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ACTIVE BALANCING METHOD FOR BATTERY CELL EQUALIZATION

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Abstract: The emerging need for more power has led to the development of series-parallel connected battery cells. Having a more complex system also brought with it new challenges. One of these is the problem of cell imbalance. Balancing algorithms are based on extracting or adding charge in order to have balanced cells. Their goal is to protect the battery from damage and to help prolong the battery's life. Without a balancing system the individual cell voltage will drift away, the total capacity of the pack will decrease more rapidly during operation and also the estimation of the state of charge will be unreal. This paper presents the theory behind the most important balancing algorithms developed so far and also proposes another method of cell balancing, method tested both through simulation and implementation.

Keywords: *battery cell, balancing algorithm, charge*

I. INTRODUCTION

Different algorithms are discussed when considering battery cell balancing. The most typical manifestation of unbalance is represented by voltage difference, which is attempted to be corrected either instantaneously or gradually through by-passing cells or by energy conversion. However, the underlying reasons for voltage differences on the level of battery chemistry and discharge kinetics are not widely understood. Means used to perform cell balancing typically include by-passing some of the cells during charge and sometimes during discharge, by connecting external loads parallel to the cells through controlling corresponding FETs. Typical by-pass currents range from a few milliamps to amperes [1].

Batteries like lead-acid or nickel-cadmium have simpler balancing algorithms as their balance is reached through overcharge. In lead acid batteries, overcharging causes gassing which coincidentally balances the cells. This strategy is accepted by these chemistries without high risks or without affecting the battery. Li-ion cells are designed to provide a voltage in the range of approximately 3.0 to 4.3 V. It is extremely important to maintain the voltage of a Li-ion cell between its designed limits at all times, or the cell will be irreparably damaged. If a cell's voltage is allowed to drop below 3.0 V, the cell can go into a state of deep discharge, from which it may take hours or even days to recover. In fact, deep discharge may cause the cell to short-circuit, an event from which it will not recover. Overcharging to a voltage greater than 4.3 V can be even worse because this can damage the cell, possibly with severe overheating or other catastrophic results. In simple applications using only a single Li-ion cell, the electronic control circuit must protect the cell by disconnecting the load when the cell voltage drops below 3.2 V and limiting the voltage during charging to less than 4.2 V [2].

There are several factors mentioned when talking about imbalance: differences in charge storage volume due to production, difference in internal resistance, difference in state of charge or thermal differences across the pack.

II. BALANCING ALGORITHMS

The recommended way to implement cell balancing is to provide a conditioning cycle on initial pack charge that balances during discharge and charge.

Cell balancing is usually categorized into two types: passive and active. The passive cell-balancing method, also known as "resistor bleeding balancing", is simple and straightforward: discharge the cells that need balancing through a dissipative bypass route. This bypass can be either integrated or external to the IC. Such an approach is favorable in low-cost system applications as in [3]. The main drawback is that all of the excess energy from the higher energy cells is dissipated as heat, and also being applied during discharge, will practically shorten the battery's run time.

The balancing method used for lead-acid and nickel based batteries is also included in the passive category because these batteries can be brought into overcharge conditions without permanent cell damage [4]. The principle is simple: after receiving a bulk charge they can be trickle charged at a low current until all cells reach full charge. However, this means that some cells will receive at least a slight overcharge which is unacceptable for Li-ion since this leads to ignition of the cell.

Dissipative resistor is a special balancing method because of its reliability and simplicity. Figure 1 shows the basic dissipative resistor balancing circuit topology.

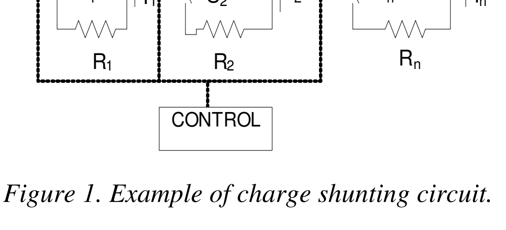

Figure 1. Example of charge shunting circuit.

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The same topology could work in two modes, continuous mode and detecting mode. In continuous mode, all the relays are controlled by the same signal, that is on or off at the same time. They will only be turned on during charging. The cell with a higher voltage will have less charging current so as to wait for other cells to be charged. This is effective during the whole charging process and if the resistor value is properly selected, it could be very effective. The advantage of this mode is that it doesn't need complex control [5].

For the detecting mode, voltage monitors are added to each cell. A microcontroller senses the imbalance conditions and determines if the dissipative resistor should be connected to remove the excessive energy from the cell.

In the same field of detecting mode method, the targeting mode can be included.

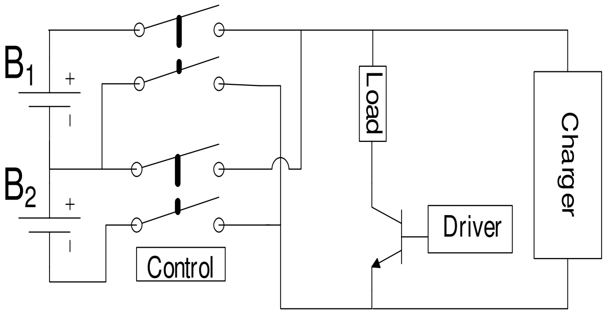

Figure 2. Example of targeted equalization.

In this method a voltage reference is used. The microcontroller measures the voltage on the cell, compares it to the voltage reference, and according to the difference, the microcontroller establishes which switch should be closed. If the voltage on the cell exceeds the reference the charge will be dissipated across a resistance, and if it's below the reference the cell will be connected to a charger. The process won't be stopped until the voltage on the cell reaches the voltage reference.

In [6] a microcontroller in the central module has access to all of the cell voltage measurements, and therefore can select any cells that need equalization. Another microcontroller in each local ECU determines the proper relay settings for the equalizer. Once a cell is selected by the equalizer it is not released until its voltage equals the average cell voltage. Therefore, the relays typically only operate at most once every few minutes. Several techniques can be used to measure the cell voltages, but the most obvious method of using resistive voltage dividers can produce excessive measurement errors unless very high precision resistors are used. Another simple and much more accurate method that is also presented in [6], where transconductance amplifiers are used to change the voltage measurements into current signals for cells.

In expensive Uninterruptible Power Supplies (UPS), for best results, cells inside the battery system are individually charged. Complete shunting is an alternative to parallel chargers. The principle is that when one cell reaches maximum voltage, the cell is completely shunted by using switches. The charge finishes when the last cell in the string in fully charged [5]. Such a principle is shown in Figure 3.

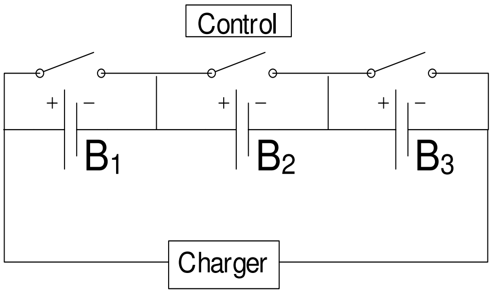

Figure 3. Example of complete shunting.

Disadvantages of the charge shunting methods are the requirement for large power dissipating resistors, high current switches, and thermal management requirements. This method is best suited for systems that are charged often with small charge currents. This method seems to be quite straightforward. However, when a string is long, it may need a cascaded buck converter for which the output voltage range is very wide [11].

Another topology that takes care of active battery balancing is the resonant converter. Instead of using intelligent control to sense and generate a PWM gating signal, resonance circuits are used to both transfer energy and drive the MOSFETs.

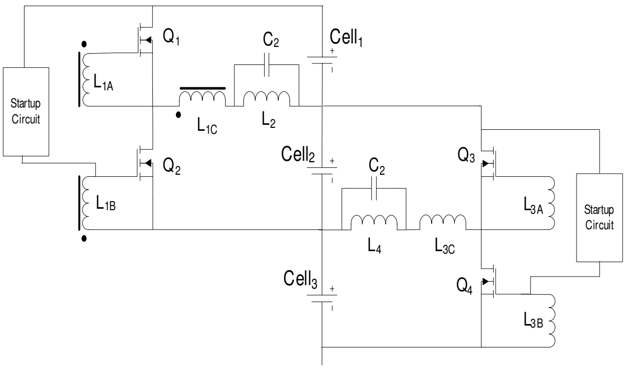

Figure 4. Resonant converter balancing circuit [11].

The inductor L1 and Capacitor C1 are used to both transfer energy and drive the MOSFET. This circuit needs a startup circuit to start the resonance. When the voltage across L1 is positive, Q2 is on, with the decrease of inductor voltage, Q2 turns off. With the increase of the voltage in the other direction, Q1 turns on, and L1 and C1 will resonate with the first cell. The resonance will cause a reverse current in L1 and then turn off Q2 and turn on Q1 which is the starting of another cycle of the resonance. If cell1 has a higher voltage than cell2, the average current flow through inductor L2 will be positive so as to balance [11].

In passive balancing, the practical goal is to achieve capacity balance at the end of charge, but, due to the low balancing current, little can be done to also correct voltage imbalance at the end of discharge. In other words, overcharging of weak cells can be avoided, but it may not be possible to improve battery run time because the extra energy is wasted in the bypass resistance as heat.

In the active balancing part however the idea is to use external circuits to actively transport energy among cells so as to balance the cells. The active balancing methods can be used for most modern battery systems because they do not rely on the characteristic of cells for balancing [5]. Active cell balancing overcomes the energy loss of the passive method by using capacitive or inductive charge storage and shuttling to deliver energy to where it is needed most, and with little loss. Thus it is preferable for applications where delivering maximum run time is top priority. Simple approach to redistribute the energy between the cells is to connect a capacitor first to higher the cell voltage, than to lower the cell voltage. More complicated implementations allow the connection of not only two nearby cells, but also for cells far away in the stack for faster equilibration [1].

In Figure 5 a simple charge shuttling circuit is shown, where a single capacitor flies between several cells.

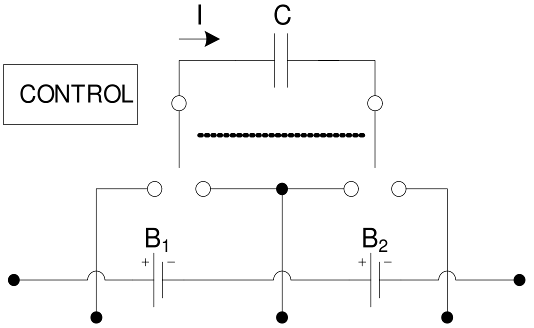

Figure 5. Example of charge shuttling circuit using a single flying capacitor.

The main problem with this method is that significant energy losses occur during capacitors charging, as maximal efficiency of this process is 50%. Another problem is that high voltage differences between the unbalanced cells exist only in highly discharged state.

Because in this method transfer rate is proportional to voltage differences, it only becomes efficient near the end of discharge so total amount of unbalance that can be removed during one cycle is low.

Energy conversion cell-balancing methods use inductors or transformers to move energy from a cell or group of cells to another cell or group of cells. Their advantage is that they offer a smalleri balancing rate excluding the disadvantage of small voltage differences between cells.

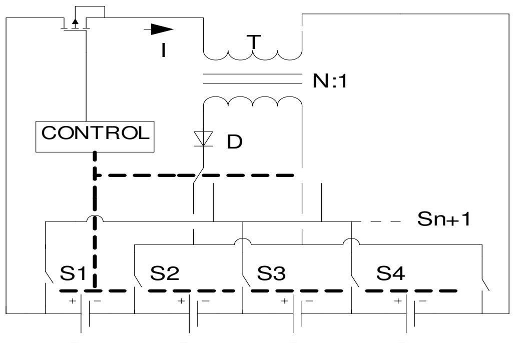

Figure 6. Example of switched transformer.

Two active energy converter methods are the switched transformer and the shared transformer. The switched transformer method shares the same switching topology as the flying capacitor method (Figure 6). Current I is taken from the entire pack and is switched into transformer T. The transformer output is rectified through diode D and delivered into cell B_n, which is determined by the setting of switches S. Electronic control is required to select the target cell and set switches S. This method can rapidly balance low cells at the cost of removing energy from the entire pack. Disadvantages include high complexity, high parts count in terms of control, magnetics, and switches, and low efficiency due to switching losses and magnetic losses. [5].

A shared transformer has a single magnetic core with secondary taps for each cell (Figure 7). Current I from the cell stack is switched into the transformer primary and induces currents in each of the secondaries. The secondary with the least reactance (due to a low terminal voltage on B_n) will have the most induced current. In this way, each cell receives charging current inversely proportional its relative SOC.

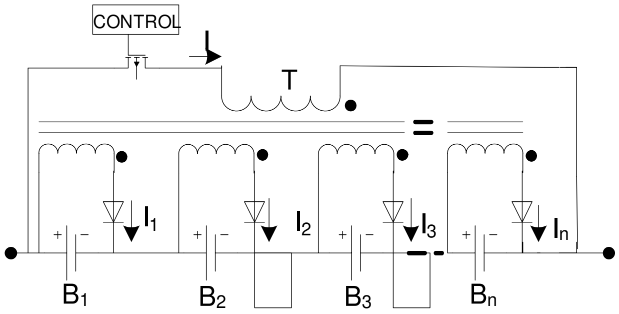

Figure 7. Example of shared transformer.

The only active component in the shared transformer is the switching transistor for the transformer primary. The shared transformer can rapidly balance a multicell pack with minimal losses. Disadvantages of this cell balancing method include complex magnetics and high parts count due to each secondary's rectifier. Another disadvantage is that it is difficult to add more cells to the pack as secondary taps are hard to be added. Several transformers can be used with the same result by coupling the primary windings instead of coupling via a single magnetic core.

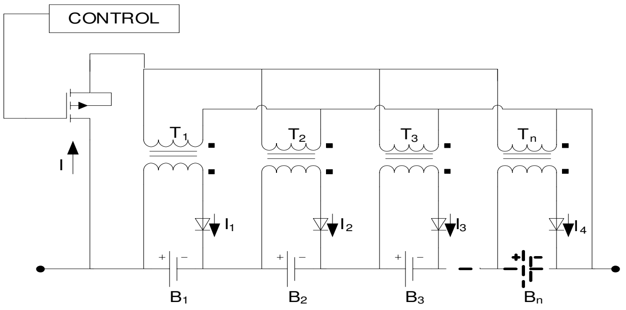

Figure 8. A shared transformer with several cores.

The benefit of this method is each cell can have its own magnetic core, thus allowing additional cells to be added to the string without altering the host controller.

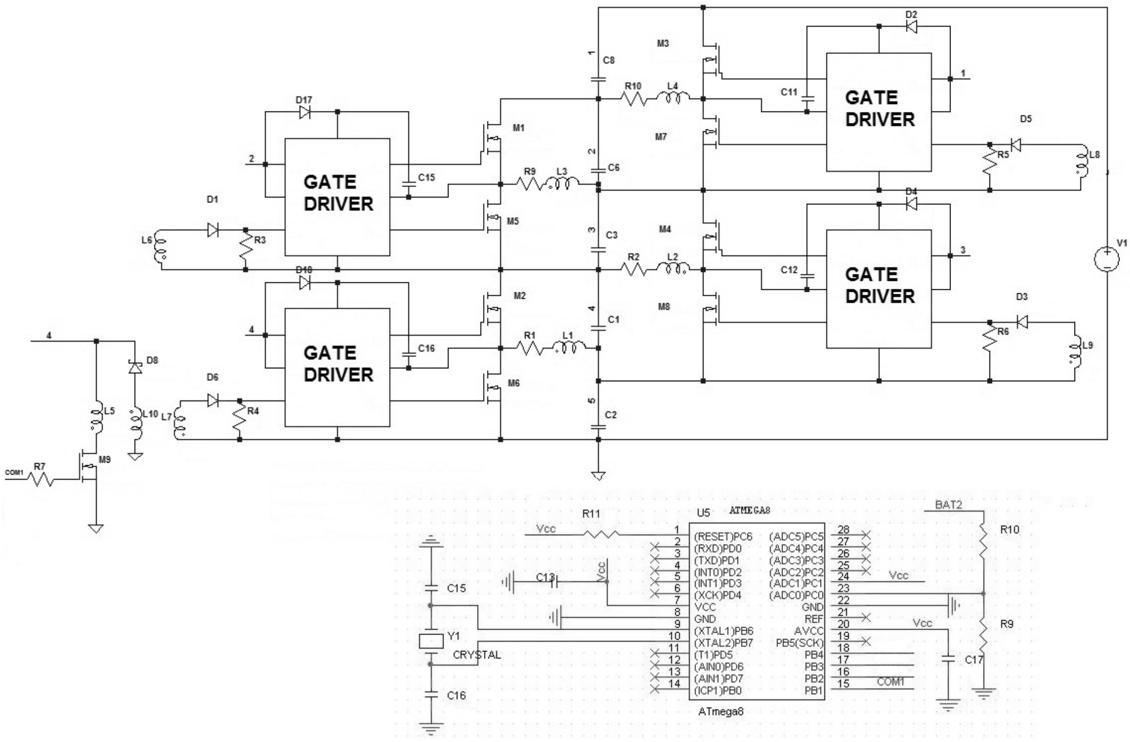

Figure 9. The proposed circuit.

III. PROPOSED ALGORITHM

The system proposed for balancing the battery pack relies on energy conversion devices as it uses inductors to move energy from one cell to another. The principle is based on the principles of half-bridge converters, having two transistors and a voltage divider. The transistors are driven by a high frequency gate driver. When the upper transistor is on, the energy is transferred from the top cell to the inductor through the top n-channel MOSFET. When the transistor is turned off, the energy stored in the inductor reaches a maximum. Because the inductor current must flow continuously, the body diode of the second transistor is forward-biased, completing the charge transfer from the inductor to the lower cell. For driving the complimentary pair switch, the specialized circuit supplies the square wave with 50% duty. In this process, energy is stored in the inductor with only minor loss due to the series resistance of the inductor and the on resistance of the body diode.

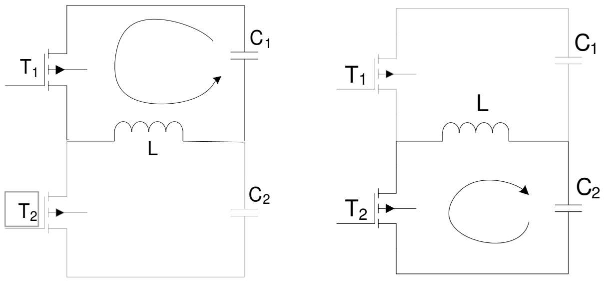

Figure 10. The current path during the transistors switch.

As three of the gate diver circuits have floating points, a transformer was implemented in order to solve this problem. Inductors L5, L6, L7, L8, L9, and L10 are all coupled in the transformer. When transistor M9 is on, diodes D1, D3, D5, and D6 are also on. All the energy accumulated from the entrance is being transferred to the gate drivers. The Schottky diode D8 is used for the demagnetization of the transformer.

Since the power MOSFET generally accounts for the majority of power loss in a converter, it is important to quickly turn it on and off, thereby minimizing the transition time and power loss. The specialized gate driver circuits were chosen to have a rapid turn-on transition for the MOSFETs. In order to operate the gate driver circuit needs an input signal, signal that was taken from an ATmega8 controller. The controller was programmed to realize the following functions: offer the PWM signal in order to operate the gate drivers, verify the status of the balancing process and also, for power consumption, it was programmed to enter a standby mode once the balancing process is over. A flowchart of the process is shown in Figure 11. The values of the voltages on all the cells are read using the ADC of the microcontroller and are compared through software algorithms in order to establish if the balancing process should continue or not.

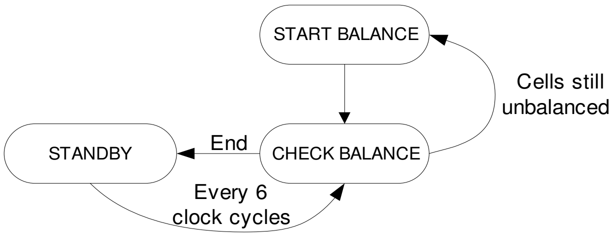

Figure 11. Balancing process flowchart.

IV. SIMULATED AND EXPERIMENTAL RESULTS

The proposed circuit was simulated using LTspice software from Linear Technologies. The results of the simulation are shown in Figure 12.

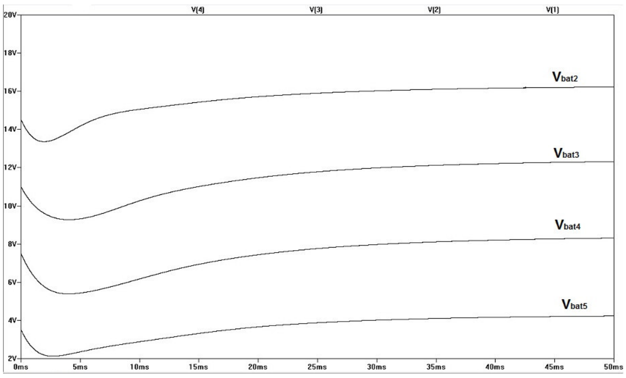

Figure 12. Result of the simulated proposed circuit.

The circuit was implemented and it was tested on two 2.5V, 10 farads, supercapacitors in order to prove its functionality. The results were taken from the board using a USB-6009 DAQ board from National Instruments and the results are plotted in Figure 13.

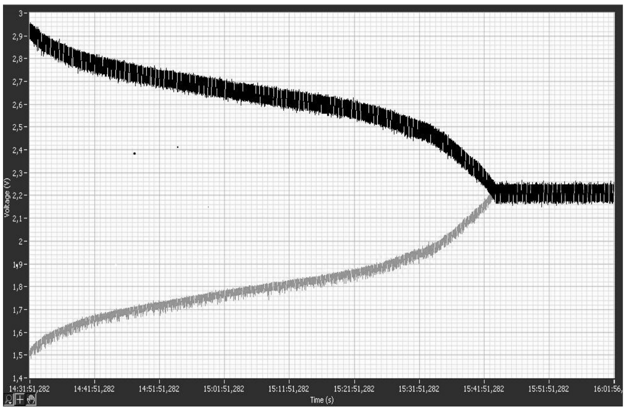

Figure 13. Results of the implemented circuit.

In order to verify the results the circuit for the two supercapacitors was also simulated using Psim software, and the results are listed below.

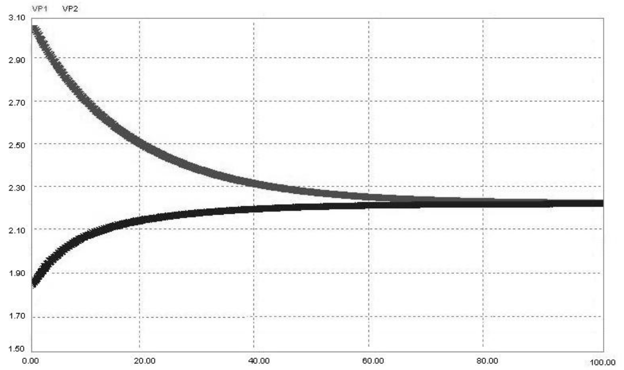

Figure 14. Simulated results with two supercapacitors.

V. CONCLUSIONS

Balancing is an important issue that has to be taken into account when developing an efficient and safe battery management system. Choosing the right balancing method is very important as these methods can end up in harming the whole system even more, if not being applied in the right way.

The circuit proposed has proven its efficiency both through simulation and implementation. The circuit can be a reliable solution and can be successfully integrated into a battery management system. The main advantage of this method is that balancing is achievable regardless of the individual cell voltages. Balancing can happen during any battery operation — charge, discharge, or rest — and even if the cell that provides the charge has a lower voltage than the cell that receives it. Compared with passive cell balancing, little energy is lost as heat. Because of the higher balancing current, this technology corrects cell imbalance much better than conventional integrated, passive balancing with internal bypass FETs.

ACKNOWLEDGEMENT

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