INTELLIGENT BALANCING OF SERIES CELLS USING A LOW PROCESSING POWER ALGORITHM

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This paper describes the implementation (hardware and software) of a technique designed to balance cells from a battery pack that are arranged in a series configuration using a low processing power algorithm. The actual balancing is achieved by individually discharging every cell before, during or after charging.

Keywords: low processing power, algorithm, cell, balancing, battery

1. Introduction

Intelligent battery management systems have become a must-have in all battery-powered applications. Concerns with their safety and longer lasting life have driven the implementation of various protection measures and balancing schemes but this had led to an increase in complexity, board space, cost and processing power [1].

In this paper, most of those problems are addressed by implementing an algorithm on an (presumably already existing) microcontroller that is optimized to consume an amount of processing power that is as low as possible without sacrificing precision. This algorithm is set to the specifications of Li-Ion [2] and Li-Polymer batteries, but it can easily be adapted for any battery chemistry with small changes in voltage levels.

The presented algorithm is designed for balancing Li-Ion batteries in a series configuration [3][4][7]. This is the riskiest case, because, while charging and discharging the whole pack, some component cells might discharge to a lower voltage or might charge faster, thus leading to an unbalance that may damage or even completely destroy some cells.

This system can be modified to implement a charging algorithm as described in [5] and [8] with minor hardware and software modifications. After

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proper power components scaling, a fast charging algorithm can also be implemented by following the instructions from [6].

2. Balancing methods

The most battery-friendly method of charging a battery made out of series cells is by charging each cell individually (Fig. 1). This inherently offers great cell balancing with minimum cell usage.

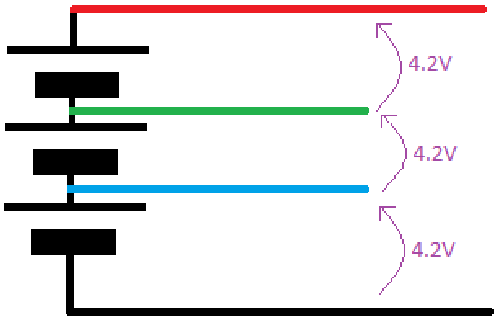


Fig. 1. Individually charged cells

However, in order to provide each cell with its own charging scheme, galvanic isolated power supplies must be used. In practice, this is not feasible because it implies great power losses in the DC/DC galvanic isolators and it is hard to scale to a greater number of series cells.

The most common type of charging is achieved by connecting the charging power supply at the plus and minus power terminals of the battery pack (Fig. 2).

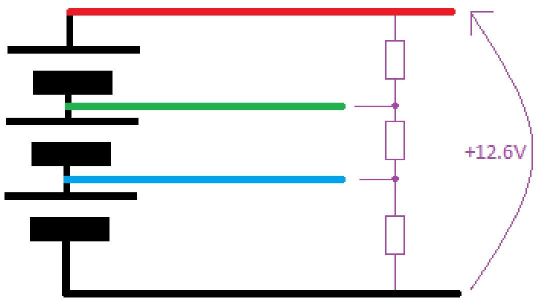


Fig. 2. Common charged cells

By doing this, only one high-voltage high-power charger is needed without any galvanic isolation, but all cells receive the same charging current. By discharging every cell individually, the charging current can be maintained even if one or more cells have reached the charge termination voltage and the balancing can even be maintained after the charging has stopped.

The major drawback of this balancing method is the amount of power dissipated while balancing. This is an issue only for badly balanced or damaged cells because they may force the balancing algorithm to discharge a large number of cells and so, dissipate large amounts of power. However, most battery packs are made with pre-balanced and factory matched cells and the balancing circuit will have to dissipate little to no power.

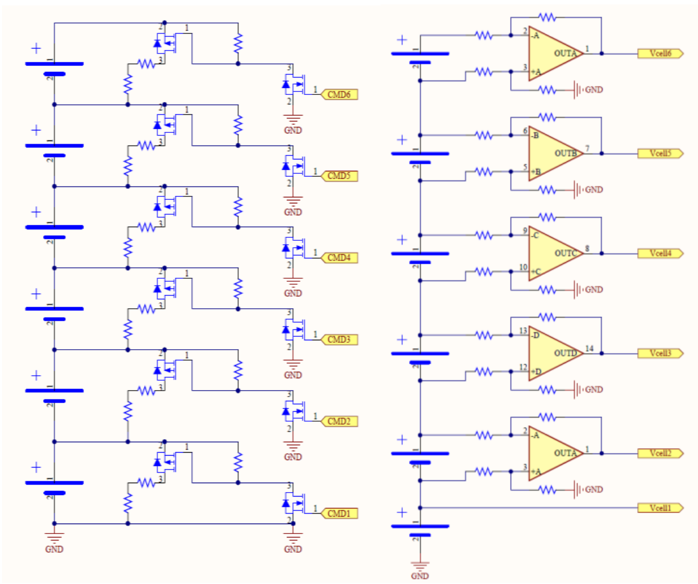
3. Describing the experimental platform and algorithm

In order to exemplify the balancing algorithm, a test platform was designed, composed of:

- a PIC16F1789 microcontroller on which the balancing algorithm was implemented,

- 2x 3.9Ω 3W resistors in series (7.8Ω total) for each cell to discharge (Fig. 3.a),

- operational amplifiers in differential amplifier configuration for each cell voltage measurement (cell 1 was measured directly by the microcontroller) (Fig. 3.b),



a) b)

Fig. 3. a) Discharging circuit; b) Measuring circuit

- power transistors for switching the resistors in parallel with each cell,

- optional: display to show each cell voltage and different indicators.

The balancing algorithm uses the idea of switching on a load in parallel with the desired cell, so by discharging it until all cell voltages are equal (to within a set threshold). The process is more complex than this.

The first step in deciding what cell needs to be discharged is to measure the voltage of each cell. This is done after the discharge process is stopped and 100ms have passed. The discharge is stopped, so that the voltage drop across the wires going to each cell is zero (because there is no current passing through it) and the time passed is there so that the chemistry of each cell has some time to recover (so the voltage will rise closely to the no load voltage). While this time is passing, the microcontroller can execute other tasks, so the processing time is as low as possible.

After the 100ms delay, the algorithm takes over the microcontroller and starts measuring each cell voltage with the integrated ADC (Analog to Digital Converter). This process is the most time consuming but can further be improved by using an external ADC.

When all the voltage level data is acquired, the cell with the highest voltage and the cell with the lowest voltage are determined and the difference between them is calculated. The algorithm has 3 voltage difference steps: 100mV, 50mV and 10mV. Each voltage step can be adjusted to better fit the chemistry.

This voltage difference is compared with the step, and the algorithm decides what cells needs to discharge. If the voltage difference between the biggest cell voltage and the smallest cell voltage is more than 100mV, only the cells that have their voltage bigger with more than 100mV over the smallest cell voltage measured will be discharged. This is an important part of the discharge process because it allows the battery pack to more properly balance. Doing so, there will never be a time where all cells except one are at the same level. Instead, the discharge will start first for the cells that have the biggest voltage then progress to the cells that are closest to the minimum.

The discharge time is also proportional to the voltage difference. So, when the voltage difference is bigger than 100mV, the discharge time (the time the cells are being discharged) is 4sec. When the voltage difference is between 100mV and 50mV, the discharge time is 2sec and when the voltage difference is between 50mV and 10mV, the discharge time is 1sec. By varying the discharge time, the algorithm only interferes in the usual operation of the microcontroller from time to time while also ensuring that the cells are not over-discharged.

When all cell voltages are within the minimum limit, all discharging stops and the battery pack is considered balanced.

Because of the limited resolution of the ADC (10 bit) and the voltages measured (maxim 4.2V (on the 5V range)), the actual resolution of the measurements is ~5mV. Using a better ADC, better precision can be achieved.

Calculating the processing time for the balancing algorithm, the worst case scenario is 1% of the time occupied (10ms in every 1sec), while the best case scenario is 0.25% (10ms in every 4sec).

The presented algorithm also features some safety elements. The first (and major) protection system is the under-discharge voltage of 3.3V. The cells, no matter the unbalance, will never get discharged under this voltage.

Another safety feature is the over-charge protection: the cells that pass the 4.2V mark will always be discharged (the delay time will not be applied to them). By doing so, the voltage measuring process will lose some precision, but the cell will not over-charge. At this point, if the microcontroller is also connected to the charging power source, it can either stop the charging until the cells are better balanced or it can decrease the charging current so that the discharge (balancing) system can maintain all cell voltages in the safe zone.

To monitor and record the results, a display was added to the test platform (Fig. 4). Here, some parameters can be observed, such as:

- individual cell voltages,
- minimum and maximum cell voltage indicator (battery empty and battery almost full),
- what cells are being discharged (down pointing arrow).

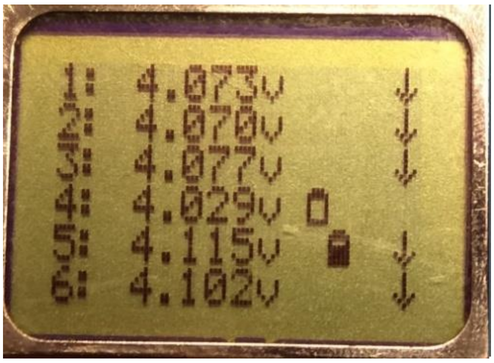


Fig. 4. Display for user interface

Another feature for best voltage measurement is the rolling average that is implemented for 6 counts. This helps in reducing noise and offers better voltage accuracy.

4. Experimental results

To test the functionality of the algorithm, 4 types of batteries were tested: a very small and a very large capacity battery, and a very balanced and unbalanced battery in 2 situations: while charging (the most frequent scenario) and without charging (usually used before storage).

Those experiments were designed to test how the system would response in different scenarios, such as: the discharge current is bigger or smaller than the charging current, a cell battery is damaged or the time it take to balance without charging is too big.

4.1. Balancing of a 4 cell, 240mAh battery while charging

The battery tested in this scenario was composed of 4 cells arranged in a 4S1P configuration (4 cell is series and 1 in parallel). Because of the capacity, the charging current was 150mA (0.6C (60% of the capacity)) but the discharge current was not modified and remained ~0.5A, resulting in a faster rate of discharge compared with charging and a decrease in cell voltage. The results can be observed in Fig. 5.

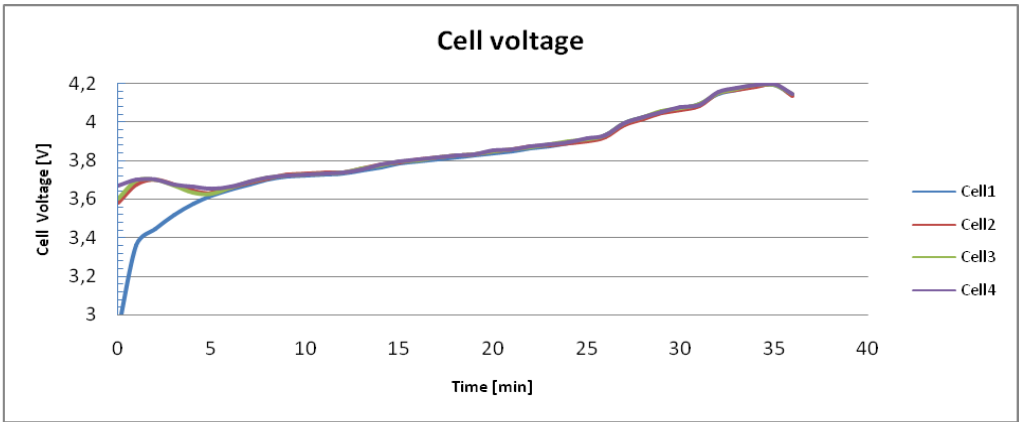


Fig. 5: Balancing while charging a 4 cell 240mAh battery

For the first 3 minutes, the battery was charged without the balancing circuit started because of cell 1 that was over-discharged to under 3V. This was done manually to exemplify a poorly balanced battery. After 3 minutes, the balancing circuit was started, and the actual balancing time was under 2 minutes. A decrease in cell voltage can be observed for cells 2, 3 and 4, decreased caused by the overpowering discharging circuit. While this was happening, cell 1 voltage was still rising. After all cells reached a similar voltage, the balancing circuit was only active for short periods of time to maintain balance.

To better understand the cell voltage difference, the graph from Fig. 6 was created.

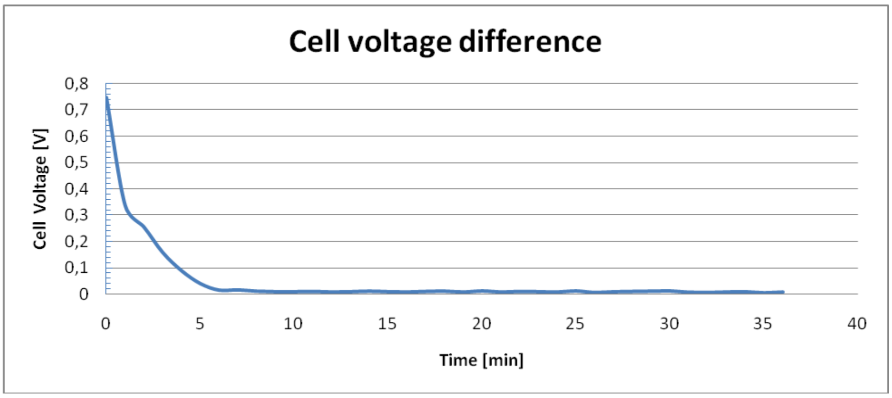


Fig. 6: The difference between the biggest and lowest cell voltage

As a result of this test, the experimental algorithm and circuit can be used successfully to balance a very small capacity battery.

4.2. Balancing of a 5 cell, 11Ah battery while charging

The next test involved balancing a very large capacity, 5S6P battery while charging at a current of 2A (0.2C). This simulated a behavior similar to when the charging circuit is overpowering the balancing circuit, resulting in a much larger balancing time. The result can be found in Fig. 7.

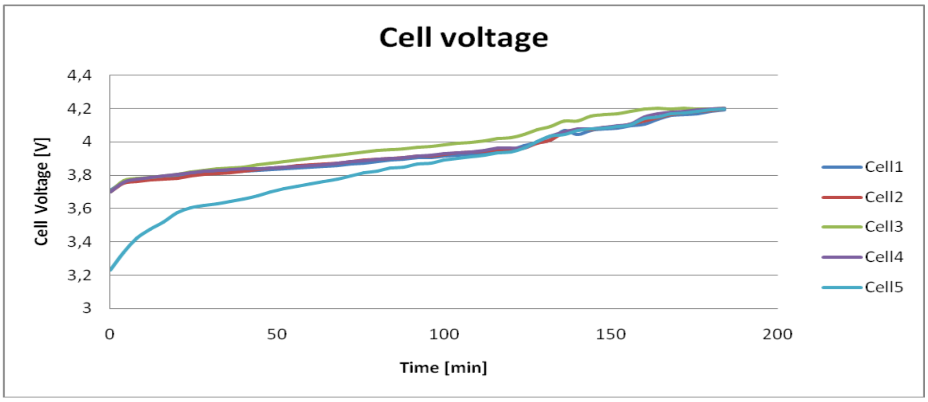


Fig. 7: Balancing while charging a 5cell, 11Ah battery

As expected, the balancing took very long. Because of the great imbalance, the balancing was active almost all the time for one cell in particular (cell 3) and half of the time for cells 2, 4 and 5, resulting in an increase of power dissipation.

However, the balancing was achieved when most of the cells were reaching their maximum charging voltage of 4.2V and the current decreased to a more manageable value.

In conclusion, although the experimental device can successfully balance a very large capacity battery, some adjustments must be made to the discharge current to speed up the process.

4.3. Balancing a damaged 6cell battery (~1500mAh) while charging

This battery was designed and created to be as unbalanced as possible by using damaged cells with different capacities and levels of wear to test the behavior of the balance algorithm. The result can be observed in Fig. 8.

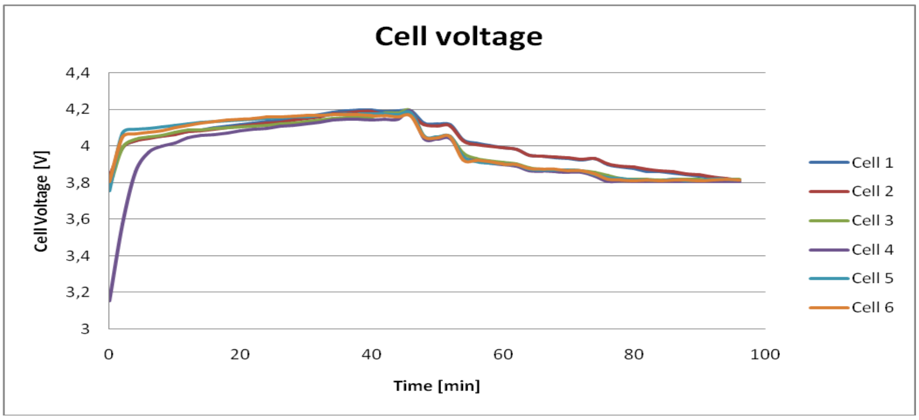


Fig. 8: Balancing while charging a 6 cell, ~1500mAh damaged battery

The results from Fig. 8 reflect the poor performance of this battery: the difference between cells is almost constant and after the charging has stopped, the cells become even more unbalanced. The algorithm is struggling to maintain balance but is unable to do so because of one of the cells that has an extremely high self-discharge current. In the end, after the cell stops self-discharging, the cell balance is quickly regained.

The conclusion of this experiment is that, no matter the intelligence put in place to balance a battery, if the battery is damaged, there is little that can be done. The only think that can be done is signal the user that this battery is faulty and the user can then replace the battery or repair it by changing the faulty cell/cells. However, this signaling can only be done if the balancing and monitoring system is integrated into the charger. This has not yet been implemented, but the design phase is undergoing.

4.4. Balancing a 3 cell, 2200mA battery without charging

The final scenario tested involved a very well balanced and matched battery pack composed of 3 cells in series. This balancing was done without charging to test the rapidity of a normal battery to be balanced. The result can be found in Fig. 9.

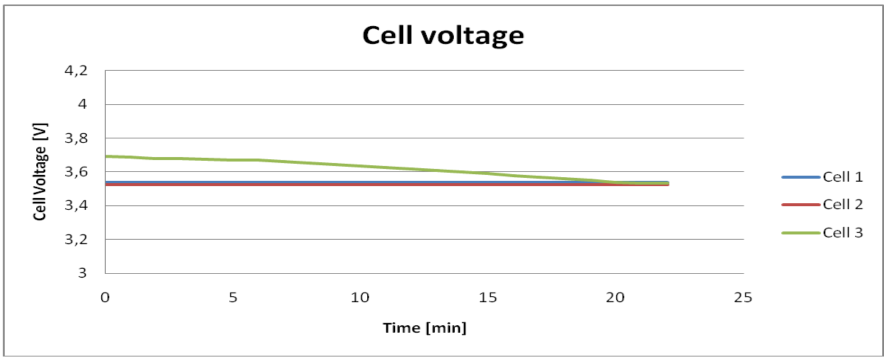


Fig. 9: Balancing without charging a 3 cell, 2.2Ah battery

As it can be seen from Fig. 9, the balancing only took 22 minutes and the power dissipation was kept to a minimum. Because only one cell had its voltage higher than the other 2, the discharge was localized to that particular cell (best case scenario).

5. Conclusions

This paper has described and tested a balancing algorithm (running on a self-designed platform) designed to use as little processing power as possible for balancing of Li-Ion and Li-Polymer batteries made from cells configured in series. The system is designed for battery packs that are charged at high currents by the main terminals and can handle a maximum of 6 cells. This limitation can be increased by changing the microcontroller with another one that has a higher number of pins and by changing the code to accommodate the new number of cells.

Adding a microcontroller to a balancing circuit has some advantages, such as more precise voltage measurements, adaptive discharging and adds some features, like overvoltage protection (the discharge will be permanently on if the cell voltage is over 4.2V) and over-discharge protection (the discharge will not happen if the cell voltage is under 3.3V).

The algorithm was successfully tested in 4 different scenarios. While balancing a small capacity battery, the balance was achieved very fast and the power dissipation was minimal.

When balancing a high capacity battery, the balancing was slow but manageable and the cell balance was ultimately achieved when all the cells reached their maximum voltage.

If a badly unbalanced battery with damaged cells is being used, the results are unpredictable, even if the balancing algorithm is well implemented. In the tested scenario, because of a deficient cell with high self-discharge, the other cells were greatly discharged, and the battery pack was unable to finish charging. In this case, if the balancing circuit had been connected to the charging power supply, a working or error message would have been generated to notify the user that a cell is damaged and needs replacement.

The balancing should be done while charging. However, it can also work statically. In the last tested scenario, the balance was achieved rapidly, even when not charging, while the battery was in preparation for storage.

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