Active Charge Balancing for Li-ion Battery Stacks

Infineon's E-Cart electric vehicle is used to demonstrate the electrical features of a hybrid car. The necessity for battery management with charge balancing is a prerequisite and the simple conventional solution - dissipating power for charge equalisation - was replaced by an active energy shift between the cells. The resulting active system has much better performance at material costs comparable to a passive solution.

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The E-Cart (see Figure 1) is powered by a big Lithium-Ion (Li-Ion) battery stack. Nickel-Cadmium cells and their successors, Nickel-Metal Hydride cells, have been the dominating technology for many years. Recently, new Li-Ion batteries came onto the market. With significantly better performance, their market share has been rising rapidly. These cells have amazing energy-storage capacity. Nevertheless, this capacity is insufficient to support a hybrid motor using a single cell. The voltage and the current are both too low. To increase the current capability, cells may be connected in parallel. Higher voltages can be achieved by connecting cells in series.

Battery assemblers describe their arrangements usually using shorthand terms such as '3 P 50 S', which means 3 cells in parallel and 50 cells in series. A modular architecture is ideal for battery management with many cells in series. A serial connection of up to 12 cells is combined into one block in a 3 P 12 S array, for example. These cells are managed and balanced by an electronic circuit with a microcontroller in its heart. The output voltage of a block depends on the number of cells in series, and the cell voltage. The voltage of Li-ion cells is typically between 3.3 and 3.6V. This leads to block voltages between 30 and 45V. Hybrid drives need a DC supply voltage in the range of 450V. To compensate for variations in cell voltage depending on the charge state, a DC/DC converter is a suitable link between the battery stack and the motor drive. The converter is also able to limit the current. For optimal operation of the DC/DC converter, a stack voltage of 150 to 300V is required. Therefore, 5 to 8 blocks have to be connected in series.

Figure 1: **E-Cart prototype**

Necessity for balancing

Li-Ion cells are very susceptible to damage outside the allowed voltage range (Figure 2). If the upper and lower voltage limits (e.g. 2 and 3.6V for nanophosphate types) are exceeded, the cells may be damaged irreversibly. At a minimum, an extended self-discharge rate is the consequence. Over a wide state-of-charge (SOC) range, the output voltage is stable. The risk of leaving the safe area is low. However, at the beginning and at the end

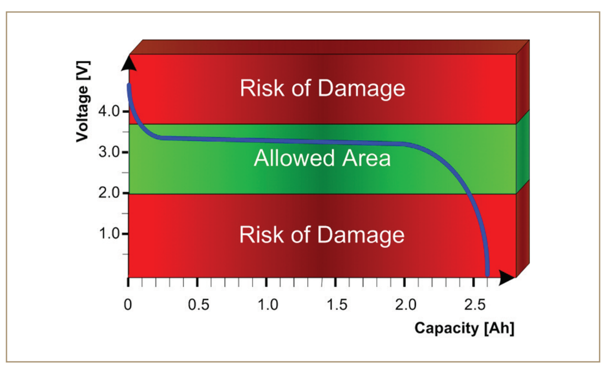

Figure 2: **Li-ion discharge characteristics (nanophosphate type)**

of the safe range, the curve steepens sharply. As a precaution, the voltage has to be monitored carefully.

If the voltage reaches a critical value, the discharge or the charge process has to be stopped immediately. With a strong balancing circuit, the voltage for the affected cells can be driven back into a safe area. To reach this target, energy must be moved among the cells whenever the voltage of any cell in the stack begins to differ from the others.

In the conventional passive method, each cell is connected to a load resistor via a switch. In such a passive circuit, individually selected cells can be discharged. This method is only suitable in the charge mode to suppress a voltage rise in the strongest cells. In order to limit the dissipated power, small currents in the range of 100mA are used, resulting in balancing times that may take several hours.

Various methods for active balancing can be found in the literature. A storage element to move energy is required. Using a capacitor requires a huge array of switching elements to link the storage capacitor to any cell. It is more efficient to store the energy in a magnetic field. The key component of the circuit is a transformer. A prototype was developed in co-operation with VOGT electronic. It is used for moving energy between the cells and multiplexing the single cell voltages to a ground-voltage-based Analog-to-Digital-Conversion (ADC) input.

The construction principle is the flyback converter. This type of transformer can store energy in a magnetic field. An air gap in the ferrite core increases the magnetic resistance to avoid the magnetic saturation of the core material. The primary side of the transformer is connected to the complete battery stack, and each cell is connected to a secondary winding (see Figure 3). A feasible model of the transformer supports up to 12 cells. The limiting factor is the number of possible connections. The prototype transformer described has 28 pins. The switches are realised with OptiMOS3 MOSFETs that have an extremely low on-resistance, so the conducting losses are negligible.

Each block is controlled by an 8bit microcontroller (XC886CLM) featuring a flash and 32kbyte data memory. Two hardware-based CAN interfaces support communication using the common automotive Controller Area Network (CAN) bus protocol with a low processor load. A hardware-based multiplication and division unit (MDU) speeds up the calculation process.

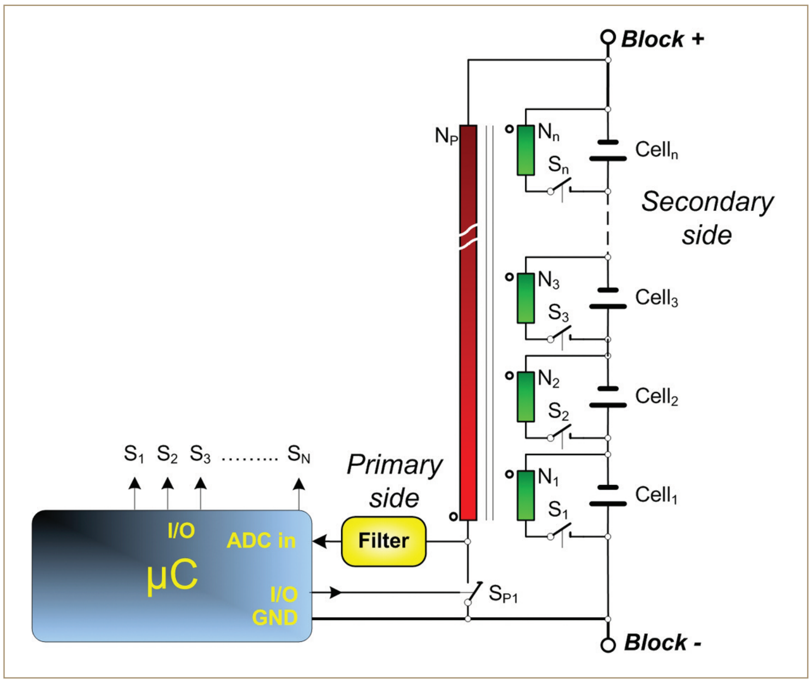

Figure 3: Principal circuit of a battery-management module

Balancing methods

The bi-directional use of the transformer allows the application 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

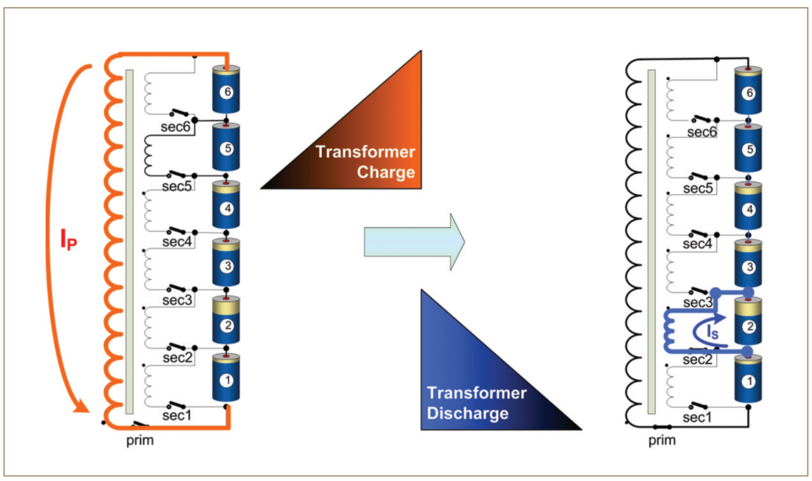

Figure 4: Bottom-balancing principle

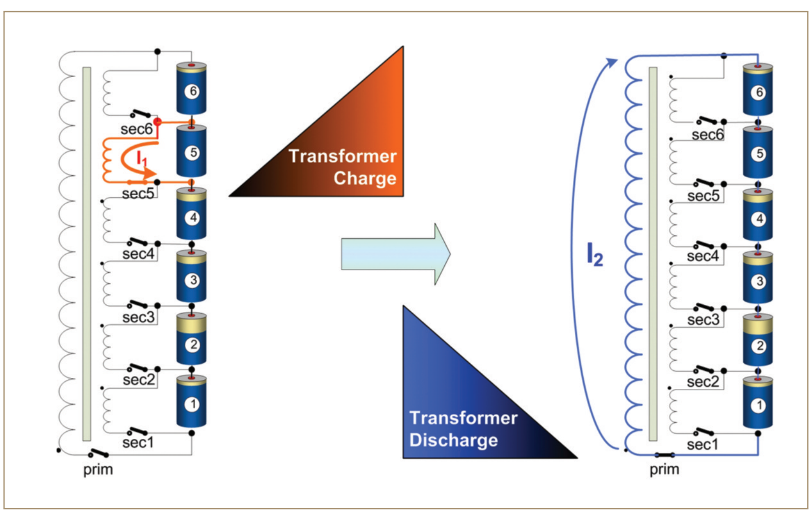

Figure 5: Top-balancing principle

higher, the top-balancing variant is applied.

The example in Figure 4 shows a situation in which the bottom-balancing method is required. Cell 2 is recognised as weakest cell which has to be supported. When the primary ('prim') switch is closed, the transformer is charged from the stack. After the primary switch is opened, the stored energy of the transformer can be shifted into a selected cell. This happens if the corresponding secondary ('sec') switch - in this example sec2 - is closed.

A cycle period consists of two active pulses and a pause. In this example, the period of 40µs equates to a frequency of 25kHz. The transformer should be designed for a frequency over 20kHz to avoid a whistling noise in the audible frequency range generated by the magnetostriction of the transformer's ferrite core. Especially where the lower end of the SOC of a cell has been reached, the bottom-balancing method helps to prolong the operational time of the stack. As long as the current drawn from the stack is less than the average balancing current, vehicle operation can be continued until the last cell is empty.

If one cell has a higher voltage than the others, it is useful to draw energy from the cell. In the charge mode, this is absolutely necessary. Without balancing, the charging process has to be stopped immediately when the first cell is full. Balancing will help to avoid this by keeping the cells at the same voltage.

The example in Figure 5 shows the energy flow in the top-balancing mode. After the voltage scan, cell 5 has been detected as the strongest member of the stack. When the switch sec5 is closed, a current flows from the battery into the transformer. Because of the inductance, the current 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 out of the cell is stored as a magnetic field. After sec5 is opened, the prim switch has to be closed. The transformer behaviour changes into a generator mode. The energy is fed into the complete stack via the large primary winding. The current and timing conditions are similar to the bottom-balancing example. Only the sequence and current directions are reversed.

With the prototype configuration used in the E-Cart, an average balancing current of 5A is reached. This is 50 times higher compared to the passive method. The power dissipation in the complete block caused by the balancing with 5A is only about 2W. This requires no special cooling effort and improves the energy balance of the system.

Voltage scanning

To manage the charge-state of the individual cells, their individual voltages have to be measured. As only cell 1 is inside the ADC range of the microcontroller, voltages in the remaining cells of the block cannot be measured directly. A possible solution would be an array of differential amplifiers, which would have to sustain the voltage of the complete battery block.

The method described below allows the measurement of all voltages with only a small amount of additional hardware. The transformer, whose main task is the charge balancing, can be used as well as a multiplexer. In the voltage-scanning mode, the flyback mode of the transformer is not used. When one of the switches S1 to SN is closed, the voltage of the connected battery cell is transformed to all windings in the transformer. Simply preprocessed by a discrete filter, the measurement signal is fed into an ADC input of the microcontroller.

The measurement pulses generated when one of the switches S1 to Sn is closed may be very short. A practical on-time is 4µs. Therefore, there is not much energy stored in the transformer. In any case, after the switch is opened, the magnetically stored energy is fed back to the complete battery block via the primary transistor. Consequently, the energy content of the battery block is not affected. After one scanning cycle over all cells, the system returns to the original state.

Conclusion

The benefits of the new Li-ion batteries for vehicle applications can be advantageous only with a capable battery-management system. An active charge-balancing system offers significantly better performance than the conventional passive approach. The ingenious use of a relative simple transformer helps to keep the material costs low.