissimilar case is between 3.42% and 10.25% degradation. In other words, a method to control these currents and balance or equalize them is predicted to improve cycle life between 1.14% and 2.29% in the homogenous case, and between 3.42% and 10.25% in the dissimilar case for the batteries tested and for the cases tested. Note that while the ambient temperature changes the cycle-life of the battery substantially it doesn't change the relative % degradation, but it may change the % increase in RMS current. Therefore the results presented here may turn out to be conservative. An important finding is that current balancing can help achieve longer cycle life even in homogenous cases. Another important factor of the approach described here is that it can be tuned to the actual 6T packs. At this point we lack sufficient data to accomplish this, but once this data becomes available the predictions can become more accurate.

Table 3. Predicted life degradation over balanced currents for different RMS current increases

% increase of RMS current	% of cycle life degradation over equalized current case using Delta converter
5	1.14
10	2.29
15	3.42
20	4.56
25	5.70
30	6.83
35	7.97
40	9.11
45	10.25

Controlling Current Swings

Up to this point we have assumed an electronic hardware is used to control the battery currents to achieve current balance or equalization. Current balancing attempts to avoid the current swings, which are hypothesized, based on analysis and simulations, to degrade the life of the batteries. During this project we have created a prototype capable of achieving current balancing and tested its performance with two dissimilar 6T batteries from the manufacturers A and B. Note that we are referring here to the equalization of the currents of each individual battery in parallel; this is different to active balancing methods used to balance a number of cells or batteries in series. The initial prototype developed is a power transfer converter designed to fit into a commercially available lithium-ion 6T battery from one of the currently available manufacturers. This power converter is 95% efficient with the potential to reach even higher levels of efficiency. We use two of these converters, one on each battery type. A picture of the first prototype of this converter is shown in Figure 20. With these converters we were able to control currents individually in open loop. That is, every converter (two in total) is connected to their 6T battery and to one another via CAN interface.

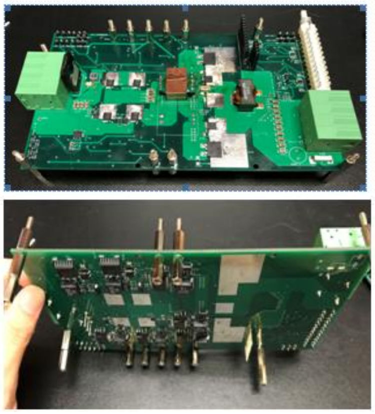

Figure 20. GEN 1 Power converter prototype used for equalizing currents in parallel intermixing tests.

One of the converters (either one) is then connected to a PC, which is used by a user to set the desired current out of the battery packs. This process can be done automatically to balance the currents. However, the purpose of these initial tests was to demonstrate that we can control currents individually at will, which is an important step towards the goal of balancing the currents automatically.

Figure 21 shows the terminal voltage and currents of each battery, where each battery is controlled by its associated converter. This test result is sub-divided in three sections. The observed fluctuation of the battery currents is a consequence of the user setting the current each converter is allowed to pass through to the load. In segment 1 the user tested the possibility of setting the currents of each battery to a level higher than the other battery. During the first 5 minutes battery B-1 is set to deliver more current, and between minute 5 and minute 12 battery A-1 is set to deliver more current. These current levels are set on the PC by the user and commanded to the respective converters via a single communication port. Segment 2 in Figure 21 shows a manual attempt to maintain the currents approximately equal. Since this is a human-driven control the currents are not perfectly balanced, but this clearly show the possibility for an automatic control to achieve balancing once it is implemented. Segment 3 shows the possibility to boost the total terminal voltage of the battery by using the prototyped converters. Note that the voltage of the batteries is different to the terminal voltage of the parallel interconnection due to the presence of the converters, which are also capable of balancing the battery packs in series while maintaining a regulated total terminal voltage.

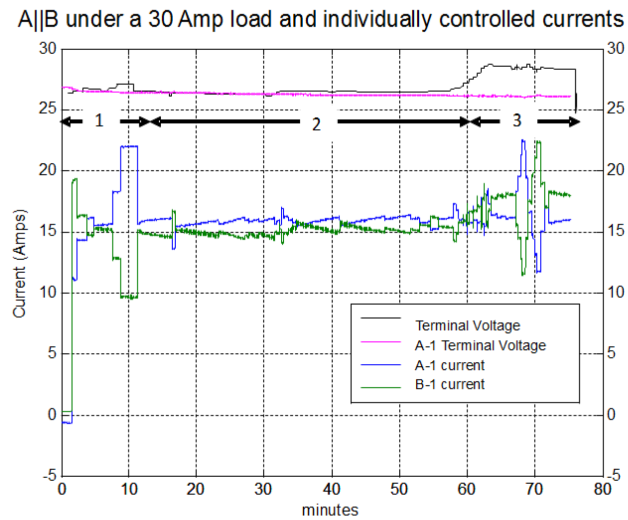

Figure 21. A||B with individually controlled currents under a 30 Amps load. During segment 2 current is maintained approximately balanced in open loop

CONCLUSION

The parallel interconnection of homogenous and heterogeneous lithium-ion 6T battery packs is required by the U.S Army. However, the direct parallel interconnection of battery packs results in current swings and circulating currents that may degrade efficiency and cycle life of the batteries being interconnected. To reduce these current swings, parallel balancing or equalization of currents is deemed a suitable solution to improve performance, especially in terms of cycle life. Our initial models anticipate improvements in cycle life by up to 3% in the homogeneous case and up to 10% in the dissimilar case at room temperatures and when performing current control equalization. Our estimates are subject to further validation and are expected to increase under higher current levels and dissimilar aged batteries. Further tests are needed to answer the question of how current swings change over long periods of time. In homogenous parallel interconnections current swings may decrease in amplitude because homogeneous batteries may naturally balance their internal impedances as they share the load in inverse proportion to their internal impedance values. However, current swing dynamics over long times in heterogeneous intermixing is less certain, particularly since the OCV(SOC) characteristic is likely to remain different as batteries age together.

Finally, the control of current swings via a power converter approach was demonstrated in this paper. The converters used for this work are also capable of balancing series interconnection of lithium-ion 6T packs without additional power paths and while maintaining a regulated terminal voltage.

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