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Modularized battery management for large lithium ion cells☆

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ABSTRACT

A modular electronic battery management system (BMS) is described along with important features for protecting and optimizing the performance of large lithium ion (LiIon) battery packs. Of particular interest is the use of a much improved cell equalization system that can increase or decrease individual cell voltages. Experimental results are included for a pack of six series connected 60 Ah (amp-hour) LiIon cells.

1. Introduction

The high energy density of lithium ion (LiIon) has made it the battery of choice in applications ranging from cell phones and laptops to large electric vehicles. Low power LiIon batteries typically consist of packs with a few small cells, but high power applications require packs that may have upwards of 80–120 large cells connected in series. When properly managed, these cells provide excellent service, but caution is required because even slight misuse can cause the cells to ignite. As might be expected, proper cell management becomes more of a design challenge as the size of the pack increases.

To provide safe operation and optimum performance, these large LiIon packs must be supervised by an electronic battery management system (BMS) that monitors and services each of the individual cells. At a minimum, a typical BMS must provide the following functions:

- Measure various temperatures throughout the pack.
- Measure the battery current.
- Measure each cell voltage.
- Adjust the charge on the cells so that they all remain close to the same voltage (equalization).

Temperature and current measurements are fairly simple and can be implemented with a wide variety of sensors. Cell voltage measurements are more complex since the series connected cells are at different voltage reference levels, and each measurement must be transferred to a common level. Equalization is probably the most challenging of these basic functions, and a wide variety of methods have been proposed [1–16,18]. This process is required because maximum charge is limited by the highest cell voltage, and maximum discharge is limited by the lowest. Because of the volatility of LiIon, each cell must be equalized individually, i.e., the pack cannot be trickle charged like a lead acid battery since even a slight overcharge on any cell can create a serious fire hazard.

To obtain good accuracy at a reasonable cost, one cell voltage measurement technique is to use a transconductance circuit to produce a current signal proportional to the cell voltage, and then change back to a voltage at the common reference level. A description of such a circuit will be provided later.

Although there are a wide variety of proposed equalizers (EQUs), the most common technique is the dissipation method such as in [9,16]. Dissipation, or D type, EQUs simply connect a small resistor across each cell until it discharges to the same value as the lowest cell voltage in the pack. Although simple to implement, D type EQUs are inefficient and can be very slow when equalizing higher capacity cells, e.g., 60 Ah cells. Charge transfer, or C type, methods also have been developed [1–5,9–12,15,18], but these systems are more complex and do not seem to have been widely implemented.

A relatively simple, yet very effective technique is to use a relay circuit [6–8,13,14] that provides both charge and discharge capability for the individual cells, i.e., a C/D type. Since it only processes the deviant cells, this system can provide a much higher equalization current and therefore is both fast and efficient. Miniature sealed

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relays can be used for accessing the cells, and some of these devices are quite small, as shown by the 5 A/30 Vdc relay in Fig. 6. Since the relays in this system only switch under no load, their reliability is quite high, and can easily exceed 5,000,000 lifetime operations [17]. This far exceeds the expected number of lifetime operations in EQU applications since the time between relay operations typically varies between 10s of seconds to several minutes.

Details of an experimental BMS with a C/D EQU are included along with comparisons with a D type EQU for a LiIon pack containing 6 series connected 60 Ah LiIon cells. The test results for these two systems show improvements in equalization time by factors ranging from 2× to 15× for the C/D EQU, depending on the type of imbalances in the cells. It is also shown that these factors of improvement will tend to increase in proportion to the number of series cells in the pack. This 6 cell system is similar to earlier versions that have been implemented successfully in much larger systems, one of which was for an autonomous underwater vehicle which contained 80 series connected cells in each of 5 battery packs [13].

However, there are some major differences between the present C/D EQU and that described in [13]. First, this new system uses simplified relay logic that has fewer contacts per cell and simpler relays. Second, the new EQU uses charge/discharge devices can be turned off briefly while the cell voltages are measured. This allows the EQU and the measurement circuit to share the same set of sensing lines, whereas the system in [13] required two separate sets of lines. This provides a major reduction in the size of the wiring harness. Third, since the small cell charger in the old EQU is operating while the voltage measurements are performed, EMI from this charger can increase the measurement error. In the new system, this EMI is not present since the cell charger is turned off while the measurements are taken. Of course the cost of a C/D type is probably higher than a D type, but the total system cost increase is slight and not an issue for applications that require higher performance.

This present study also provides data that compares the performance of the C/D EQU to the more conventional D type. Ref. [13] was only intended as a brief introductory paper, and no C/D vs. D type comparisons were presented since a D type for the same size battery pack was not available.

2. Battery management system (BMS) modularization

To increase reliability and decrease the length and bulk of the wiring harness between the cells and the BMS, a large battery pack is usually divided into separate sets of cells. This type of BMS includes a Local control module for each set, and a Central control module to coordinate the Locals via a serial data link such as CAN (controller area network). The block diagram for a typical system is shown in Fig. 1, which is similar to those presented earlier in [6,8,9].

Each of the Locals, L1–L4, in Fig. 1 consists of two parts, an electronic control unit (ECU) and an equalizer (EQU). Each ECU contains a microcontroller to perform at least the following functions:

- Communicate with the Central.
- Perform temperature and cell voltage measurements.
- Direct the EQU to equalize a specific cell(s).
- Perform safety checks and operations.

The EQU merely implements the ECU equalization instructions, i.e., it applies a supplemental charge (boost) or discharge (buck) to the specified cell.

The Central in Fig. 1 also contains a microcontroller that communicates with the Locals and processes the data they send. The Central has complete control of the pack since it contains the temperature and voltage data from all of the Locals. As a safety precaution, it also controls the 12 Vdc power to the Locals. This is necessary since the Local EQUs have the ability to boost or buck the cells. In the event of a Local malfunction, the Central can disable the 12 Vdc source to insure that no unmonitored boost or buck can

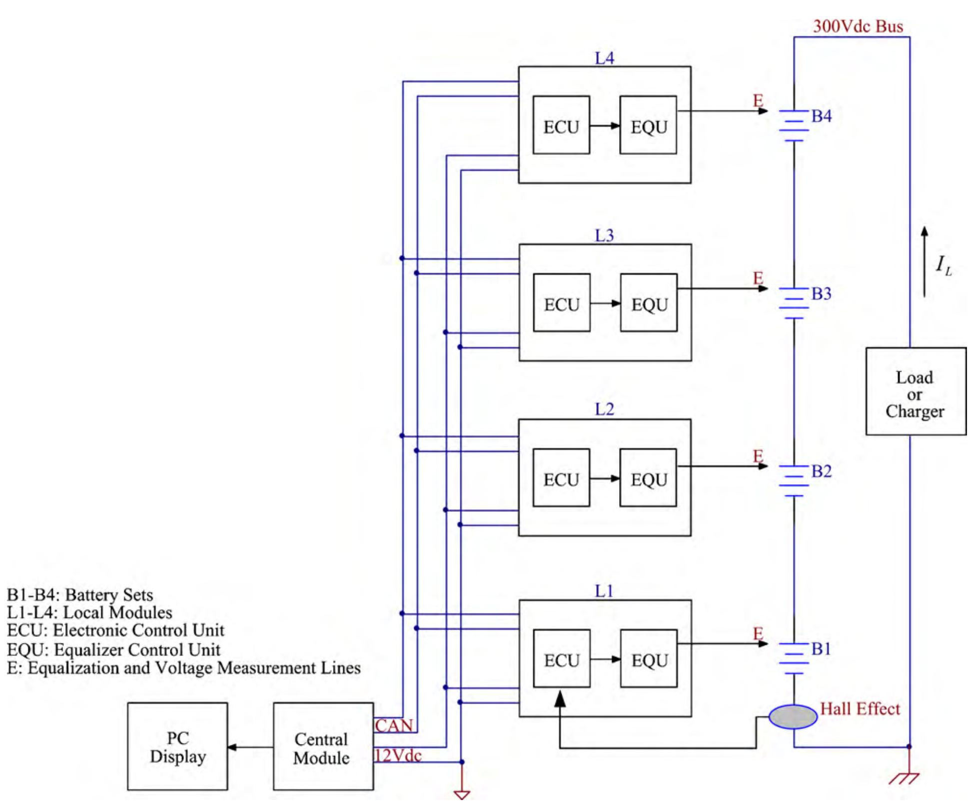

Fig. 1. Modularized battery stack and BMS with four locals of 20 cells each.

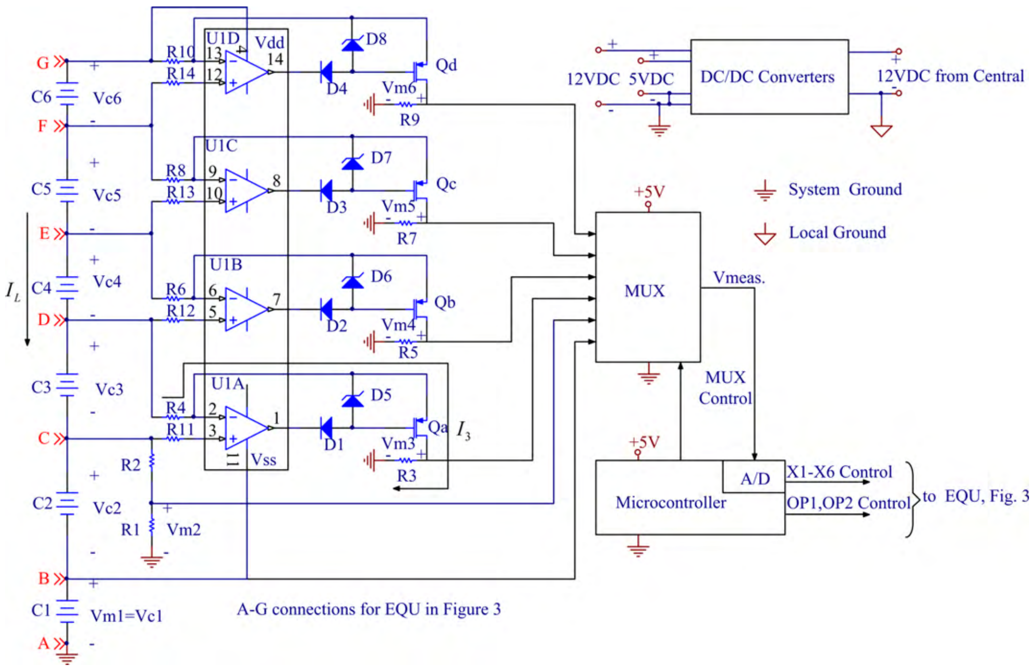

Fig. 2. ECU cell voltage measurement circuit.

occur. One option for powering this 12 Vdc source is to use a small DC–DC converter connected to the battery pack itself.

Periodically, e.g., every 10 s, the Central requests all the Locals to simultaneously measure each of their assigned temperatures and cell voltages. The voltage measurements at each Local are sequential, but delays between the measurements should be minimized to reduce the “skewing effect” which can occur if the battery current has large and rapid variations during the measurement period. Sample and hold circuits can be used to further reduce the skewing effect, but this adds significant cost and is unnecessary in many cases. The Locals send all of their data to the Central once the measurements are complete.

The Central scans all of the data for the pack to determine if any limits have been exceeded, and if so, corrective action is taken. The average cell voltage is calculated next, and the highest and lowest cells for each Local are identified. Those cells exceeding the average by a specified tolerance are selected for equalization, and this data is sent to the Locals along with the next measurement request. However, once a cell is selected by the EQU, it is not released until its voltage has been adjusted to match the average value. This is done to avoid excessive relay operations, which could decrease relay lifetime.

As an example, suppose the BMS in Fig. 1 has 4 Locals of 20 cells each and each Local EQU can service two cells simultaneously. Therefore this 80 cell system can only equalize 8 cells at the same time, but as will be shown, relatively large EQU currents can be used, and this provides a much faster and more efficient process than a D type EQU. This particular arrangement was developed for an autonomous underwater vehicle (AUV) for the Naval Oceanographic Office [13] and is now in the test phase.

For applications where it is necessary to charge the pack close to an SOC = 100% (State of Charge), it is important for the charger to be controlled by the Central. To avoid overcharge, none of the LiIon cells are allowed to exceed 4.2 V, which corresponds to an SOC = 100% at open circuit. Therefore the charger must always operate in a constant current mode, which should be controlled by the Central. This is necessary because only the Central knows all the cell voltages, i.e., control of the charger is determined by the individual cell voltages, not total pack voltage.

For example, charging a 60 Ah pack might begin at 30 A, but the highest cell voltage may reach 4.2 V before the other cells are fully charged. To fully charge the rest of the pack, the current should continue, but it must be reduced in steps by the Central each time the maximum cell reaches 4.2 V. Because of the series resistance of the cell, each time the current is reduced the maximum cell voltage will drop slightly below 4.2 V, and the pack will continue to charge at the lower current. Thus the original 30 A might be reduced in 5 A steps until it reaches 5 A, after which it is reduced in 1 A steps, finally stopping when 4.2 V is reached at 1 A.

The above example only describes the control of the external charger, and it does not include the action of the EQU which is actually operation simultaneously with the charger. Once the highest cell reaches 4.2 V at a charge current of 1 A, the charger turns off, and the C/D EQU will continue to boost the low voltage cells (buck operation stops) until all cells are within 10 mV of $V_{max} \approx 4.2$ V.

Normally the Central does not have control of the discharge current, but it can disconnect the load whenever the lowest cell exceeds the minimum voltage limit. This value varies somewhat for various cell manufacturers but usually is close to 3.0 V.

3. Cell voltage measurement

Since the maximum cell voltage is 4.2 V, each cell could be measured directly by a 5 V A/D converter if the cell voltage and the A/D were at the same reference level. For a set of series cells such as C1–C6 in Fig. 2, the easiest way to do this would be to measure C1 directly and use resistive voltage dividers for C2–C6 instead of the circuit shown in the figure. However, the error tolerances of these dividers can build to unacceptable levels when measuring more than 5 or 6 cells. This is because each divider actually measures the sum of the cell voltages at its connection point, and the cell voltages themselves are obtained from the differences between the divider measurements. For example, suppose we measure the top cell in a stack of (20) 4 V cells, each measurement having a tolerance of ±0.1%. The measured value for the 20th 4 V cell could be as large as, $20 \times 4 \times 1.001 - 19 \times 4 \times 0.999 = 4.156$ V, which corresponds to an error of 3.9%.

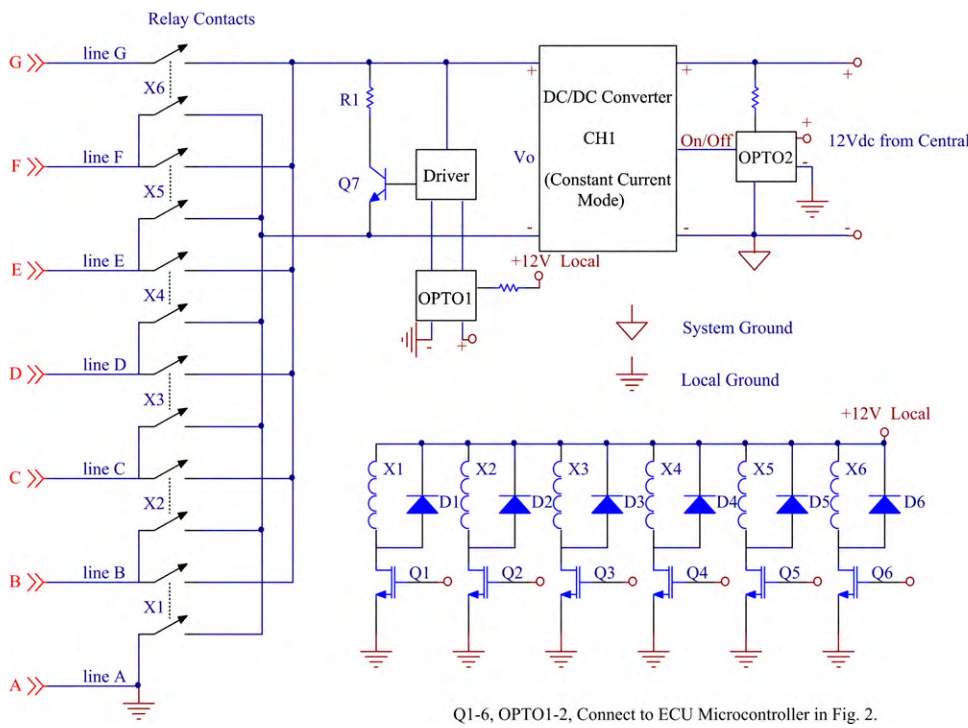

Fig. 3. C/D EQU circuit (connects to cells in Fig. 2 via A–G).

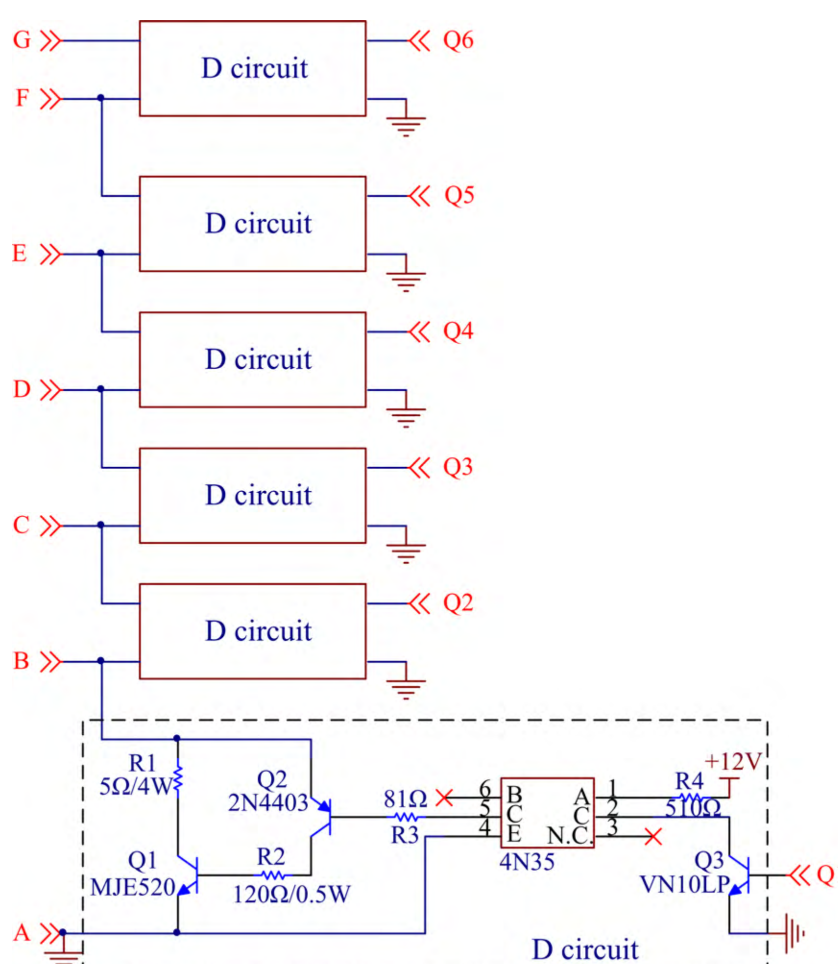

Fig. 4. Experimental D type EQU circuit.

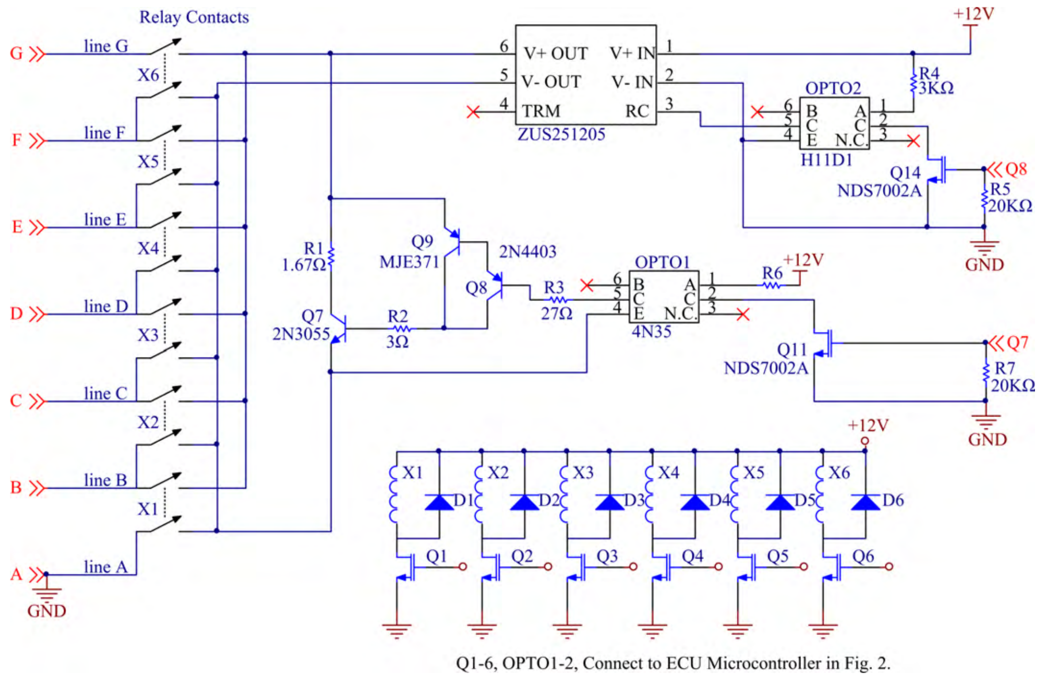

Fig. 5. Experimental C/D EQU circuit.

Accuracy is significantly improved using the actual measurement circuit in Fig. 2. In this circuit V_{c1} is measured directly, and the measured V_{c2} is obtained as follows:

$$V_{m1} = V_{c1} \tag{1}$$

$$V_{meas.c2} = \frac{R_1}{R_1 + R_2}(V_{c1} + V_{c2}) - V_{m1} \tag{2}$$

Thus as far as the sensing circuit is concerned, the accuracy of V_{m2} depends only on the tolerances of R_1 and R_2. For the V_{m3} measurement, note that in the active region, the input voltage to U1A must be virtually zero, i.e.,

$$V_{c3} = I_3 R_4 \tag{3}$$

Which means U1A will increase the source to gate voltage of Q_a until the condition in (3) is met. Therefore,

$$V_{m3} = I_3 R_3 = V_{c3}\frac{R_3}{R_4} \tag{4}$$

$$\text{or if } R_3 = R_4, \text{ then } V_{m3} = V_{c3} \tag{5}$$

V_{m3} depends only on the tolerances of R_3 and R_4, similar to V_{m2}. R_{11} is used only to cancel the effect of any offset voltage caused by any small leakage currents at the U1A input.

The quad op amp in Fig. 2 is powered by the battery pack itself, but it must be connected so that V_{dd} is sufficiently above and V_{ss} is sufficiently below any of the input voltages. Although this requirement is easily met, it could also be avoided using other types of op amps. D_1 and D_5 are added as a precaution to protect Q_a from any excessive momentary voltages that may occur when the sensing lines are connected and disconnected from the battery cells.

The operation is similar for V_{m4}–V_{m6}, and an additional op amp can be added for each additional cell. For example, 20 cells would require 18 operational amplifiers, which could be implemented using 5 quad packages such as the common LM324. If more than one Local is used, the 12 Vdc supply and the Local cannot share a common ground since the grounds for the different Locals are connected to different voltage levels in the battery pack. Thus in general, different grounds are required for the Local and the 12 Vdc supply, as indicated in Figs. 2 and 3.

4. Equalization

The basic EQU circuit chosen for this system is shown in Fig. 3 [14]. Other relay configurations such as those in [6,8,13] also can be used to reduce the number of relays slightly, but this system was chosen because of its relative simplicity. Note that the cells are purposely not shown in this circuit, but only the points A–G which connect to the circuit in Fig. 2, i.e., the two circuits share the same sensing lines that connect to the cells. This provides an important reduction in the size of the wiring harness, but it also means that the EQU should be turned off while measuring the cell voltages, otherwise parasitic voltage drops due to the EQU currents will create errors in the measurements. Fortunately, this is easily done using optical couplers OPTO 1 and 2, and does not require any operations of the relays.

A cell can be selected for equalization by one of the SPDT relays X_1–X_6 in Fig. 3, which are controlled by an ECU similar to that in Fig. 1. A cell boost is supplied by the small charger, CH_1, which

Fig. 6. 60 Ah lithium ion cell and 5A/30Vdc SPDT relay.

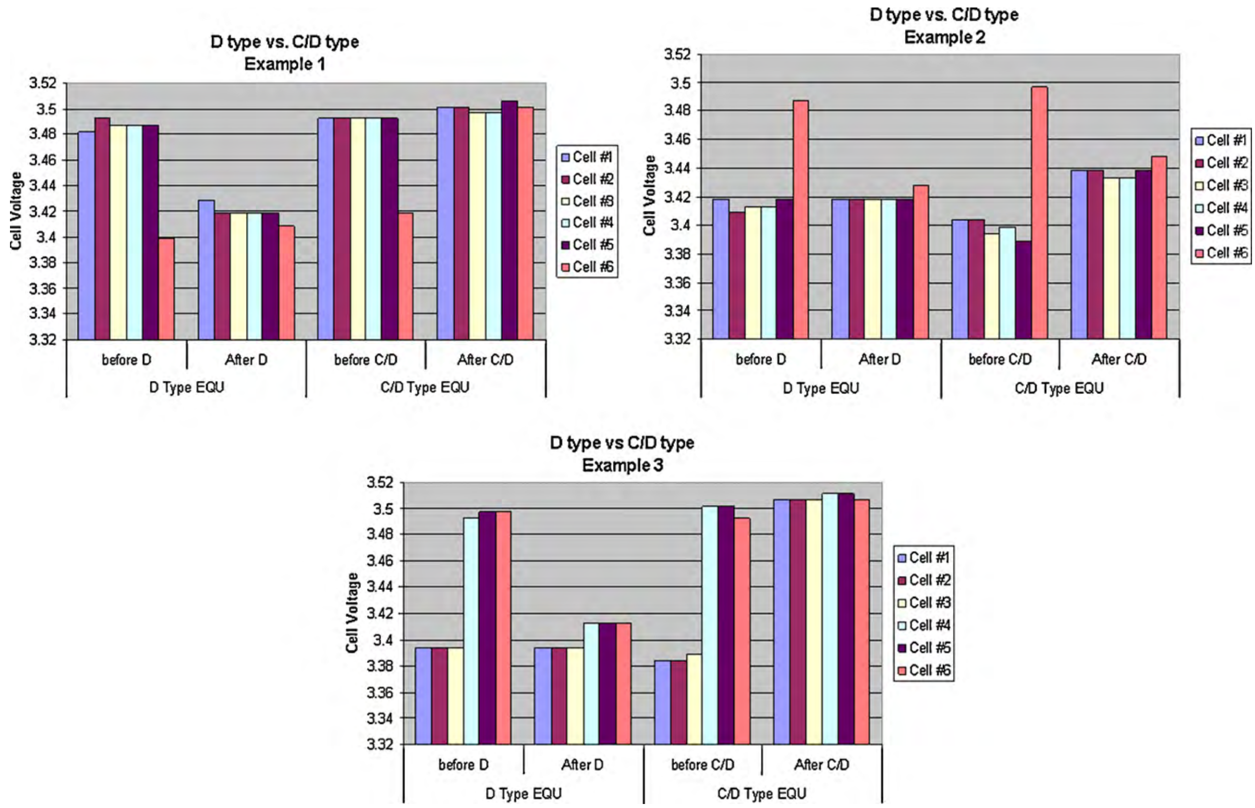

Fig. 7. Equalization results for the D and C/D EQUs.

is simply a small DC/DC converter operating in the constant current mode to provide about 5 A to the selected cell. If a cell buck is required, this is achieved by connecting R_1 across the cell via Q_7. This current also can be set to about 4–5 A, but in the actual circuit this was reduced to about 2–3 A. to reduce the power rating of R_1. This current of course varies with the cell voltage which varies from 3 to 4.2 V.

At the start of a typical cycle, e.g., every 10 s, the Central tells the Local ECU if a specific cell needs a buck or boost from the EQU. The ECU then activates the proper relay, and turns on Q_7 or CH_1, as required. Although the relays are rated to switch the EQU currents under load, Q_7 and CH_1 are always turned off before switching the relays in order to reduce the stress on the contacts. As mentioned earlier, to avoid cell voltage measurement errors due to the EQU current, Q_7 and CH_1 are also turned off while the cell voltages are being measured, typically a few milliseconds.

5. Experimental results

To compare the performance of D vs. C/D equalization, an experimental 6 cell version of each type was built and tested [14]. The D type circuit is shown in Fig. 4, and the C/D type is in Fig. 5. The cells used in these tests were the GAIA HE-602050 3.6 V/60 Ah units identical to the one shown in Fig. 6. Fig. 6 also shows one of the miniature Panasonic SPDT relays.

When one of the discharge circuits in Fig. 4 is turned on it will draw a discharge current of about 0.55 A when the cell voltage is 3.5 V. Therefore if 5 of the 6 cells are being equalized, the dissipation will be $5 \times 3.5 \times 0.55 = 9.63$ W.

To provide a common basis of comparison, R_1–R_3 in Fig. 5 were selected so that the dissipation in the EQU buck mode would be close to the maximum value of 9.63 W, calculated above for the D type in Fig. 4. The final result was about 2.65 A at 3.5 V or 9.28 W, which includes the total current drawn by Q_7–Q_9. The cell boost current in Fig. 5 was somewhat higher, about 5 A at 3.4 V.

This seems to provide a logical basis of comparison, but it should be noted that the difference in performance would be more pronounced for a larger number of cells. For example, suppose 19 of 20 cells were being equalized by the D EQU.

To maintain the same level of maximum dissipation, the allowable current for each cell would only be 0.145 A instead of 0.55 A. Therefore because of the lower current, the equalization time for a 20 cell D type EQU would be about 4× that for a 6 cell D type EQU.

To compare the performance of the D and C/D EQUs, a series of tests were conducted for three different cases of deliberate cell voltage imbalance. The pack was at rest during these tests, so the only cell currents were those due to the EQU. The resulting cell voltages before and after the tests are shown in Fig. 7 for all three examples. The criterion for equalization was for each cell to be within ±10 mV of the Vavg value for all six cells. The initial conditions for these examples are summarized in Table 1, where ΔV = voltage deviation.

Table 1
Initial conditions for Examples 1, 2, and 3.

Example	Symbol	D type (V)	C/D type (V)
1	Vavg	3.472	3.479
	$V6$	3.399	3.418
	ΔV	−0.073	−0.061
2	Vavg	3.427	3.414
	$V6$	3.487	3.497
	ΔV	0.060	0.083
3	V123avg	3.394	3.386
	V456avg	3.495	3.498
	ΔV	0.101	0.112

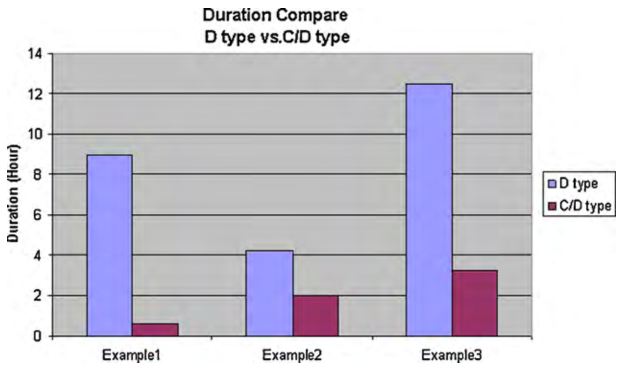

Fig. 8. Equalization time required for D and C/D EQUs.

As expected, the results shown in Fig. 7 indicate both EQUs were able to eventually equalize the pack, but the final cell voltages were somewhat higher for the C/D, especially for Examples #1 and #3. This also is to be expected since the boost capability of the C/D was used to an advantage in these two cases. Somewhat surprising was the higher voltage in Example #2 since one would expect the only operation to be a buck (discharge) for cell 6. However, once cell 6 reached *V*avg for the C/D type, other cells apparently were below *V*avg by more than 10 mV, and therefore some additional boost operations were performed until the pack was equalized.

Perhaps of more importance are the graphs in Fig. 8 showing the equalization time required for each of these three examples. In Example #1 where cell 6 was lower than *V*avg, the time required for the D type was 9 h, but the C/D type required only 0.6 h. In Example #2 where cell 6 was higher than *V*avg, the D type required about 4.25 h, whereas the C/D type required only 2 h. Finally for Example #3 where there were 2 groups of 3 cells each with an initial difference between the 2 groups, the D required 12.5 h, but the C/D required only 3.25 h.

Although the C/D type was always much faster than the D type, the differences do not necessary match the differences in the nominal values of the equalization currents for the two types. Reasons for this include variations in the actual currents during boost or buck and nonlinearities in the charge vs. voltage characteristics for the cells. Also, in most cases the C/D type will employ a combination of boost and buck operations which use one value of current for boost and a different value for buck, i.e., 2.65 A for buck and 5 A for boost.

6. Conclusion

This modularized BMS provides a relatively simple yet accurate means of managing the large LiIon packs such as those found on commercial electric vehicles or aerospace applications. This includes a C/D type EQU system that has proven to provide much faster equalization than a comparable D type. To minimize equalization time for all types of cell voltage imbalance, the C/D EQU provides both boost and buck equalization, and it can be used while the battery is in charge, discharge, or at rest. This is borne out by the experimental results for three cases which indicate improvements in equalization time by factors ranging from 2× to 15×, depending on the type of imbalance. Because of its boost capability, the C/D type should always be significantly more efficient than the D type. If desired, it also can be programmed to operate only in the boost mode, although this will usually increase the equalization time somewhat.

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