A Low Cost Hybrid Equalizer for Lithium Ion BESS

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***Abstract*— Several Battery Energy Storage Systems (BESS) have been installed by electric utilities, and reports indicate their development is going to accelerate. The vast majority of these now use lithium ion batteries (LIB which require electronic equalizer circuits (EQU) to balance the cell voltages. Several types of EQUs have been proposed, but all present versions have either cost or performance issues. However, a new type of hybrid EQU called the Bilevel Equalizer (BEQ) has been proposed to provide a balance between cost and performance. This study provides additional insight into the analysis and design of these systems.**

***Index Terms*—Lithium ion, equalizer, bilevel, passive, active**

I. INTRODUCTION

All lithium ion batteries (LIBs) for Battery Energy Storage Systems (BESS) require an equalizer circuit (EQU) to balance the voltages of the series connected cells (typically about 200 to 300). Almost all of these EQUs currently are cheap Passive Equalizers (PEQs) that only provide an Amp Hour (Ah) battery discharge capacity equal to that of the worst cell in the pack. Several types of much better Active Equalizers (AEQs) have been developed [1-8], but industry has avoided them due to their high cost, even though engineers predict they will increase the lifetime capacity by about 25 or 30%. This paper describes a new AEQ/PEQ hybrid called the Bilevel Equalizer (BEQ) [9, 10] that provides a high capacity close to an AEQ but at a low cost that is close to a PEQ. Some LIBs are now specified to last 10 or even 20 years, so the BEQ will be especially beneficial as the pack ages and large cell imbalances develop.

PEQs 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. PEQs are simple and cheap, but produce heating and energy loss. They also are of no use during discharge since they cannot transfer charge to lower voltage cells, and thus the Ah discharge capacity of the battery is equal to that of the worst cell in the 300 cell pack. This problem becomes very important as the battery ages and large variations develop among the cells. This capacity reduction also increases the lifetime cost, and it is unlikely that many of these batteries will avoid a large loss in capacity (perhaps 30%) due to a few weak cells over their 10 or 20 year targeted lifetime.

In many cases PEQs are only used when the battery is inactive, and long time periods are required to balance the cell voltages. This approximately balances the SOCs (state of charge) of the individual cells, but it does nothing to help compensate for imbalances in cell capacities. Thus the user is often led to believe that the cells are balanced capacity wise, when in fact they are not.

There are several types of active equalizers (AEQ) [1-8] that transfer charge between cells and thus avoid some of the problems with PEQs, but they are rarely used in large applications due to their complexity and much higher cost. Most of these AEQs use a separate DC-DC converter for each cell so charge can be transferred to or from the cell and the rest of the pack. This proves to be expensive even for small AEQ currents, and the cost becomes even more prohibitive for the higher AEQ currents required for large cell imbalances and load currents.

Thus the designer has faced a stark choice between a low performance PEQ and a prohibitively expensive AEQ. This quandary has motivated this new hybrid BEQ which is described in the following sections. Analysis methods presented earlier in [10] also are used to show examples of how to calculate the required equalization currents for various operating conditions.

II. BILEVEL EQUALIZER

A new hybrid AEQ/PEQ has been developed that provides performance close to present AEQs, but with only a modest cost increase above a PEQ. This circuit is called the Bilevel Equalizer (BEQ) because it provides equalization at two different voltage levels. It appears to be especially advantageous for BESS applications because it can be added to an existing PEQ system as a retro kit. Fig. 1 shows an inductive AEQ circuit that is quite simple; B1 – B3 may be individual cells or sections of series connected cells. This is cheaper than other AEQs since it contains no transformers, switching matrices, or high voltage FETs. Components Q1, Q2, and L1 constitute one AEQ unit, so this circuit has 2 units. To reduce the size of the inductors, the FETs typically switch in the range of 15 to 20 kHz. 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 (no. of sections – 1), whereas an AEQ with a bidirectional DC-DC converter for each cell would require 196 AEQ units. Therefore when operated at the same value of equalization current, the BEQ cost will be much lower than using an AEQ for each cell.

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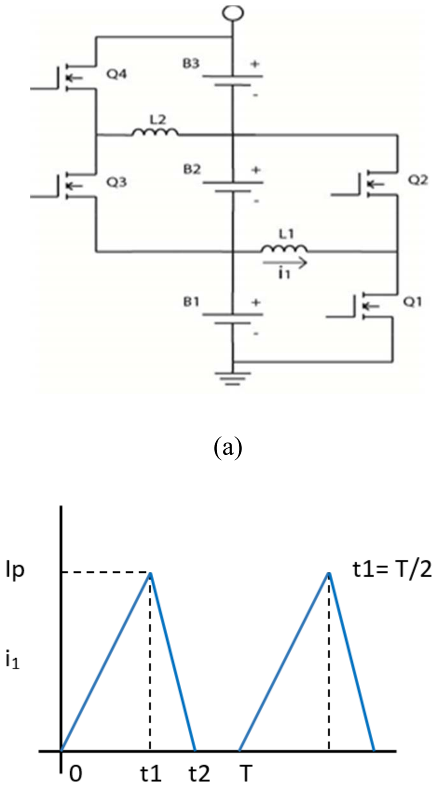
A block diagram of a BEQ where the cells are divided into 5 sections is shown in Fig. 2. This might represent a 70 cell LIB with 14 cells/section and a maximum voltage of about 290 Vdc. This system uses a PEQ for each section to provide equalization at the cell level for the cells in that section. AEQ units identical to those in Fig. 1 are used to equalize the section voltages. The AEQ boxes shown in blue in Fig. 2 are the only new items needed to convert a PEQ to a BEQ.



(a)

(b)

Fig. 1. AEQ with 2 Units (a) Schematic; (b) Current in L1 [10]

III. 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 (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. PEQs, AEQs and BEQs all can do this. 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 can assist the battery pack so it will fully charge, but they cannot assist it 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 shown using the 5 section BEQ in Fig. 2. The degree of imbalance and location of any weak sections are random and therefore impossible to predict, but a simple model can be used for analyzing the AEQ units of the BEQ.

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,

Fig. 2. BEQ for a Battery with 5 Sections of Cells [10]

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 1.0

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 Ahr 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.

$$(Id + Ip1 - n \times I1)T = AH1 = AHw \tag{1}$$
$$(Id + Ip2 + I1 - n \times I2)T = AH2 \tag{2}$$
$$(Id + Ip3 + I2 - n \times I3)T = AH3 \tag{3}$$
$$(Id + Ip4 + I3 - n \times I4)T = AH4 \tag{4}$$

$$(Id + Ip5 + I4)T = AH5 \quad (5)$$

During discharge, the PEQ is not used since it cannot add charge to a weak cell, so we assume Ip1 to Ip5 = 0.
Define AHw = AH1 and AH = AH2 to AH5.
If we also define P = 1/T, then in matrix form we have,

$$\begin{pmatrix} n & 0 & 0 & 0 & AHw \\ -1 & n & 0 & 0 & AH \\ 0 & -1 & n & 0 & AH \\ 0 & 0 & -1 & n & AH \\ 0 & 0 & 0 & -1 & AH \end{pmatrix} \begin{bmatrix} I1 \\ I2 \\ I3 \\ I4 \\ P \end{bmatrix} = \begin{bmatrix} Id \\ Id \\ Id \\ Id \\ Id \end{bmatrix} \quad (6)$$

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 (6),

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 hrs. the battery reaches full discharge, and the discharge capacity = 94.8 amp hrs. or 94.8% of rated capacity. With a conventional PEQ the capacity would have only been 80 amp hrs.

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 x Vs) (7)

So the total for I1 – I4 is,

P1-4 = (1 – n)Vs Ii = 80.7 W. (8)

The total BEQ energy loss is,

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

Eb = 5 x 43.2 x 30 x 3.16 = 20,477 Whr, 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 Whr., which is 3,188 Whr less than with a BEQ.

Example 2

As stated above, the capacity of a section is defined to be that of its weakest cell, and these are random. This example is the same as Example 1, except with the following capacities: AH1 = 80, AH2 = 90, AH3 = 95, AH4 = 100, and AH5 = 90. The directions of the SEQ currents are assumed to be those shown below.

I1: Section 2 => Section 1
I2: Section 3 => Section 2
I3: Section 4 => Section 3
I4: Section 4 => Section 5

In matrix form,

$$\begin{pmatrix} n & 0 & 0 & 0 & AH1 \\ -1 & n & 0 & 0 & AH2 \\ 0 & -1 & n & 0 & AH3 \\ 0 & 0 & -1 & 1 & AH4 \\ 0 & 0 & 0 & n & AH5 \end{pmatrix} \begin{bmatrix} I1 \\ I2 \\ I3 \\ I4 \\ P \end{bmatrix} = \begin{bmatrix} Ic \\ Ic \\ Ic \\ Ic \\ Ic \end{bmatrix} \quad (9)$$

Solving (9),

I1 = 3.88, I2 = 4.52, I3 = 3.36, I4 = 0.6 Adc, and T = 3.0 hrs. The maximum is 4.52 Adc, so the maximum design value of 5.4 Adc from Example 1 is more than adequate.

Example 3

Equation (6) indicates I1 – I4 will be directly proportional to Id, and this can be verified by repeating Example 1 with Id = 50 Adc. In this case, I1 = 8.98, I2 = 7.18, I3 = 5.11, and I4 = 2.73 Adc, all of which show an increase of 67%, the same as the increase in Id.

Of course the discharge rate is now C/2 instead of C/3.33, so AH and AHw actually would have lower values for this case, which also would change I1 – I4.

III. EXPERIMENTAL RESULTS

A battery management system (BMS) with a prototype BEQ (previously described in [10]) 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. These cells were about 9 years old and had some limited cycling, but 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. A block diagram of the system is shown in Fig. 3, and the BMS prototype test fixture is shown in Fig. 4. The blue AEQ boxes in Fig. 4 represent the additional hardware required to convert a BMS with a PEQ to one with a BEQ.

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. As with the GAIAs, the capacity of this module had decreased to a value that was much smaller than the original rating, and it was less than the GAIA cells.

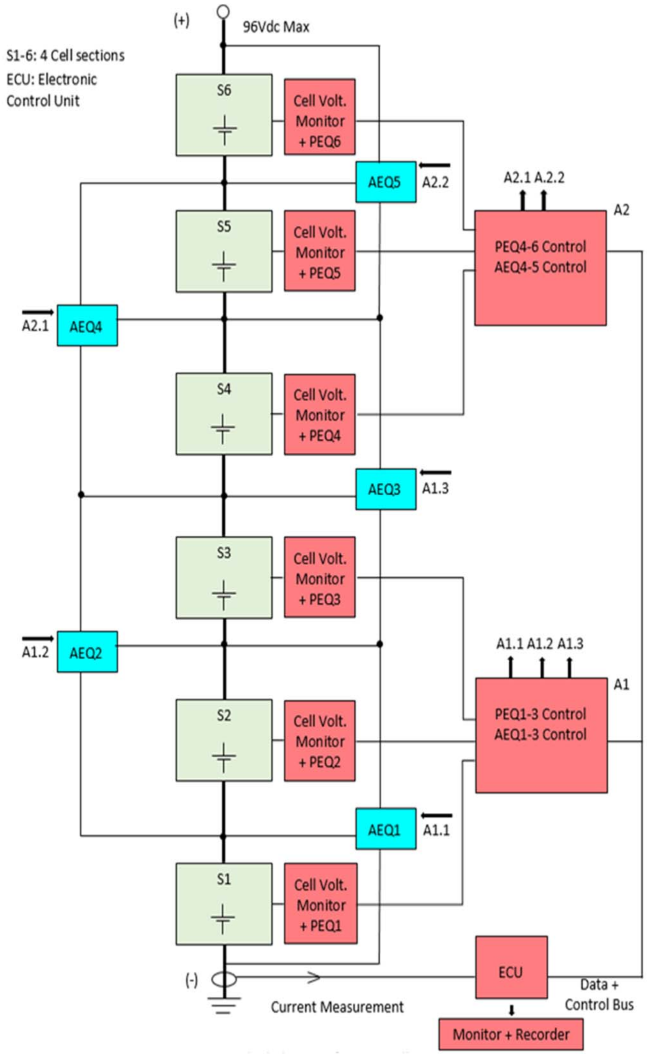


Fig. 3. Block diagram of the BMS engineering prototype.

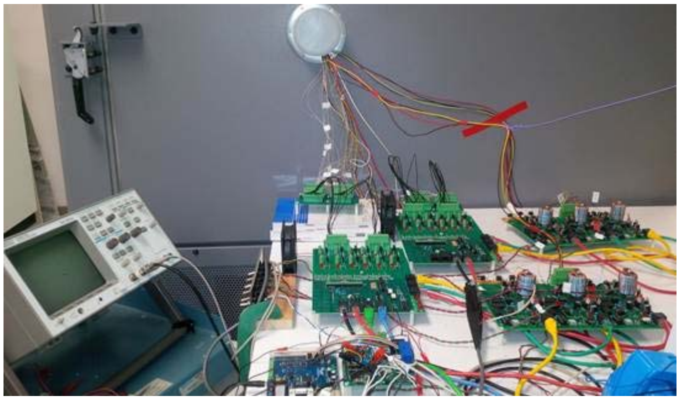


Fig. 4. BMS prototype for a 24 cell Li Ion battery.

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 use frequencies in the range of 15 to 20 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. Note there is a very slight distortion in the negative slope at the top of the triangle. This indicates there is a small degree of core saturation, but not enough to cause any significant measurement error.

The BEQ algorithm used to collect the data in [10] had no limit on the number of simultaneous AEQ charge transfer operations. Thus there might be 3 or 4 transfers in progress at the same time. There also was no limit to the number of PEQ operations in each of the sections. 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. Table 1 shows the results from [10] for comparison with the next proposed algorithm.

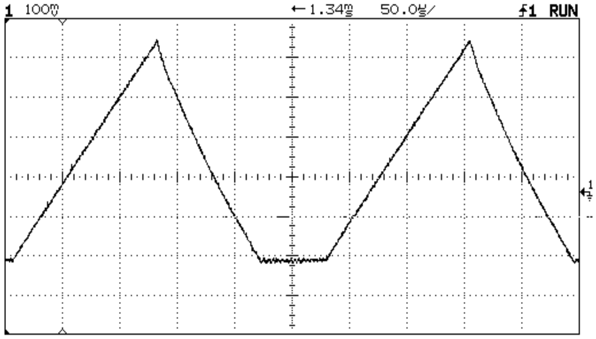


Fig. 5. Inductor current for one of the AEQ units. Vertical: 2 Amps/div, Horizontal50 us/div.IA.

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. There also were indications that equalization could be maintained with a smaller number of operations. 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, i.e., a total of 6 maximum. To make a fair comparison, the PEQ version also was limited to the 6 highest voltage cells. As before, the PEQs were only operated during charge, not discharge.

The results for this second series of tests are shown in Table 2. The average BEQ increase in discharge capacity of 26% is not quite as large as the 31% from [10], 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 1. The average Ah capacities are slightly less in Table 2, but this is probably within the repeatability range of the tests.

TABLE 1
DISCHARGE DATA WITH 23 GAIA CELLS AND 1 BOSTON POWER MODULE OF 8 PARALLEL CELLS [10]

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 2
DISCHARGE DATA WITH 23 GAIA CELLS AND 1 BOSTON POWER MODULE OF 10 PARALLEL 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%

IV. 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 [10], 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. 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 [10].

GLOSSARY

A: Amps
Ah: Amp Hours
BEQ: Bilevel Equalizer
BMS: Battery Management System
ECU: Electronic Control Unit
EQU: Equalizer
FET: Field Effect Transistor
hrs: Hours
I: Current
LIB: Lithium Ion Battery
MCU: Microcontroller Unit
PEQ: Passive Equalizer
AEQ: Active Equalizer
SoC: State of Charge
T: Time
Vdc: DC Voltage

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