Battery Cell Balancing: What to Balance and How

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ABSTRACT

Different algorithms of cell balancing are often discussed when multiple serial cells are used in a battery pack for particular device. The 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. The typical by-pass current ranges from a few milliamps to amperes.

A difference in cell voltages is a most typical manifestation of unbalance, which is attempted to be corrected either instantaneously or gradually through by-passing cells with higher voltage. However, the underlying reasons for voltage differences on the level of battery chemistry and discharge kinetics are not widely understood. Therefore goals and extent of bypassing charge can not be clearly defined and attempted balancing can often achieve more harm than good. In fact, many common cell balancing schemes based on voltage only result in a pack more unbalanced that without them. This presentation explains existing underlying causes of voltage unbalance, discusses trade-offs that are needed in designing balancing algorithms and gives examples of successful cell balancings.

I. INTRODUCTION

Different algorithms of cell balancing are often discussed when multiple serial cells are used in a battery pack for particular device. 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.

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II. TYPES OF BATTERY CELL UNBALANCE AFFECTING CHARGE/DISCHARGE VOLTAGE

A. *State of Charge (SOC) Unbalance*

State of charge unbalance is caused by cells being charged to different state of charge (SOC) levels. For example if we have 3 x 2200mAh cells (Q_{max}), and discharge one by 100mAh (Q1), second by 100mAh and third by 200mAh from a fully charged state, the first and second cells chemical state of charge will be $(Q_{max}-Q1)/Q_{max}$ = 95.4%, but third cell will be 91%. So we can say cell 3 is imbalanced by 4.4%. This in turn will result in a different open circuit voltage for cell 3 compared to cells 1 and 2, because the open circuit voltage (OCV) is in direct correlation with chemical state of charge. Note that while % SOC unbalance remains constant during entire discharge, voltage differences between the cells vary with state of charge because dV/dSOC varies with SOC. Fig 1 shows OCV differences between the cells at constant SOC unbalance but at different states of charge.

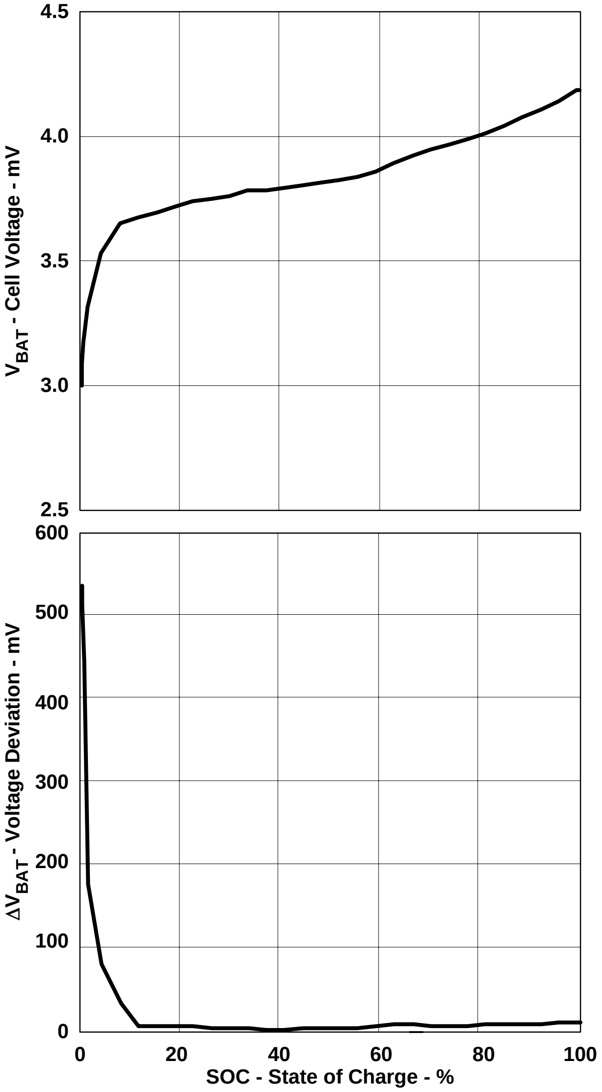

Fig. 1. (top) OCV dependence on SOC (bottom) OCV differences at different states of charge between two cells with SOC unbalance of 1%.

Voltage under load can be approximately modeled for DC case as:

$$V=OCV(SOC) + I \bullet R(SOC)$$

(considering that discharge current is negative). Because function R(SOC) is rapidly increasing its value at low SOC values, the voltage differences between the cells with fixed SOC unbalance increases in highly discharge states, as shown in Fig. 2. This gives the impression that there is increased need of balancing near end of discharge. However, if SOC unbalance is removed during other stages of discharge, increased voltage differences that it causes near end of discharge is eliminated without need of high by-pass currents.

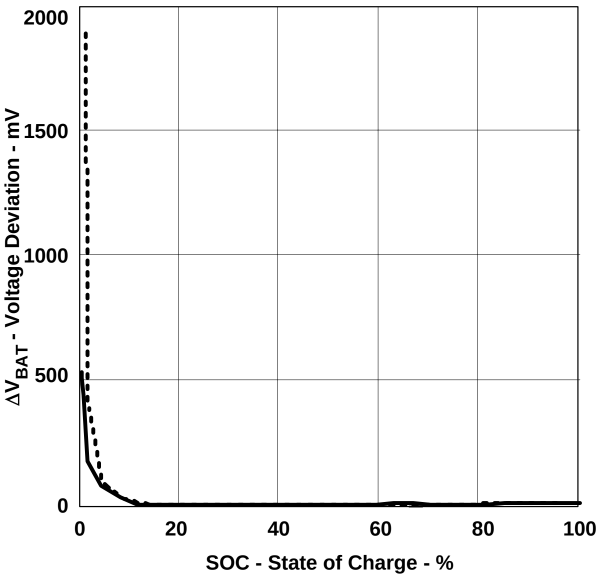

Fig. 2. Voltage differences under C/2 load at different states of charge between cells with 1% of SOC unbalance. Solid line shows differences for OCV case for comparison.

B. Total Capacity Differences

It can be that a cells total chemical capacity, Q_{MAX}, was different to start with. But even if all cells were discharged by an equal amount from a fully charged state, their chemical state of charge will be different. Indeed, if all 3 cells are discharged by 100 mAh, but cell 3 has different total capacity (eg: 2000 mAh instead of 2200 mAh), the resulting chemical states of charge will be 95.4 and 95%.

This in turn will also cause different OCVs. As can be seen, 200 mAh difference in Q_{MAX} causes only 0.4% difference in SOC. Because SOC correlates with voltage, this indicates that capacity imbalance causes less voltage difference than charge unbalance (cause 1).

C. Impedance differences

Internal impedance differences between the cells can be expected to be approximately 15% per production batch as can be seen in Fig. 3 (a).

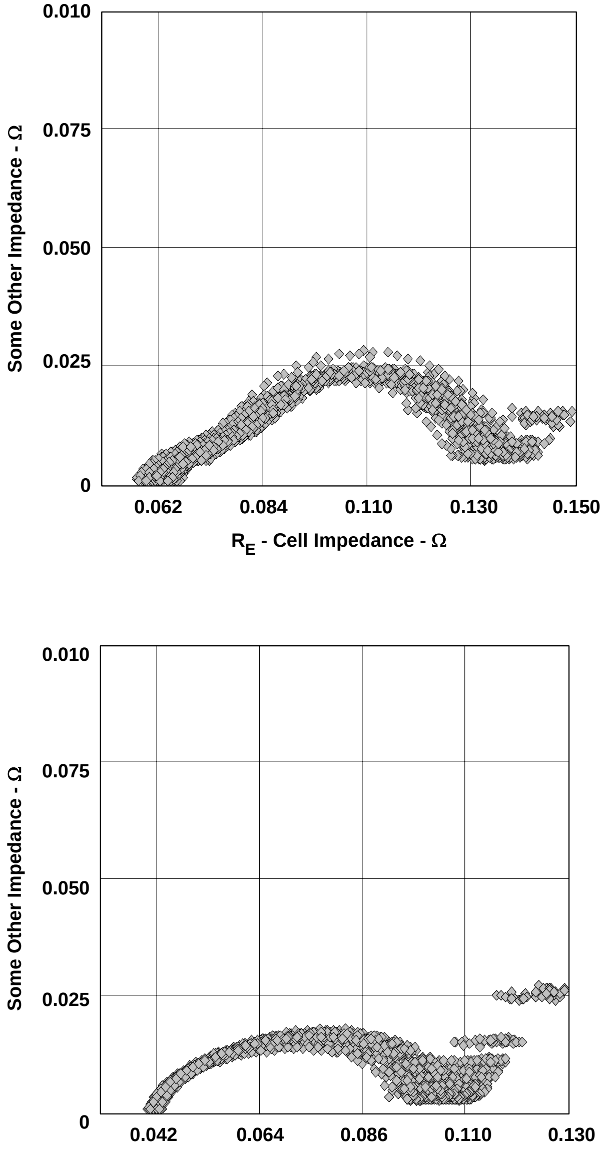

Fig.3 Impedance spectra differences between 50 cells in 1 batch for manufacturer (a) and manufacturer (b). Data is shown from 1kHz (left) to 10mHz (right)

Impedance unbalances do not cause differences in OCV. However they will cause differences in cell voltage during discharge. Indeed, cell voltage can be approximated as V = OCV + I • R. If current is negative (discharge), the voltage will be lower for a cell with higher R. If current is positive (charge), the voltage is higher for a cell with higher R.

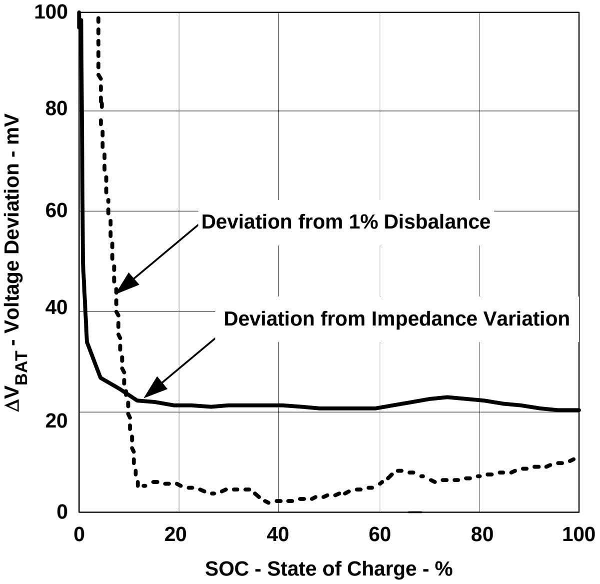

Fig. 4. Voltage differences between 2 cells with 15% impedance unbalance at C/2 discharge rates, solid line. Doted line shows difference between the cells with 1% SOC unbalance for comparison.

No balancing algorithm can help against the resistance imbalance. However, it can significantly distort attempts to balance what we can – namely the SOC. Note in Fig. 4 that for absolute majority of discharge(from 10 to 100% SOC) the distortion caused by impedance deviation is larger than that caused by SOC unbalance. If we try too look at the voltage under load and use it to decide that we need to pass more charge through a cell that has higher voltage, we will not know if this difference in voltage is really caused by differences in SOC or by impedance (note that difference can be in opposite direction of that caused be actual SOC unbalance if any). If it is caused by impedance unbalance, bypassing more current through this cell will result in the opposite effect – increase the SOC difference from other cells to larger value than it would be without balancing. As result, the open circuit voltage of this cell at the end of charge will be different from the other cells and can reach high levels, potentially causing the safety circuit to trip.

If a by-pass FET is turned ON based on voltage during charge, it can cause an actual increase of unbalance through bypassing the cell with higher impedance. At the end of charge the IR rise becomes insignificant because of current decrease, so that FET switches ON at the other cell. However, it happens too late so at the end of charge this procedure results in higher SOC and higher voltage for low impedance cells. Eventually it leads to increased cell degradation.

Problems can be reduced if cell balancing switches ON only near the end of charge when current is reduced and so I*R drop has smaller effect on battery voltages.

Unbalance is even higher when by-pass is ON during both charge and discharge because discharge does not have low-rate phase and wrong by-pass is never reversed resulting in higher accumulated unbalance per cycle.

III. HOW UNBALANCE HARMS PERFORMANCE

A. Premature Cells Degradation Through Exposure to Overvoltage

In both cases of SOC or total capacity unbalance, the cell with higher resulting SOC is exposed to higher voltages. For example, what happens if one cell has less capacity than the other three serially connected in the pack, if they all start in the same state of charge? CC/CV (constant current/constant voltage) charging will bring the pack to 4.2 x 4 = 16.8 V (typical). However, individual cell voltages will not be equal. As you can see in Fig. 5 below, the “low capacity” cell will have a much higher voltage than the remaining cells, while the normal capacity cells will have a lower voltage than achieved in normal charging.

As shown in Fig. 5, when the lower cell has a total capacity deficiency above 10%, its cell voltage begins to rise into dangerous area above 4.3 V which will result in additional degradation of this cell or even become a safety concern.

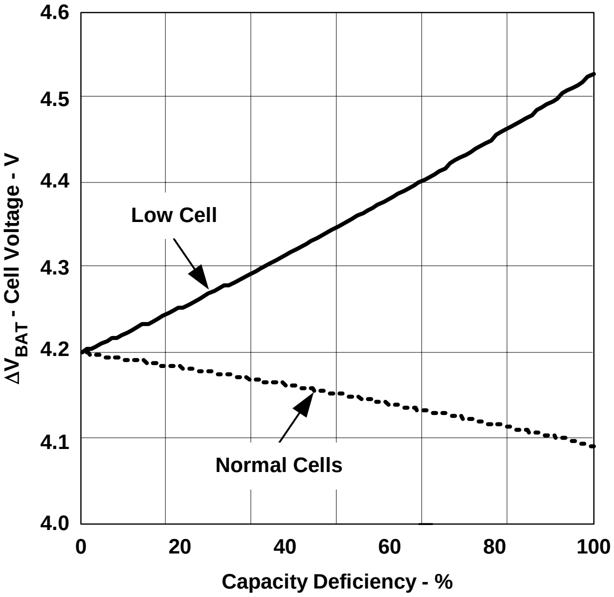

Fig. 5. Individual cell voltage vs. capacity deficiency from nominal.

To make the matters worse, the affects of cell degradation caused by imbalance is auto-accelerating, once a cell has a lower capacity, it is exposed to increasingly higher voltage during charge which makes it degrade faster so its capacity becomes even less, which closes the runaway circle.

Note that not all battery chemistries are equally affected by cell-unbalance. While Li-ion chemistry is specially vulnerable because of its ability to store almost 100% of all energy delivered, Lead-acid, NiMH and NiCd-s are relatively tolerant to overcharge because they can respond to increased voltage by internal shuttle reactions that are equivalent to a chemical short-circuit inside the cell. For example in NiMH battery oxygen and hydrogen generated after the end of charge recombine inside the cell building water. This causes extensive heating because all the energy of the charger is converted to heat rather than stored. Still, overcharge at high rates does cause increased pressure inside the cell and creates a chance for explosion or venting. Needs for cell balancing has to be evaluated in conjunction with rate capability, cooling and other properties of charging system.

B. *Safety Hazards from Overcharged Cells*

Li-ion batteries have very high electric energy concentrated in small volume. While possibility of their release through short-circuit can be prevented by appropriate mechanical protections, the co-existence of highly reactive chemicals in close proximity makes this battery inherently dangerous. Overcharging and overheating of the battery causes reaction of active components with electrolyte and with each other ultimately causing to explosion and fire. Thermal run-away can be caused merely by overcharging a single cell to voltages above 4.35V. Other cells of the pack will also join the explosive chain reaction if one cell is compromised. That is why cell balancing should prevent any cells from reaching the dangerous voltage territory, and safety protection circuit should terminate the charge if this still happens.

C. *Early Charge Termination Resulting in Reduced Capacity*

Safety issues will be prevented by additional safe-guards present in the bq20xxx devices such as cell overvoltage control. The bq20xxx series gas-gauging IC will terminate charging if one of cell voltages exceeds the programmable Cell Over Voltage Threshold (default 4.35V). However, termination of charging at this parameter means the pack will be severely undercharged. Therefore, despite prevention of a safety hazard useful life of the pack is severely reduced. This consideration makes cell balancing one of the most critical issues related to the cycle life of a battery pack. Successful balancing can significantly increase useful cycle life.

D. *Early Discharge Termination*

To prevent over discharge of cells and resulting damage, battery managements system will terminate discharge if any of the cells reached low voltage threshold. Cell based termination voltage is usually set to lower value than pack based threshold divided by number of serial cells, so that the difference can allow for a small unbalance. For Li-ion battery it varies from 2.7 to 2.2V depending on typical discharge rate.

Bypassing the low cell during end of discharge phase can increase battery useful discharge time, but to be effective it requires high-rate capable by-pass capability which is expensive to implement. Approach with more effective hardware utilization is to gradually remove any existing SOC unbalance during the entire charge/discharge and not only when it results in acute voltage differences (at the end of discharge).

IV. HARDWARE IMPLEMENTATION OF BALANCING

A. *Current Bypass*

Simple implementation of cell-balancing includes a FET placed in parallel with each cell and controlled by a comparator for simple voltage based algorithms that turn-on the bypass FETs during the onset of voltage differences, or by microcontroller for more complex and effective algorithms that can work continuously regardless of variations of voltage differences. General setup is shown in Fig. 6.

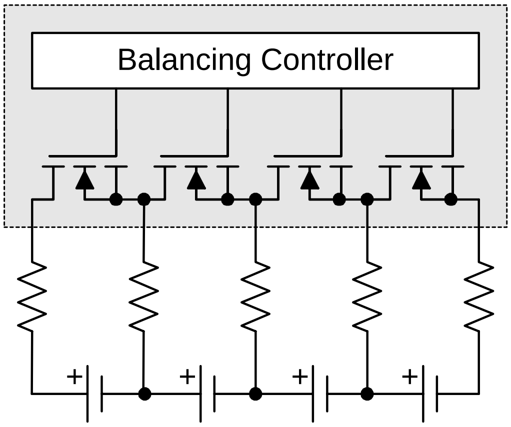

Fig. 6. Cell balancing set-up using by-pass FETs.

Main choice here is to use FETs that are integrated in the balancing controller IC and typically have by-pass currents from 9 to 2mA (depending on the choice of the external resistors), or to use external FETs with by-pass capability that can be freely tailored to particular application needs.

In Li-ion batteries which have very low self-discharge and therefore accumulative unbalance per cycle is usually less than 0.1%, bypass current of internal FETs is sufficient to keep the pack continuously balanced. In other chemistries where self-discharge is much higher and therefore differences in self-discharge rates between the cells results in higher SOC differences per cycle, higher rates might be needed.

B. Charge Redistribution

The disadvantage of current by-pass approach is that the energy of the by-passed charge is wasted. While this can be acceptable during charge while system is connected to power grid, during actual usage of the battery in portable applications every milliWatthour is precious. This asks for a possibility to have a cell-balancing approach that would allow to drain the “high” cells to the bottom using most efficient way.

The ultimate approach for this is to use a pack that has no serially connected cells at all. The step-up converter would then assure that device will obtain sufficient voltage. This way energy waste from cell-balancing is completely eliminated. The trade-off however is lower efficiency of the power supply, as well as its increased size and complexity.

Other solutions can include circuits that allow to transfer energy from high cells to low cells rather than burning it in a by-pass resistor.

Charge Shuttles

Simple approach to redistribute the energy between the cells is to connect a capacitor first to higher voltage cell, than to lower voltage cell, as shown in Fig. 7 (a).

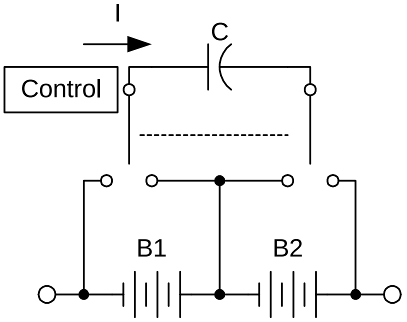

Fig. 7a. (a) simple capacitor-based shuttle cell balancing circuit.

More complicated implementations allow the connection of not only two nearby cells, but also cells for far away in the stack for faster equilibration (Fig. 7 (b)).

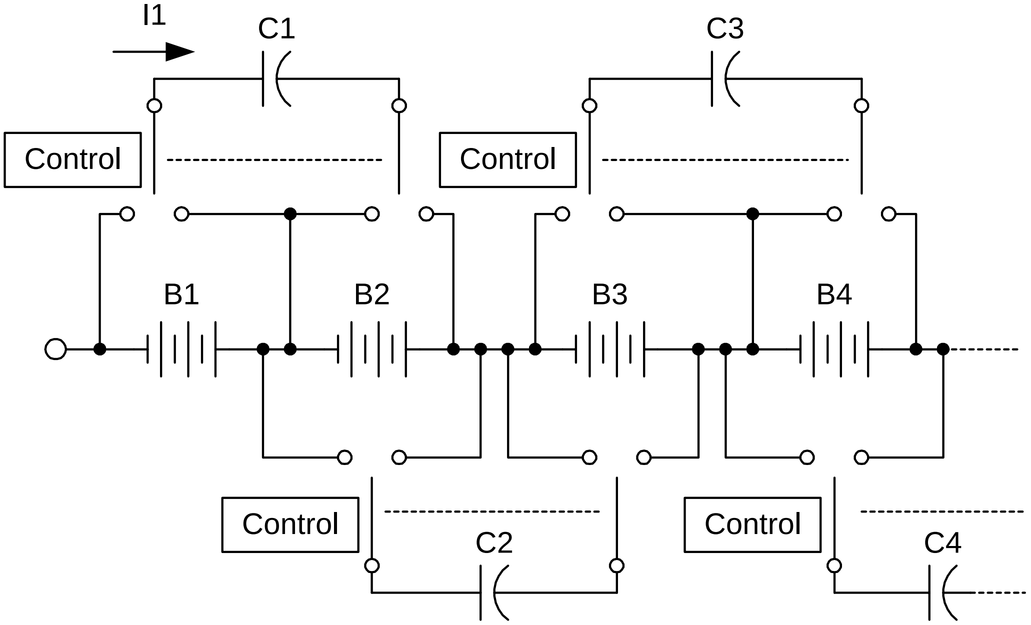

Fig. 7 (b) shuttle circuit with remote cells connection capability. Reprinted from S. W. Moore and P. J. Schneider, Delfi application note 2001-01-0959

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 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.

Inductive Converters

A cell-balancing method that is free from the disadvantage of small voltage differences between cells decreasing the balancing rate is implemented by transferring pack energy into single cell by directing pack current through a transformer which is switched to one of the cells that needs additional charge.

However, efficiency of such converter is limited, and the need to use a transformer results in increased price and size of the overall solution. So far no commercial implementations of such system in portable devices have been successful. Probably area where it could be more practical are high-power systems such as EV and hybrid vehicles.

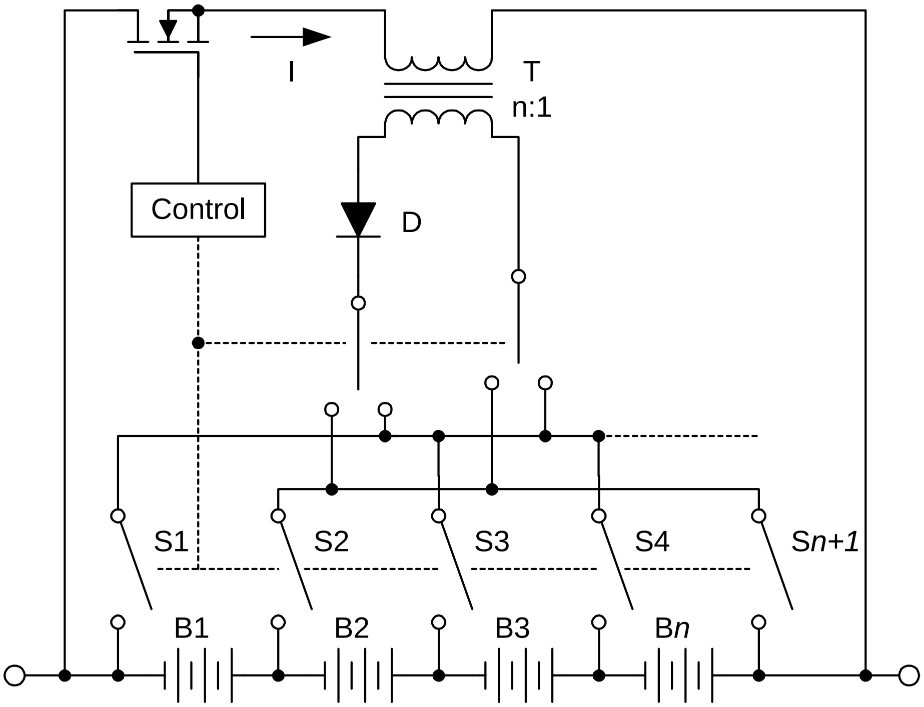

Fig. 8 Inductive converter cell balancing circuit. Reprinted from S. W. Moore and P. J. Schneider, Delfi application note 2001-01-0959.

V. BALANCING ALGORITHMS

Regardless of particular hardware implementation, there is always a decision to be made, when to turn ON bypass switch or when to engage the energy exchange circuit to particular cell. Different algorithms of making this decision are reviewed below. For simplicity we will refer to the case of current bypass because transfer of the logic to other balancing schemes is trivial.

C. Cell voltage based

Simplest algorithm is based on voltage difference between the cells. If difference exceeds predefined threshold, bypass is engaged. To resolve several problems of this simple method, more complicated modifications can be implemented if microcontroller is used to execute the algorithm:

- **Balancing during charge only** is used to save energy in portable applications.
- **Balancing at high states of charge only** is used to decrease the effect on SOC balancing that can come from impedance unbalance.
- **Simultaneous multi-cell balancing** makes decision on which cells have to by bypassed under considerations of the entire pack and not only neighboring cells as it is the case with comparator-based solutions

One of the advanced implementation of voltage-based algorithms using all above optimizations is used in bq2084 battery fuel-gauge. Fig. 9 is showing voltage convergence of multiple cells during balancing.