A Bilevel Equalizer for Lithium Ion Batteries

Ngalula Sandrine Mubenga, *Member, IEEE*, and Thomas A. Stuart, *Senior Member, IEEE*

***Abstract*— Electric powered aerospace vehicles such as drones (UAVs) are now in widespread use, and recent reports indicate their development is going to accelerate. Virtually all of these types of UAVs now use lithium ion batteries (LIB), but LIBs require electronic equalizer circuits (EQU) to balance the cell voltages. Several types of EQUs have been proposed, but all present versions have cost and/or performance problems. However, a new type of hybrid EQU called the Bilevel Equalizer (BEQ) has been proposed that avoids these problems.**

***Index Terms*—Lithium ion, equalizer, bilevel, battery management, passive, active, discharge capacity.**

I. Introduction

ELECTRIC powered aerospace and military vehicles such as drones (UAVs) are now undergoing intense development, and these use lithium ion batteries (LIB) almost exclusively. However, all large LIBs require equalizer circuits (EQU) to balance the voltages of the series connected cells (perhaps 200 or more), and all EQUs currently in use have certain cost and/or performance problems. However, previous references [4, 5] have described a new type of hybrid EQU called the Bilevel Equalizer (BEQ) that mitigates these problems. This present study provides further insight into the BEQ design and proposes possible criteria that can be used for designing both the active and passive parts of the system.

The vast majority of large LIBs presently use passive equalizers (PEQ), which simply use a transistor to connect a resistor in parallel with each cell until it discharges to the same level as the lowest cell voltage in the pack. A typical circuit is shown in Fig. 1. PEQs are popular because they are simple and cheap, but heating and energy loss are obvious disadvantages. PEQs also are of no use during discharge since they cannot transfer charge to lower voltage, and thus the Ah discharge capacity of the battery is equal to that of the worst cell in a pack of perhaps 200-300 cells. This problem is usually not important when the cells are new and well balanced, but as they age, large variations develop, and the loss in discharge capacity due to even 1 or 2 weak cells can become serious. This reduces the useful life of the battery, which of course increases the lifetime cost. PEQ heating problems also must be considered. This severely limits the size of the equalization currents, typically to less than 200-300 mA, and this limits the ability of the PEQ to equalize the pack when large imbalances are present.

There are several types of active equalizers (AEQ) [1-3] that transfer charge between cells and thus avoid the problems with PEQs, but they are rarely used due to their complexity and much higher cost. All of these prove to be expensive even for modest AEQ currents, and the cost becomes prohibitive for the higher AEQ currents that are required for large cell imbalances and load currents.

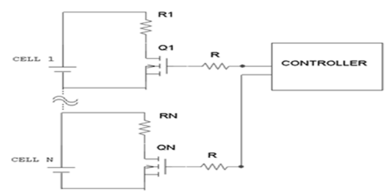

Fig. 1. Basic PEQ Circuit.

The limitations of PEQs are widely recognized, but since presently available AEQs bring new cost and complexity problems, designers of battery management systems (BMS) have avoided them. Another problem is system inertia. Once a company has an operational BMS with a PEQ, they are reluctant to change, especially if the advantages of an AEQ do not become important until after a few years of service. Thus, these problems persist, and if left uncorrected they will degrade the lifetime performance of these large LIB applications.

II. Bilevel Equalizer

This quandary has motivated the design of a new EQU that provides performance close to an AEQ, but with only a modest cost increase above a PEQ. This circuit is a hybrid AEQ/PEQ called the Bilevel Equalizer (BEQ) because it provides equalization at two different voltage levels. In this system, the battery is organized into sections of series connected cells. The AEQ portion balances the section voltages, and there is a PEQ for each section which balances the section cells. This is especially advantageous for large applications such as those for electric aerospace vehicles because the BEQ can be implemented by adding an AEQ to an existing PEQ system with only minor changes to the original hardware.

Fig. 2 (a) shows the AEQ circuit that constitutes the active part of the BEQ. In this system B1 – B3 represent sections of series connected cells. The number of cells/section is usually 4 to 14, and for sections of 12 -14 cells the efficiency is typically

This research was sponsored by grants from the Ohio I-Corps Program Grant #60050257 and the Ohio Third Frontier Technology Validation and Start-up Fund Grant TEC20160471.

Ngalula Sandrine Mubenga is with Electrical Engineering Technology Department, University of Toledo , Toledo, OH 43606 USA (e-mail: Ngalula.Mubenga@ utoledo.edu).

Thomas A. Stuart is with Electrical Engineering and Computer Science Department, University of Toledo , Toledo, OH 43606 USA (e-mail: Thomas.Stuart@ utoledo.edu).

in the range of 85 to 90%. Components Q1, Q2, and L1 constitute one AEQ unit, so this circuit has 2 units. To transfer charge from B1 to B2, Q1 is turned on for $0 < t < t1$, and i1 flows into L1. At t1, Q1 turns off and i1 flows from L1 into B2 via the body diode of Q2. The period $t2 - t1$ is less than t1 because of a slight gap in the FET gate drive signal and parasitic losses. Since the B's can consist of any number of cells, a 196 cell battery might be organized into 14 sections of 14 cells each. This would only require 13 AEQ units (number of sections – 1), whereas an AEQ with a bidirectional DC-DC converter for each cell would require 196 AEQ units. Therefore if both types are operated at the same value of equalization current, the cost of the AEQ in the BEQ will be much lower than using an AEQ for each cell. Another important cost advantage is the absence of the transformers that are present in virtually all other AEQs.

AEQs with a DC-DC converter for each cell are presently limited to EQU currents less than 1 Adc, and they are still quite expensive even at these low current levels. Currents in this range also are inadequate for larger batteries that might require EQU currents in the range of 5 Adc or more. Because of its relative simplicity and the low number of AEQ units, the circuit in Fig. 1 can easily be designed to economically provide equalization currents in these higher current ranges.

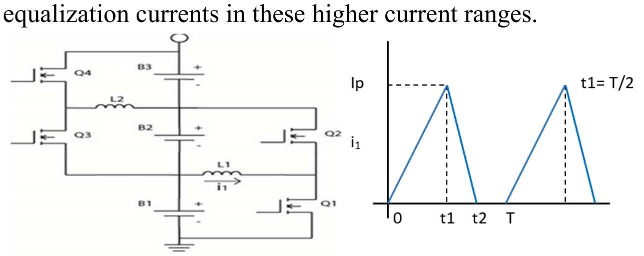

Fig. 2. AEQ with 2 Units (a) Schematic; (b) Current in L1

The block diagram of a BEQ where the cells are divided into 5 sections is shown in Fig. 3. This might represent a 60 cell LIB with 12 cells/section and a maximum voltage of about 240 Vdc. This system uses a PEQ for each section to provide equalization at the cell level for the cells in that section. AEQ units identical to those in Fig. 2 (a) are used to equalize the section voltages. The AEQ boxes shown in blue in Fig. 3 are the only new hardware items needed to convert a PEQ to a BEQ.

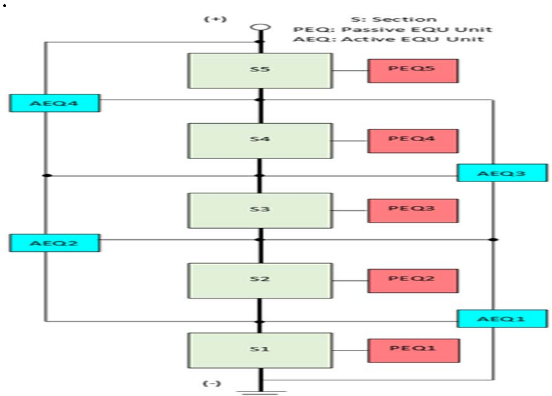

Fig. 3. BEQ for a Battery with 5 Sections of Cells

Although the conversion of a PEQ to a BEQ does not require any significant hardware changes, it does require new software since the equalization strategy is different, e.g., the PEQs now drain the cells to the lowest cell voltage in each 12 cell section instead of the entire pack.

III. BEQ Analysis

Weaker cells will charge and discharge faster than other cells since their lower capacity and higher resistance will cause them to reach their voltage limits sooner (typically 4.2V. max and 2.8V. min). Therefore the EQU needs to remove charge from the weaker cells during charging to allow more time for the other cells to fully charge. During discharge the EQU needs to do the opposite, i.e. charge needs to be transferred to the weak cells to allow more time for the other cells to fully discharge. However, only AEQs and BEQs have this capability. PEQs cannot assist the battery pack to fully discharge, which of course is the most important parameter.

The difference in discharge capacity between a battery with a PEQ and one with a BEQ can be dramatic, and this can be shown using the 5 section BEQ in Fig. 3. The degree of imbalance and location of any weak sections is random and therefore impossible to predict, but we can define a simple model that can be used for designing the AEQ units. The following analysis is only an estimate, but it provides a frame of reference for comparing different designs.

The capacity of a section is considered to be the capacity of the weakest cell in the section. For a section containing at least one weak cell, the worst case is when it is at one end of the stack since it only receives charge directly from one adjacent section instead of two. The relevant variables are,

Ahi = rated Ah discharge capacity of section i (i = 1 to 5), amp.hrs.
Id = discharge current, Adc
Ipi = average PEQ current for all cells in section I, Adc
t = discharge time, hours
Ik = average AEQ current flowing from one section to another (k = 1 to 4), Adc. I1 flows between sections 1 and 2, I2 flows between sections 2 and 3, etc.
n = efficiency of each AEQ unit, 0 to 1.

As the battery discharges, assume the weakest cell is in S1, and it will attempt to discharge faster than the other cells, but S2 – S5 will simultaneously transfer charge toward S1. The design criterion is that S1 – S5 all reach full discharge at the same time, T, and (1) – (5) show the total discharge Ah for all five sections. In (2) for example, I1 flows out of 2 towards 1; n x I2 flows into 2 from 3. Id is the discharge current for the battery, and the efficiency of the AEQ circuit is designated by n. The AEQ current directions are obvious in this case, but in other cases they are not. If the wrong direction is chosen for any of the AEQ currents, they will have negative values, and the equations can be corrected.

During discharge, the PEQ is not used since it cannot add charge to a weak cell, so omit the PEQ currents.
Define Ahw = Ah1 and Ah = Ah2 to Ah5.
If we also define P = 1/t, then in matrix form we have,

$$\begin{pmatrix} n & 0 & 0 & 0 & Ahw \\ -1 & n & 0 & 0 & Ah \\ 0 & -1 & n & 0 & Ah \\ 0 & 0 & -1 & n & Ah \\ 0 & 0 & 0 & -1 & Ah \end{pmatrix} \begin{bmatrix} I1 \\ I2 \\ I3 \\ I4 \\ P \end{bmatrix} = \begin{bmatrix} Id \\ Id \\ Id \\ Id \\ Id \end{bmatrix} \qquad (1)$$

It should be noted that (1) assumes the AEQ is able to detect the weak cell in S1 and send I1 to it continuously during the discharge time, t. Equalizers usually depend on the measured cell voltages to do this, but in fact, there may be slight variations in the SOC vs. voltage curves for each of the cells. This means voltage measurements alone may not be able to always determine the weak cell, and the AEQ will not provide current to the weakest cell over the entire discharge cycle. Therefore, these calculations are only approximate, and the actual discharge capacity will be somewhat less than that predicted by (1).

Example 1

Assume Ah = 100, Id = 30, Ahw = 80 (20% low), and n = 0.87. n is based on the measured efficiency for an AEQ unit transferring charge between two 12 cell sections, each with a nominal voltage, Vs = 43.2 Vdc (Vcell = 3.6 Vdc avg.).

Solving (1),

I1 = 5.4, I2 = 4.3, I3 = 3.1, I4 = 1.64 Adc where I1 – I4 are the average values of the equalization currents. Therefore the circuit should be designed for the maximum, 5.4 Adc at 100% duty cycle, and the I2 – I4 circuits will operate at lower duty cycles to produce the proper average current.

At t = 3.16 h the battery reaches full discharge, and the discharge capacity = 94.8 Ah. or 94.8% of rated capacity. With a conventional PEQ the capacity would have only been 80 Ah.

It is also interesting to calculate the total BEQ power loss and the discharge energy efficiency of the complete battery. The loss associated with I1 is, $Pl = (1 – n)(I1 \times Vs)$ (2)

So the total for I1 – I4 is,

$P1\text{-}4 = (1 – n)Vs \sum Ii = 80.7$ W. (3)

The total BEQ energy loss is,

Eloss = 80.7 x 3.16 = 255 Wh, and the total discharge energy of the battery is,

Eb = 5 x 43.2 x 30 x 3.16 = 20,477 Wh, so the BEQ losses are only 1.25% of the discharge energy. The discharge energy for a PEQ would have been

Epeq = 5 x 43.2 x 80 = 17,289 Wh., which is 3,188 Wh less than with a BEQ.

Example 2

The previous example used 5 sections with 12 cells each, but it is also interesting to compare this with 15 sections with 4 cells each. All other conditions are the same except the measured n= .76 and Vs = 14.4 Vdc. Solving the 15 equations similar to (6), the maximum AEQ is I1 = 6.17 Adc and the minimum is I14 = 1.54 Adc. The discharge time, t = 3.17 h., is almost the same, as is the discharge capacity = 95.12 Ah.

From (2), the total AEQ power loss for I1 to I14, Ploss = 241.58 W, and energy loss, Eloss = 766 Wh, are about 3x higher, but the discharge energy of the battery, Eb = 20,542 Wh, is about the same.

This 15 section design allows the use of somewhat cheaper components for the inductor and the two FETs, but the disadvantages are the higher Ploss and the extra cost of 14 AEQ units instead of only 4.

Example 3

The analysis for charging is more complex than for discharge since the SEQ and PEQ are operating simultaneously. If Ic = charging current and Id = discharge current, some applications such as electric vehicles often have Ic > Id, and the SEQ design for Id will be too small for Ic. However, the PEQ now can be used to supplement the SEQ. For charging, the voltage for the section is now based on the highest cell voltage in the section, which is still the weakest cell. For the single weak cell case used to derive (1), the SEQ current now flows away from the weak section, #1, since the low capacity (weak) cell in this section will charge faster than the other cells. The derivation for the charging equation matrix can be derived similarly to (1), except the PEQ currents, Ip1, etc., are accounted for by setting,

Ic1 = Ic – Ip1, etc.

(Ic1 – I1)T = Ah1 (5)

(Ic2 + n x I1 – I2)T = Ah2 (6)

(Ic3 + n x I2 – I3)T = Ah3 (7)

(Ic4 + n x I3 – I4)T = Ah4 (8)

(Ic5 + n x I4)T = Ah5 (9)

$$\begin{pmatrix} 1 & 0 & 0 & 0 & Ahw \\ -n & 1 & 0 & 0 & Ah \\ 0 & -n & 1 & 0 & Ah \\ 0 & 0 & -n & 1 & Ah \\ 0 & 0 & 0 & -n & Ah \end{pmatrix} \begin{bmatrix} I1 \\ I2 \\ I3 \\ I4 \\ P \end{bmatrix} = \begin{bmatrix} Ic1 \\ Ic2 \\ Ic3 \\ Ic4 \\ Ic5 \end{bmatrix} \qquad (10)$$

The PEQ design procedure can now be derived using the following example. First assume the PEQ is inactive so Ic1 = Ic2 = Ic, etc. and all the parameters are the same as Example 1 except Ic = 50 Adc. Solving (10) yields, I1 = 8.78, I2 = 6.10, I3 = 3.78, I4 = 1.76 Adc. Example 1 was used to design the SEQ at Id = 30 Adc, so I1max = 5.4 Adc. Therefore set Ip1 as follows,

Ip1 = 8.78 – 5.4 = 3.38 Adc., use 4 Adc.

The new values of I1 to I4 and t for charging can now be found by setting Ic1 = 50 - 4 = 46 and solving (10) again. This yields, I1 = 5.27, I2 = 3.66, I3 = 2.27, and I4 = 1.06 Adc, and t = 1.96 hrs. Since all these currents are below the discharge design value of 5.4 Adc max, this design should be adequate to fully charge the pack. However, the PEQ power loss for a single cell at 3.6 Vdc is, Pp = 3.6 x 4 = 14.4 W, which is rather high and will be even higher at 4.2 Vdc. It actually might be better to increase I1 max in order to reduce Ip1.

IV. Experimental Results

A battery management system (BMS) with a prototype BEQ, (previously described in [5]) was designed and tested for a battery pack with 24 randomly selected GAIA HE-602050 lithium ion cells with an original rating of 50 Ah based on a 2.8 to 4.2Vdc cell voltage range. The exact amount of usage was unknown. However, age and usage had reduced the cells' discharge capacity considerably. These experiments also used a slightly smaller voltage range of 2.8 to 4.0 Vdc, which further reduced the capacity. The system can be operated as a BEQ with 6 sections of 4 cells each, or as a PEQ with 24 cells. These two modes were used to compare BEQ vs. PEQ performance using the same battery, measurement circuits, and PEQ control circuitry. The 24 cell GAIA battery pack is shown in Fig.4.

Fig. 4. 24 cell GAIA battery pack.

To simulate the effect of one dominant weak cell, GAIA cell #7 was replaced by a module of 10 Boston Power Swing 4400 cells connected in parallel. This module had an original rating of 10 x 4.4 = 44 Ah based on the same voltage range as the GAIA. The cells in this module had undergone several thousand charge/discharge cycles, but the exact number of cycles and its age were unknown.

The AEQ current waveform is shown in Fig. 5. A rather low frequency of 3.64 kHz was used for this initial study, but future versions will perhaps use frequencies in the range of 20 to 50 kHz to reduce the size and cost of the inductors. The first half of the triangle is the input current flowing from a section, and the second half is the output current flowing into the adjacent section. The area of each half, the conduction times, and the period were used to measure the DC values of these two currents.

For comparison with this present study, data from [5] is shown in Table I. The results from these earlier tests showed an average discharge capacity increase of about 31%.

The BEQ algorithm used to collect the data in [5] had no limit on the number of simultaneous AEQ charge transfer operations. Therefore each section could have 3 PEQs on simultaneously, i.e., up to 18 for the 24 cell pack.

Likewise the algorithm for the PEQ version had no limit to the number of simultaneous PEQ operations, so it was possible to have 23 of the 24 operating at the same time.

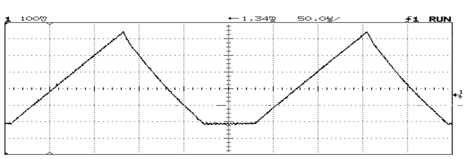

Fig. 5. Inductor current for one of the AEQ units. Vrt.: 2 A/div, Hrz:50 us/div.

This lack of restrictions on the number of EQU operations was not significant for this small 24 cell pack, but the associated power dissipation might be an issue for a large pack with perhaps 200 or 300 cells. Therefore some tests were performed with some restrictions on the number of simultaneous AEQ and PEQ operations. For the BEQ, the AEQ was restricted to one transfer going up the stack (section #1 at the bottom, #6 at the top) and one transfer going down. Thus if #4 was the low voltage section, #1 the highest, and #6 the next highest, there would only be one transfer going up from #1 to #4 and one going down from #6 to #4.The PEQs in the BEQ version also were limited to one simultaneous operation for each section. To make a fair comparison, the PEQ version also was limited to the 6 highest voltage cells were only operated during charge. The results for this second series of tests are shown in Table II. The average BEQ increase in discharge capacity of 26% is not quite as large as the 31% from [5], but this is probably to be expected since the Boston Power Module of 10 cells instead of 8 means the pack imbalance was not as large as for Table I. The average Ah capacities are slightly less in Table II, but this is probably within the repeatability range of the tests.

TABLE I [5]
DISCHARGE DATA WITH 23 GAIA CELLS & 1 BOSTON MODULE OF 8 CELLS

Test	Ah	Average Ah	Average Increase
PEQ #1	8.57 Ah		
PEQ #2	7.99 Ah	8.17 Ah	_
PEQ #3	7.42 Ah		
BEQ #1	10.74 Ah		
BEQ #2	10.73 Ah	10.70 Ah	31%
BEQ #3	10.63 Ah		

TABLE II
DISCHARGE DATA WITH 23 GAIA CELLS &1 BOSTON MODULE OF 10 CELLS

Test	Ah	Average Ah	Average Increase
PEQ #1	8.49Ah		
PEQ #2	7.61 Ah	8.05 Ah	_
BEQ #1	9.46 Ah		
BEQ #2	10.79 Ah	10.13 Ah	26%

V. CONCLUSIONS

In spite of their power losses and lack of equalization during discharge, PEQs remain the most common type of EQU due to their lower cost. AEQs provide much better performance, but they are rarely used because of high cost and complexity. This present study, along with [5], shows that the BEQ hybrid provides an attractive solution since its performance for large imbalances is much better than a PEQ, and its much lower component count and absence of transformers indicate a much lower cost than an AEQ of equivalent size. Examples are included to show how the analysis from [5] can be used to determine the proper size of the currents for the AEQ contained within the BEQ. The experimental section describes an alternate operating strategy to further reduce the BEQ power losses, and the results indicate that the performance is still comparable to that presented earlier in [5].

REFERENCES

[1] "EM1401EVM User's Guide", Texas Instruments publication SNOU128, June 2014.

[2] D. Andreas "Battery Management Systems for Large Lithium-ion Battery Packs", pp35-87, ArtechHouse, Boston MA, 2010.

[3] "LTC3300-1 High Efficiency Bidirectional Multicell Battery Balancer", Linear Technology datasheet LT1213 REV B, 2013.

[4] T. A. Stuart, "A Bilevel Equalizer for Battery Cell Charge Management", U.S. Provisional Patent Application # 62/287,575, Jan. 27, 2016.

[5] S. Mubenga, Z. Linkous, and T. Stuart, "A Bilevel Equalizer for Large Lithium Ion Batteries", Batteries, www.mdpi.com/journal/batteries, Dec. 2017.