Battery Management Systems for Large Lithium-Ion Battery Packs

Section 1.2.1 Errata

Figure 1.2:

- Prismatic and pouch cells are swapped between pictures and caption

Editing errors

Table 1.1, left column, 4th row

- Should say "Appropriateness for small project

Section 1.2.3 Errata

Editing errors

4th paragraph:

- Should say "which caught fire due to arcing inside **its** Li-Ion traction pack"

"26,650" should be "26650"

Section 1.2.5.2 Errata

Footnote on page 8:

- Should say "Peukert coefficient"

Editing errors

2nd paragraph

- Should say "while the curves in specification **sheets**"

Last paragraph on page 8:

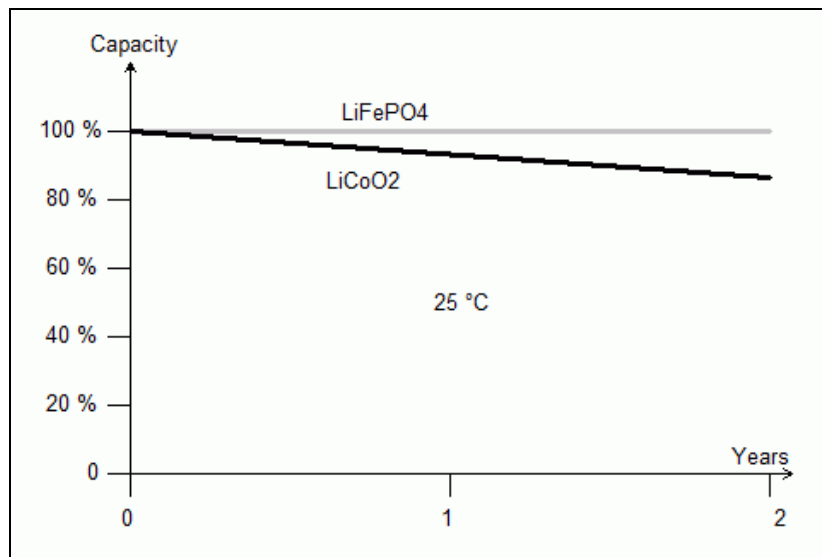- Should start with "Certain" (to avoid using the word "some" twice).

Section 1.2.6.2 Errata

1st paragraph, 2nd sentence:

- Should say "You may have seen" (no "not")

Figure 1.8:

- Wrong illustration. Should be a plot of cell characteristics over time.

Editing errors

1st paragraph, 2nd sentence: it would be clearer to say "then increases; after a few hundred cycles, it increases even more rapidly."

Section 1.2.7 Errata

Editing errors

"26,650" should be "26650"

page 12, 2nd paragraph: remove comma after "cell manufacturers".

Section 1.2.8 Errata

Editing errors

"26,650" should be "26650"

page 13, last line: should say "it is not going to go into thermal runaway"

page 14, 6th line: replace "one" with "one of the cells"

page 14, 4th line from bottom: replace "and one will be" with "and. again, one cell"

Section 1.3 Errata

Editing errors

page 15, 3rd line: Change "it is the job" to "The job"

Section 1.3.2 Errata

Editing errors

page 16, 4th line from bottom: Change "change" to "chance"

Section 1.4 Errata

Editing errors

There should be some text under the 1.4 heading.

Section 1.4.1 Errata

page 21, remove footnote, and remove footnote number on line 5

Editing errors

Figure 1.18: use shading to make bars more distinguishable

page 19, footnote: Change "damns" to "damn"

page 21, line 14: change the ';' to';' at the end of "works up to a point"

Section 1.4.2 Errata

The first sentence is actually footnote 5.

Page 23, 3rd line: add superscript 4 for footnote 4.

Page 23. footnote 5: change its number to '4'.

Editing errors

Section 1.4.2.1 Errata

Editing errors

4th line: add "you" in "Some examples may help you understand this".

Page 23, list: remove punctuation at end of each bullet point

Page 23, 4th paragraph: remove the 2nd "is", after "myth".

page 24: add a hyphen in "self-discharge"

Section 1.4.2.3 Errata

Page 39. 3rd line from bottom: should be "cell 1".

Editing errors

Figure 1.26: use gray to improve picture clarity.

Figures 1.27, 1.29, 1.30, 1.31: The SOC should range down to 0 %, not 2.5 %.

Figures 1.28, 1.32, 1.33: restore the lines that indicate the end of the SOC range

Section 2.3.1 Errata

"An example of an off-the-shelf, centralized BMS is Convert The Future's Flex BMS48 (see Chapter 4)." (page 45)

Actually, no, that BMS is not mentioned in the book.

Editing errors

Section 3.2.3.1.6 Addenda

On or about Sep 15th 2010, Jack Ricard, the strong opponent of BMSs, lost a pack due to overcharging: apparently he forgot that the charger was on, and left. Since there was no BMS to shut off the charger, the cells in the pack were damaged by over-charging.

Section 3.2.3.3 Addenda

When referring to Balancing, the terms "Passive" and "Active" have been interpreted differently by some, as to mean "Voltage based" (balancing only at the end of charge) and "SOC history based" (balancing all the time). Therefore, to avoid further confusion, we would like to start use different, more descriptive terms for the two balancing technologies: "dissipative balancing" and "non-dissipative balancing". Describe book/1.1 here.

Section 5.2.3.2 Errata

Figure 5,22 (page 141)

The 2 MOSFETs should be P-type, not N-type.

Section 5.3.5 Errata

Figure 5.27 (page 140)

The 2 MOSFETs should be P-type, not N-type.

Section 5.3.6 Errata

Figure 5.29 (page 152)

The 2 MOSFETs should be P-type, not N-type.

Section 5.4.1.1.err Errata

Page 155

"The circuit is powered by the cell itself, so it must draw low power (it must draw less current than the leakage of the cells being measured), especially during standby, in order not to discharge the cell;"

add at the end

in order not to discharge the cell... "faster that it would without a BMS".

Section 5.4.1.2.4.3 Addenda

Intersil ISO26262

Announced, no info.

Section 5.4.1.2.4.6 Addenda

Maxim MAX17830
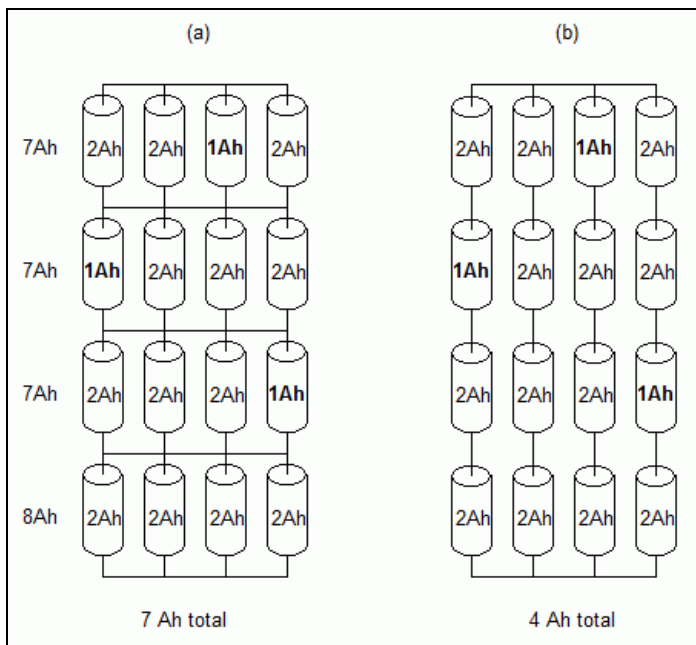
Section 6.1.1.1.1 Errata

Page 230

- 6th line from the bottom. "that an support 4 tap points" should be "that an support 5 tap points".

Page 231

- Figure 6.2.

Graph a. Top 2 rows should be 7 Ah, not 8 Ah.

Graph b. Bottom text should be 4 Ah, not 5 Ah.

- Last sentence of the 2nd paragraph

"so the total pack capacity is only 5 Ah."

should be:

"

so you would think that the total pack capacity is only 5 Ah. Actually, the capacity is only 4 Ah, because the 1 Ah cells are the limiting factor, and there are 4 strings in parallel.

Plots of cell voltage versus time, assuming a 1 A discharge current, will clarify this point (figure 6.3). With cell in parallel, the 1 A current discharges the 7 Ah blocks in 7 hours, at which point their voltage reaches the lower limit and the BMS shuts down the pack (the 8 Ah blocks will still have some charge left). Therefore, the capacity is 7 Ah. With batteries in parallel, the 1 A current is split evenly into the 4 strings: 0.25 A each. That current discharges the 1 Ah cells in 4 hours, at which point their voltage reaches the lower limit and the BMS shuts down the pack (the 2 Ah cells will still have 1/2 of their charge left). Therefore, the capacity is 4 Ah.

"

Add Figure 6.3 (replacing the removed figure 6.3) to explain with a graph the effect of figure 6.2.

"
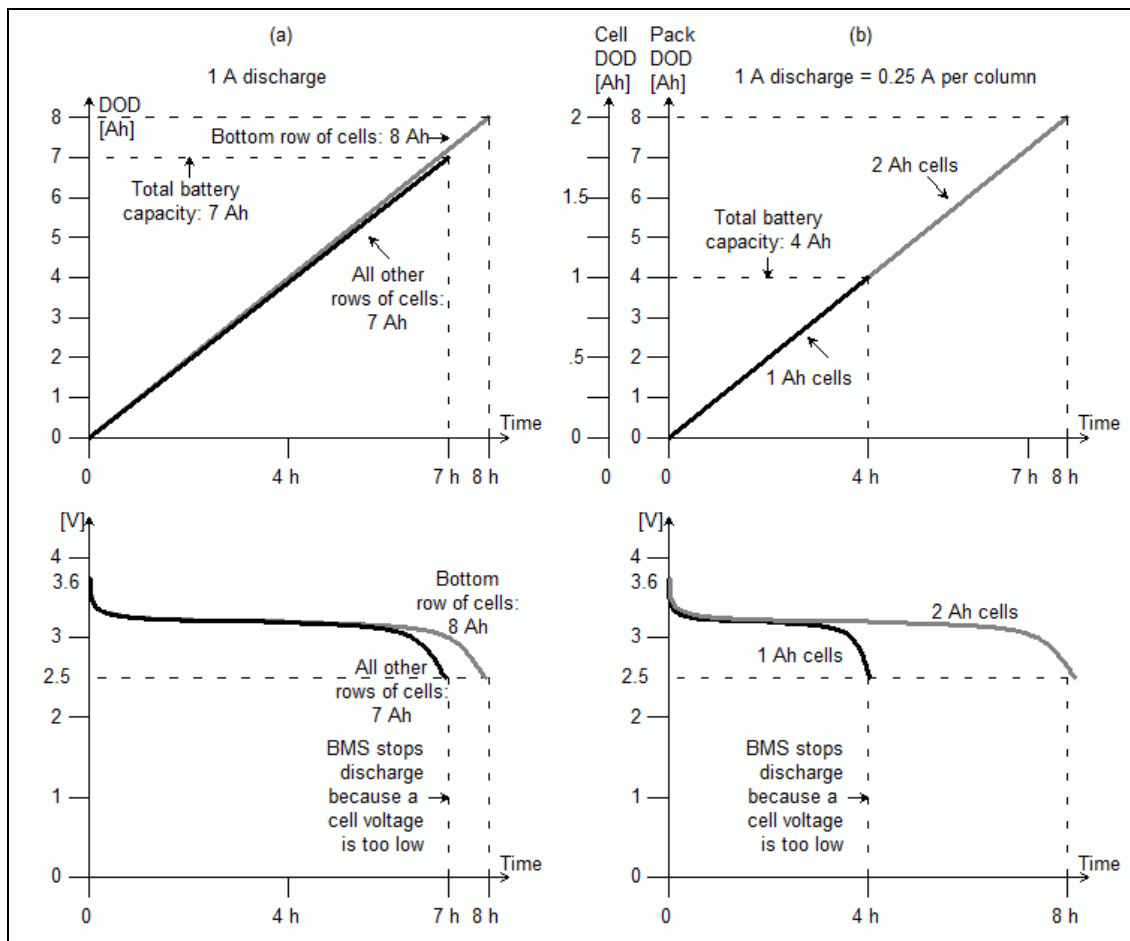
Figure 6.3 1 A discharge plot of multiple, low capacity cells. (a) With cells in parallel, the pack is discharged in 7 hours, meaning that the capacity is 7 Ah. (b) With batteries in parallel, the pack is discharged in 4 hours, meaning that the capacity is 4 Ah.

"

The point made at the end of page 231 and beginning of page 232 is not valid, and should be removed from the book.

Page 231

- 2nd paragraph, end of the paragraph. Instead of "each battery that includes a low capacity cell will have a 1 Ah capacity" should be "the 3 batteries that include a low capacity cell have a 1 Ah capacity"

- 3rd and 4th paragraph: delete.

Page 232

- - Figure 6.3: delete.

- 1st paragraph: delete.

Section 6.1.1.3.1 Addenda

Cell self-balance time

The time required to balance a set of Li-Ion cells by connecting them in parallel (before building a pack), without a power supply, depends on these factors, in order of importance:

- Average SOC level:
  - At either end of the charge curve, the voltage vs SOC curve is much steeper than at mid SOC levels, which means that the higher voltage of a more charged cell encourages more of its charge to go to lower voltage cells
  - On the other side, at either end of the charge curve the internal cell resistance is higher, reducing the resulting current
- Chemistry: Cobalt and standard LiPo are faster than LiFePO4, because their charge curve is steeper
- Amount of max initial imbalance: less imbalance (with respect to the average) is faster; fewer imbalanced cells is faster

Battery Management Systems for Large Lithium-Ion Battery Packs

- Resistance in the interconnecting wires, though this one can easily be insignificant compared to the cell resistance, and can safely be ignored
    - For example, 12 AWG (3 mm^2) wire can handle 40 A continuous, but in this case the current is a pulse, so I'd trust it at 100 A peak;
    - Assuming 2" (5 cm) between cells, a 12 AWG wire has a resistance of 0.2 mOhm, which is on the same order of magnitude than the internal resistance of the typical 100 Ah cell
    - So, typically, the resistance of wire that is larger than 12 AWG can be ignored

Depending on the above factors, the self-balance time in on the order of hours to days.

The best case is for LiFePo4 cells, when most cells are full, and just a few are just below 100 % SOC. In that case:

- The voltage difference between the full cells and the not so full ones is relatively large (on the order of 200 mV)
- The resistance of the full cells is higher, but there are lots of them in parallel, so the total resistance is low
- The resistance of the not so full cells is low, because they are not yet in the high resistance area at the end of the charge curve
- The delta in SOC is low, meaning that not much charge needs to be transferred.

Let's look at an example of that:

- 100 LiFePo4 cells
- 100 Ah, all equal
- 10 mOhm at mid SOC levels; 100 mOhm at 100% SOC
- 99 cells at 100 # SOC, 3.6 V; 1 cell at 90 % SOC, 3.4 V
- The long term RC time constant of the cells is 30 minutes
- We can accept an imbalance of 0.5 %

Then:

- A charge of 10 Ah needs to be transferred into the low cell
- The source looks like 9900 Ah, 3.6 V, 0.1 mOhm
- The load looks like 100 Ah, 3.4 V going up to 3.6 V, 10 mOhm going up to 100 mOhm
- The RC time constant for both load and source is 30 minutes

So:

- The initial current is (3.6 - 3.4) / 10 mOhm = 20A
- At that rate, that would fill the low cell in 1/5 hour = 12 minutes

Battery Management Systems for Large Lithium-Ion Battery Packs

- In reality, as the low cell gets full:
    - Its resistance increases, and does so non-linearly
    - The delta in voltage decreases, and does so non-linearly
    - The RC equivalent circuit in the cell enters into the equation, as its time constant is on the same order of magnitude as the 12 minutes (above)
- So, the curve drops down worse than plain exponentially

So, what is the time, when you consider all these factors? I used a spreadsheet to calculate this, and the result was:

- 72 minutes.

What about the worse case?

- Mid SOC levels (on the order of 2 mV delta in the OCV)
- The resistance is low
- Some cells have been exposed to significant current within the last few minutes, and their voltage has not yet relaxed
- To get a balance within 0.5 %, the OCVs must be matched to within 500 uV
- The OCV is masked by various thermodynamic effects, so the cell voltages must be allowed to relax

Let's look at an example of that:

- 100 LiFePo4 cells
- 100 Ah, all equal
- 10 mOhm at mid SOC levels; 100 mOhm at 100% SOC
- Bell curve distribution in capacity, from 30 to 70 % SOC
- OCV is within 1 mV of 3.2 V, but terminal voltage is within 100 mV of that
- The long term RC time constant of the cells is 30 minutes
- We can accept a imbalance of 0.5 %

To analyze this case, we need to employ a Monte Carlo statistical analysis. I have not yet done so. Once I do, I will add those results here.

For now, let me say that my guess is that it will take a week to two weeks to balance these cells.

Compare that to how long a BMS would take to balance those cells once they are in a pack will all the cells in series (assuming 100 mA balance current:

- Time = delta charge / current = 50 Ah / 100 mA = 500 hours = 20 days

Cell containment

Whether cell expansion should or should not be contained is up for debate. The goal is, of course, to maximize the performance of the cells, including their cycle life. On one side, containment may harm cells because the active material does expand and must be allowed to expand at high SOC levels. On the other side, allowing a cell to expand may harm cells as the deformed cell is not able to regain its original shape, resulting in delamination.

Given these contrasting requirements, I cannot give you a fast rule on containment. Guidance on containment for a particular cell should come from that cell's manufacturers; yet, I cannot find any such guidance.

My sense is that batteries should be built with cells at mid-SOC levels, and should be bound but not squeezed, using materials with some compliance.

Section Addenda

A rule of thumb is that, the resistance of a single Li-ion cell is on the order of 25 mOhm / Ah (power cell) or 100 mOhm / Ah (energy cell). So, for example, a 100 Ah prismatic cell will have a resistance of about 1 mOhm.

Section 1.1 Addenda

When referring to Balancing, the terms "Passive" and "Active" have been interpreted differently by some, as to mean "Voltage based" (balancing only at the end of charge) and "SOC history based" (balancing all the time). Therefore, to avoid further confusion, we would like to start use different, more descriptive terms for the two balancing technologies: "dissipative balancing" and "non-dissipative balancing". Describe book/1.1 here.

Battery Management Systems for Large Lithium-Ion Battery Packs

Section 1.2 Addenda

Cell expansion

There are two mechanisms that result in cell expansion:

- During charging, the active material in the anode expands slightly as it receives Lithium ions (through intercalation); this process is reversed during discharge. This expansion is proportional to the SOC.
- When the cell is nearly full, any further charging will result in part of the electrolyte to be converted to a gas; that gas is converted back to a liquid electrolyte when the cell SOC drops below 100 %. How much gas is produced depends on the chemistry of the cell, and varies considerably from manufacturer to manufacturer. The presence of this gas increases the pressure inside the cell, which may result in cell expansion (which can be quite large). Overcharging will result in this conversion of electrolyte into gas to continue, often resulting in permanent deformation of the cell, and in release of the gas, either in a controlled manner, or in an explosion.

Note that that second mechanism of expansion only occurs when the STATE of the cell is around 100 % SOC. This point is very important. The expansion is NOT due to heat, and it is NOT due to the act of charging. The expansion is the same regardless of cell temperature (cooling won't prevent the expansion) and cell current (at a given SOC level, the expansion is the same, regardless of whether the cell is charging, discharging or sitting on a shelf).

Cylindrical cells will inherently contain that expansion. Pouch cells won't do so, so they must be contained. Prismatic cells will contain expansion to a small extent, so they too need to be contained. How much containment is required is up for debate, and I discuss it in the addenda to section 6.1.1.3.2. The jest of it is that you need to allow for some expansion (for mechanism 1) , but not too much (for mechanism 2), and the answer depends on the particular model of cell.

Section 1.2.5.2 Addenda

Saying that the charge efficiency of Li-Ion cells is 100 % is an oversimplification. In reality:

- Internal self discharge (leakage) reduces that efficiency, though in a minor way
- Although close to ideal, the Peukert coefficient of Li-Ion cells is not exactly 1.00; its value is on the order of 1.05
- Due to mechanisms that are not yet understood, there is a phenomenon called "SOC unbalance evolution", which (in the absence of balancing) results in the SOC of weak cells to be reduced, as they are cycled, more than would be

expected based on the integral of the charge in and out of them. Though unexplained, this effect is seen experimentally, so it is undeniable.

I will update this section as the understanding on these effects improves.

Section 1.2.7 Addenda

Contents

The range of the time axis of 4 plots in figure 1.10 is about 10 minutes. Therefore, their do show the effect of the long time constant (1 minute, due to C2-R2); on the other side, the effect of the fast time constant (1 ms, C3-R3) is too fast for the time scale of these plots, and cannot be seen.

In these plots, it is assumed that the load current is the same. I also assumed that the resistance of R1 in 'a' is equal to the sum of all 3 resistances in the other examples (R1, R2 and R3).

Section 1.3.2 Addenda

In batteries for aerospace applications, which must have an extremely high reliability, matched cells and a much simpler BMS are used.

The battery manufacturer tests multiple manufacturers and cells to select a batch of cells of high performance and reliability. Then, the manufacturer characterizes thousands of cells from that batch, and from that batch selects a group of cells that have perfectly identical characteristics (especially capacity, resistance and self discharge). Finally, the manufacturer balances those cells and assembles them into a battery.

Because the cells are identical, and they all start at the same SOC, it becomes a relatively safe assumption that all the individual cell voltages will remain in lockstep throughout the life of the battery. Therefore, a much simpler (and more reliable) BMS can be used, which only monitors the total battery voltage.

Section 1.4.2 Addenda

Although close to ideal, the Peukert coefficient of Li-Ion cells is not exactly 1.00. Its value is on the order of 1.05

- Due to mechanisms that I totally do not understand, there is a phenomenon called "SOC unbalance evolution", which (in the absence of balancing) results in weak cells to experience a lower and lower SOC as they are cycled, compared to other cells in the pack; this mechanism is seen experimentally, so it is undeniable

Honestly, my understanding of the physics behind Peukert coefficient is too fuzzy to go into any more explanation. I will update this section as my understanding improves.

Section 5.2.3.2 Addenda

The under-voltage threshold is fixed.

Section 5.6 Addenda

Individual chargers

The individual chargers for each cell could be mounted directly on the cells, and even be built into the cell boards in a distributed BMS.

Usually, individual chargers are small AC-DC power supplies, powered by the line AC voltage; they could be small DC-DC converters, powered by a common DC bus; That bus could be powered, for example, by a single AC-DC converter powered by the AC grid, or by a distributed DC source such as solar panels. If this DC bus is connected to the battery terminals, then this implementation has in effect the same circuit as a battery-to-cells active balancer (5.4.5.1.2.3).

SOC

A disadvantage of distributed charging is that, during charging, the BMS has a hard time calculating the SOC of each individual cell, and therefore the SOC of the overall battery. The output current of each charger is different, and normally unknown to the BMS; unless the BMS has a current sensor for each cell, it cannot do Coulomb counting to determine cell SOC. All that a BMS can do is to guess the SOC during charging, and then calibrate the SOC based on cell voltage after charging is completed.

Section 6.2.3 Addenda

Often, the characteristics of a CCCV charger are less than ideal: when in the CV mode, the voltage is not perfectly constant, but varies with the current. This is due to the limitations of the charger's control circuits, and its internal resistance. Therefore, in chargers whose CV is set with a trimmer adjustment while monitoring its output voltage, you must make that adjustment at low current: either when the pack is completely full, or simply by disconnecting the charger from the battery.

Section Addenda

C: Coulomb; Celsius; the ratio: current in a cell (or battery) divided by its capacity

Date 8 February 2013