A Cost Optimized Battery Management System with Active Cell Balancing for Lithium Ion Battery Stacks

Carl Bonfiglio, *Member, IEEE* and Werner Roessler
Automotive Division
Infineon Technologies AG
Carl.Bonfiglio@infineon.com and Werner.Roessler@infineon.com

***Abstract*—A method for active cell balancing of lithium ion battery stacks is presented. Balancing the charge of cells in a multi-cell lithium ion battery stack is often employed to guard against damage and improve the lifetime of the battery. Battery stacks which are in production today largely use a passive cell balancing method, which dissipates charge through a resistor, as heat. The method described uses a flyback converter to pass charge from cell to cell with low losses and only a small cost increase from a typical passive system.**

Keywords-Cell Balancing; Lithium Ion; Battery Management; PHEV; Electric Vehicles; Ultracapacitor

I. INTRODUCTION

The recent increase in demand for highly fuel efficient vehicles has brought a great deal of investment into the development of automotive grade energy storage systems, such as Lithium ion battery stacks and ultracapacitor stacks. One of the key challenges to this development is to design a battery management system which enables safe operation, long term reliability, and cost effectiveness. In the rush to get the first systems into production, already proven methods which have been used outside of automotive applications are being employed. As the development community begins to design second generation batteries, more advanced battery management systems will be considered. These next generation systems will enhance the cycle life, calendar life, power capability and safety of the energy storage packs [1].

Because of the large amount of cells in an automotive battery stack, each with slightly varying electrical characteristics [1], the battery management system must balance the voltage of each cell in the stack. This critical task is a key contributor to the battery management system satisfying the requirements of automotive applications. The chosen method of cell balancing can have a large impact on the overall battery stack design, as well as cost.

The purpose of this paper is to describe a method of active cell balancing which has great benefit for automotive grade energy storage systems.

II. BATTERY STACK ARCHITECTURE

Modern battery cells and ultracapacitors have amazing energy storage capacities. Nevertheless, one cell is insufficient to support an electric traction motor drive. The voltage and the current produced by one cell would be too low, so to increase the current capability, cells are connected in parallel. Higher voltages can be achieved by connecting cells in series.

Battery assemblers usually describe their arrangements in terms such as “3 P 50 S”, which means 3 cells in parallel and 50 cells in series.

The type of battery management described in this document is often utilized in a modular architecture. One example would be a series connection of up to 12 cells combined in one block in a 3 P 12 S array. These cells are supervised and balanced by an electronic circuit with a microcontroller at its heart.

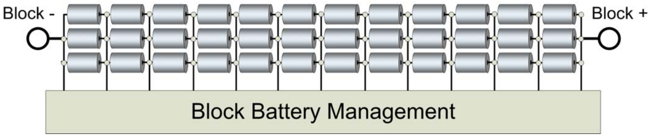

Figure 1. Block Architecture

The output voltage of a block depends on the number of cells in series and the specific cell voltage. The cell voltages of Lithium ion cells are typically between 3.3 and 3.6 V. This leads to block voltages between 30 and 45 V.

Electric motor drives in automotive applications need a DC supply voltage in the area of 450 V. To compensate for the different cell voltages, depending on the charge state, a DC-DC converter is a suitable link between battery stack and motor drive. The converter additionally is able to limit the currents.

For optimal operation of the DC-DC converter, a stack voltage of 150 to 300 V is required. Therefore, 5 to 8 blocks may have to be connected in series.

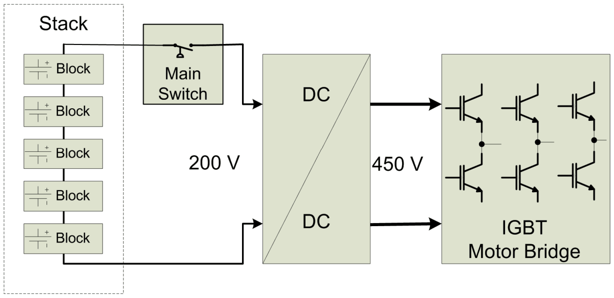

Figure 2. Hybrid power-supply system

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A. *Balancing and Voltage Scanning*

When cells are linked in parallel in a battery block, the capacity can be multiplied. In this case the voltages are forced to be equal. This leads to automatic charge balancing.

The more critical issue is the series connection. All cells are loaded with the same current. Unless there is some further equipment in the circuit, the weakest cell determines when the charging and discharging current has to be interrupted.

B. *Reasons for Balancing*

If the upper and lower voltage limits (e.g. 2 V and 3.6 V respectively for nanophosphate Lithium ion type cell) are exceeded, the cells may be damaged. The output voltage is stable over a wide SOC (state of charge) range, although at the beginning and the end, the curve changes slope very rapidly (Fig. 3).

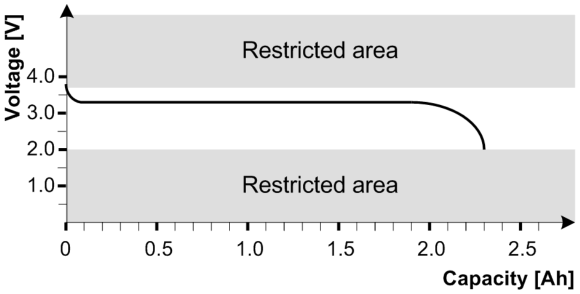

Figure 3. Lithium-Ion Discharge

If the first cell of a pack reaches one of the limits, the current has to be stopped. Therefore, it is recommended to start a charge move between the cells when the voltage of the first cell begins to differ from the others.

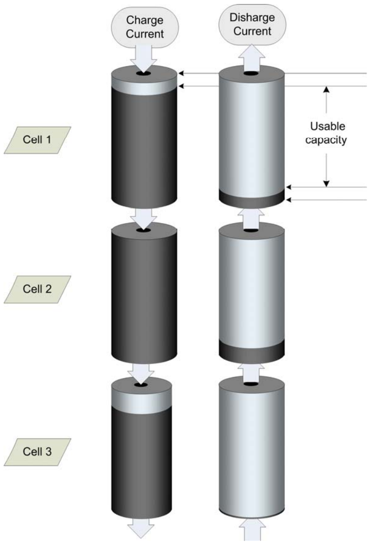

Figure 4. Example of an unbalanced battery stack

C. *Conventional Balancing Method (Passive)*

Usually battery packs are only balanced in the charge mode. Every cell has a load resistor that can be connected to the cell. This allows energy to be taken from the strongest cell. This relatively simple passive method has following disadvantages:

- Balancing is only possible in the charge mode.
- Energy is wasted, especially in mobile applications, where braking energy is used to charge the batteries and the total energy balance is not optimized. With active balancing, the reachable distance can be increased.
- The load resistors have to be cooled in case of higher balancing currents.

III. BALANCING CIRCUIT

A transformer is the central component of the circuit. It is used for:

- Moving energy between the cells
- Multiplexing the single cell voltages to a ground-voltage-based ADC input

The construction principle is a flyback converter. This type of transformer is suitable to store energy in a magnetic field. An air gap in the ferrite core increases the magnetic resistance to reduce the saturation.

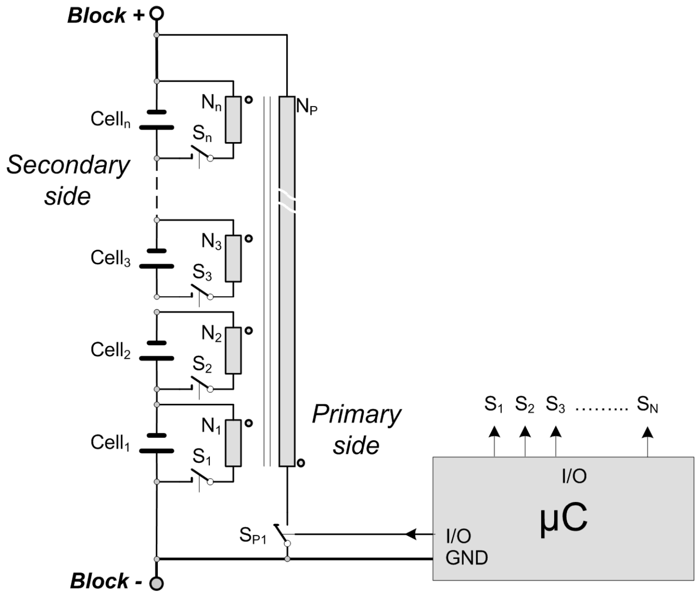

Figure 5. Balancing Circuit

The transformer has two different sides.

- The primary side is connected to the complete battery stack.
- Every cell is connected to a secondary winding.

A practical model of the transformer supports up to 12 cells. The switches are represented as MOSFETs from the Infineon Technologies OptiMOS™3 series (Fig. 5).

Every block is controlled by a modern 8-bit microcontroller from Infineon Technologies, the XC886CLM. It includes a Flash program and a 32-kilobyte data memory. Two hardware-based CAN interfaces allow communication via the CAN protocol with low processor load.

A. Balancing Methods

The bi-directional use of the transformer allows either of two different balancing methods, depending on the situation. After a voltage scan of all cells, the average value is calculated. Then the cell with the largest deviation from the average is examined. If its voltage is lower than the average, the BOTTOM balancing method is applied; if it is higher, the TOP balancing method is better.

B. Bottom Balancing

The example in Figure 6 shows a situation in which the BOTTOM balancing method is required. Cell 2 is recognized as the weakest cell. In order to support cell 2, the transformer is charged out of the stack when the primary (prim) switch is closed. After opening the primary switch, the stored energy of the transformer can be shifted into a selected cell. This happens, if the corresponding secondary switch (in this example, sec2) is closed.

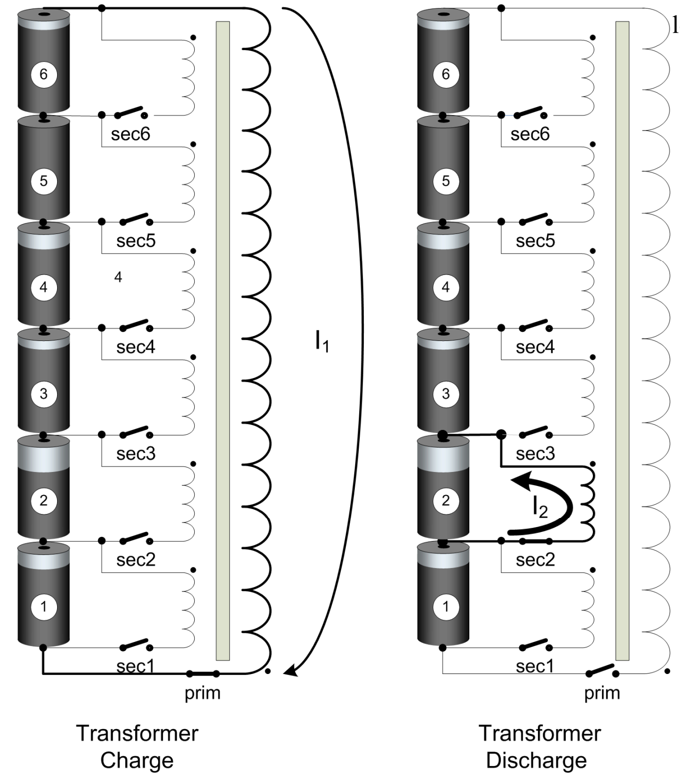

Figure 6. Bottom Balancing Principle

The timing is mostly influenced by the transformer design. The inductance values and the chosen peak current determine the necessary closing times of the switches.

The transformer used in this example has a primary inductance of 160 Microhenry (µH). With a block voltage of 40 V (12 x 3.3 V), the current rises at a rate of 0.25 A / µs.

$$\frac{dI}{dt} = \frac{U}{L_P} = \frac{40[V]}{160[\mu H]} = 0.25\left[\frac{A}{\mu s}\right] \tag{1}$$

A pulse of 8 µs generated by the microcontroller leads to a peak current of 4 A.

$$I_{peak} = t \times \frac{dI}{dt} = 8[\mu s] \times 0.25\left[\frac{A}{\mu s}\right] = 4\ [A] \tag{2}$$

The energy content of one pulse is 640 microjoules (µJ).

$$W = U \times \frac{I_{peak}}{2} \times t = 40[V] \times \frac{4[A]}{2} \times 8[\mu s] = 640[\mu J] \tag{3}$$

The current and time for the degaussing pulse can be calculated as follows:

$$I_{peak} \times t = \frac{W \times 2}{U} = \frac{640[\mu J] \times 2}{3.3[V]} = 388\ [\mu As] \tag{4}$$

The inductance of a secondary winding is 4.4 µH. This leads to a current ramp of

$$\frac{dI}{dt} = -\frac{U}{L_{Sec}} = \frac{3.3[V]}{4.4[\mu H]} = 0.75\left[\frac{A}{\mu s}\right] \tag{5}$$

The degaussing time can be calculated as

$$t = \sqrt{\frac{I_{peak} \times t}{\frac{dI}{dt}}} = \sqrt{\frac{388[\mu As]}{0.75\left[\frac{A}{\mu s}\right]}} = 22.7[\mu s] \tag{6}$$

The peak current results as

$$I_{peak} = t \times \frac{dI}{dt} = 22.7[\mu s] \times 0.75\left[\frac{A}{\mu s}\right] = 17[A] \tag{7}$$

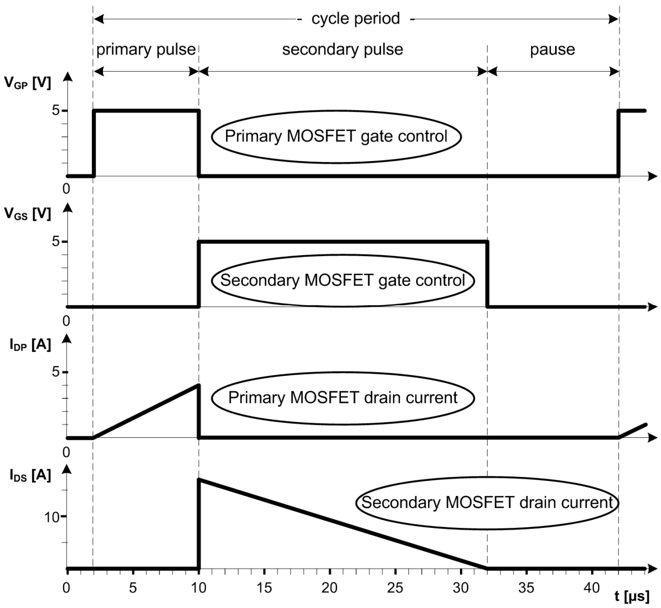

Figure 7. Bottom Balancing Waveform

A cycle period consists of the 2 active pulses and a pause. In this example, the period of 40 µs is equivalent to a frequency of 25 kHz. It is recommended to design the transformer for a frequency over 20 kHz. The transformer would create a bothersome whistling noise in the audible frequency range.

The average secondary current, which represents the balancing performance, is calculated as

$$I_{mean} = \frac{I_{peak}}{2} \times \frac{t_{\sec}}{t_{period}} = \frac{17\left[A\right] \times 22.7\left[\mu s\right]}{2 \times 40\left[\mu s\right]} = 4.8\ \left[A\right] \qquad (8)$$

Especially in a situation where the SOC of a cell has reached its maximum value, the BOTTOM balancing method helps to prolong the operation time of the stack. As long as the current quantity issued of the stack is less than the average balancing current, the operation mode can be continued until the last cell is empty.

C. Top Balancing

If one cell has a higher voltage than the others, it is useful to transfer energy from the cell. In the charge mode, it is absolutely necessary to perform this. Without balancing, the charging process has to be stopped immediately when the first cell is full. Done earlier, it helps to maintain the cells at the same voltage.

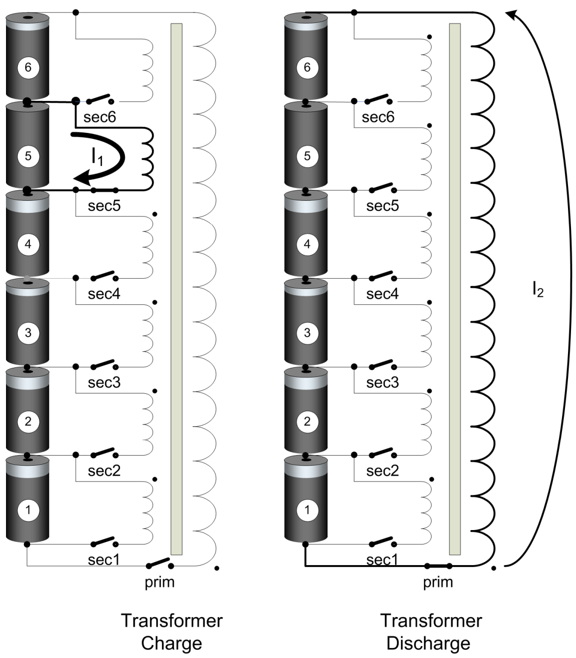

Figure 8. Top Balancing Principle

The example in Figure 8 shows a stack of 6 cells. After the voltage scan, cell 5 has been detected as the strongest member of the stack. When the switch sec5 is closed, a current out of the battery into the transformer starts to flow. Because of the inductance, the current rate rises linearly over time. As the inductance is a fixed characteristic of the transformer, the on-time of the switch defines the maximum current value. The energy portion is completely stored as a magnetic field. After the switch sec5 is opened, the *prim* switch has to be closed. The transformer behavior changes into a generator mode. The energy is fed into the complete stack via the big primary winding.

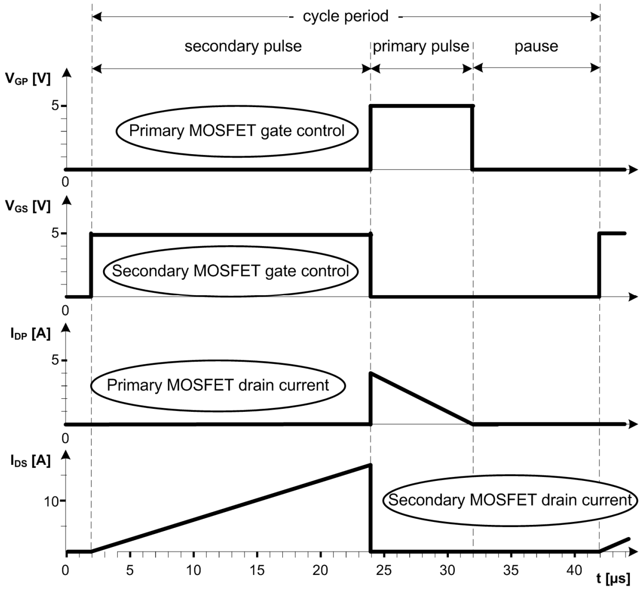

Figure 9. Top Balancing Waveform

The current and timing calculations are similar to the BOTTOM balancing example. Only the sequence and current directions are in the reverse direction.

D. Balancing Between Blocks

The method described above perfectly equalizes the charge state of the cells inside a block. However, the block charge state may diverge. A simple additional winding in the block transformers and an additional transistor on the high side of the primary winding allow balancing between the blocks. This works like the TOP balancing principle, with one difference: The energy of the strongest cells is moved into the stack instead of the block. The energy flow can be controlled by the high-side switch S_{P2}. When the switch is closed, the energy stays in the block. If the switch is open, the degaussing current is led *via* the diode into the complete stack.

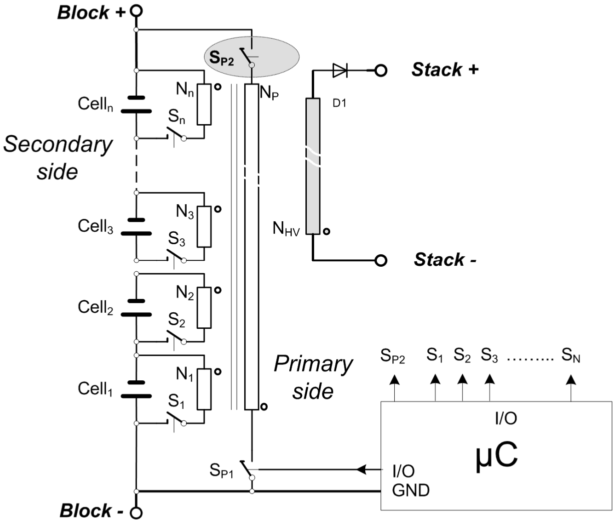

Figure 10. Balancing Between Blocks

IV. VOLTAGE SCANNING

For the charge state management of single cells, their individual voltages have to be measured. As only cell 1 is inside the ADC range of the microcontroller, the measurement of the remaining cells of the block can be difficult.

A possible solution would be an array of differential amplifiers, which have to withstand the voltage of the complete battery block.

The method described below allows the measurement off all voltages while requiring only a little additional hardware. The transformer, whose main task is the charge balancing, can be used as well as a multiplexer.

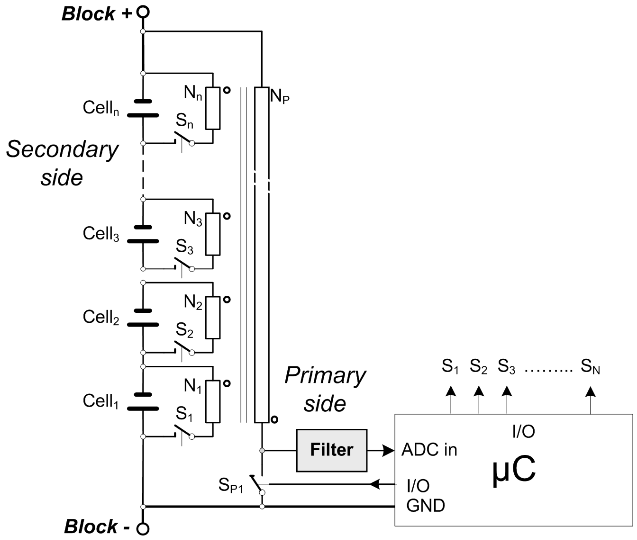

Figure 11. Voltage Scanning Principle

In the voltage-scanning mode, the energy storage capability of the flyback transformer is not of interest. When one of the switches S_1 to S_N is closed, the voltage of the connected battery cell is transformed to all windings in the transformer. The primary winding is used as receiver. Simply preprocessed by a discrete filter, the measurement signal is fed into an ADC input of the microcontroller.

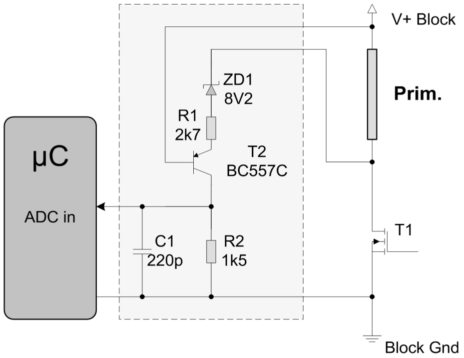

Figure 12. Voltage Scan Filter

The measurement pulses, during which one of the switches S_1 to S_N is closed, may be very short. A practical on-time is 4 µs, so the energy stored in the transformer is low. After opening the switch, the magnetically stored energy is fed back to the complete battery block *via* the primary transistor. In this way, the energy content of the battery block is not changed. After one scanning cycle over all cells, the system is in the original state.

As the degaussing current direction is from the Batt- connection point to Batt+, the integrated reverse diode of the primary MOSFET is automatically used. In order to minimize the remaining losses, the primary MOSFET can also be switched on. As the reverse diode is bypassed by the R_{DSON}, the voltage drop is reduced in this case.

V. CONCLUSION

Electric traction motor drives in automotive applications will see an enormous increase in their market share in the next few years. An essential part of the fuel-saving concept is the use of large battery or ultracapcitor stacks as energy storage buffers. Lithium-Ion batteries are the state-of-art technology for the near future. They offer high energy density with low weight, and an extremely high number of charge and discharge cycles.

However, their potentially high cycle life, calendar life, power capability and safe operation can be reached only if they are managed correctly [1].

Besides the exact monitoring of each individual cell's voltage, current, and multiple temperature measurement points, active charge balancing is fundamental.

Compared to a passive balancing procedure, the active method described in this paper has the following advantages:

- Lower power dissipation for dramatically reduced cooling effort and lower temperatures in the system.
- Better battery capacity usage based on balancing, also at the end of the discharge activity.
- Higher overall vehicle fuel efficiency through low power losses

Cell balancing methods, such as the one presented in this paper, will be a key factor in bringing energy storage systems to automotive standards at a cost effective level.

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