How True Balancing Maximizes Energy Into the Battery:

Monitor Dynamic Impedance

When you drive into a gas station, do you only fill your tank to 80% or 90% full?

Of course not! You pump gas into the tank until it's full.

You should be able to do the same thing with the battery in your EV.

Why do existing balancing systems prevent you from fully charging your car's battery?

Three Fundamental Steps for Maximizing Charge Cycles

To maximize the amount of energy that is stored in the battery the BMS must:

1. Put energy into the battery until each cell reaches full charge voltage (FCV)
2. Continue charging until each cell is at 100% SOC (which is not the same as FCV)
3. Know when to stop charging so that you don't overcharge and damage the cells

No existing commercially viable balancing system can perform all of these steps on every cell in an EV battery.

True Balancing can.

The following pages explain how True Balancing does this.

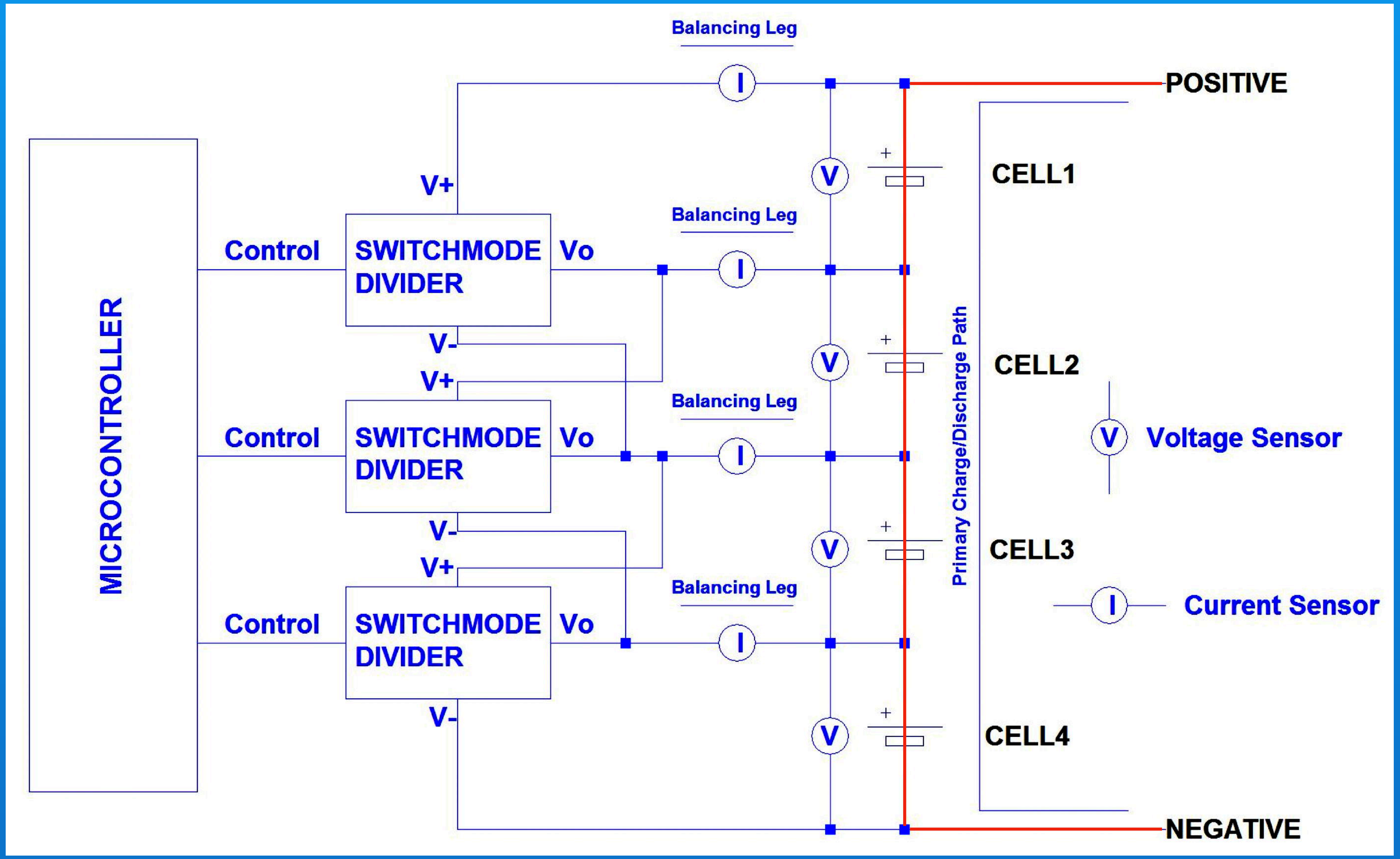
First Task: Put Energy Into Each Cell in the Battery

Start of the Charge Cycle

At the start of a charge cycle, all of the cells are usually below FCV. When this is the case, the balancing circuit isn't operating and all charging is along the primary charge path, shown here in red.

Typically, constant current charging is applied during this phase of operation.

This is not unique to True Balancing. Virtually all charging circuits use constant current charging along the primary charge path when all cells are below FCV.



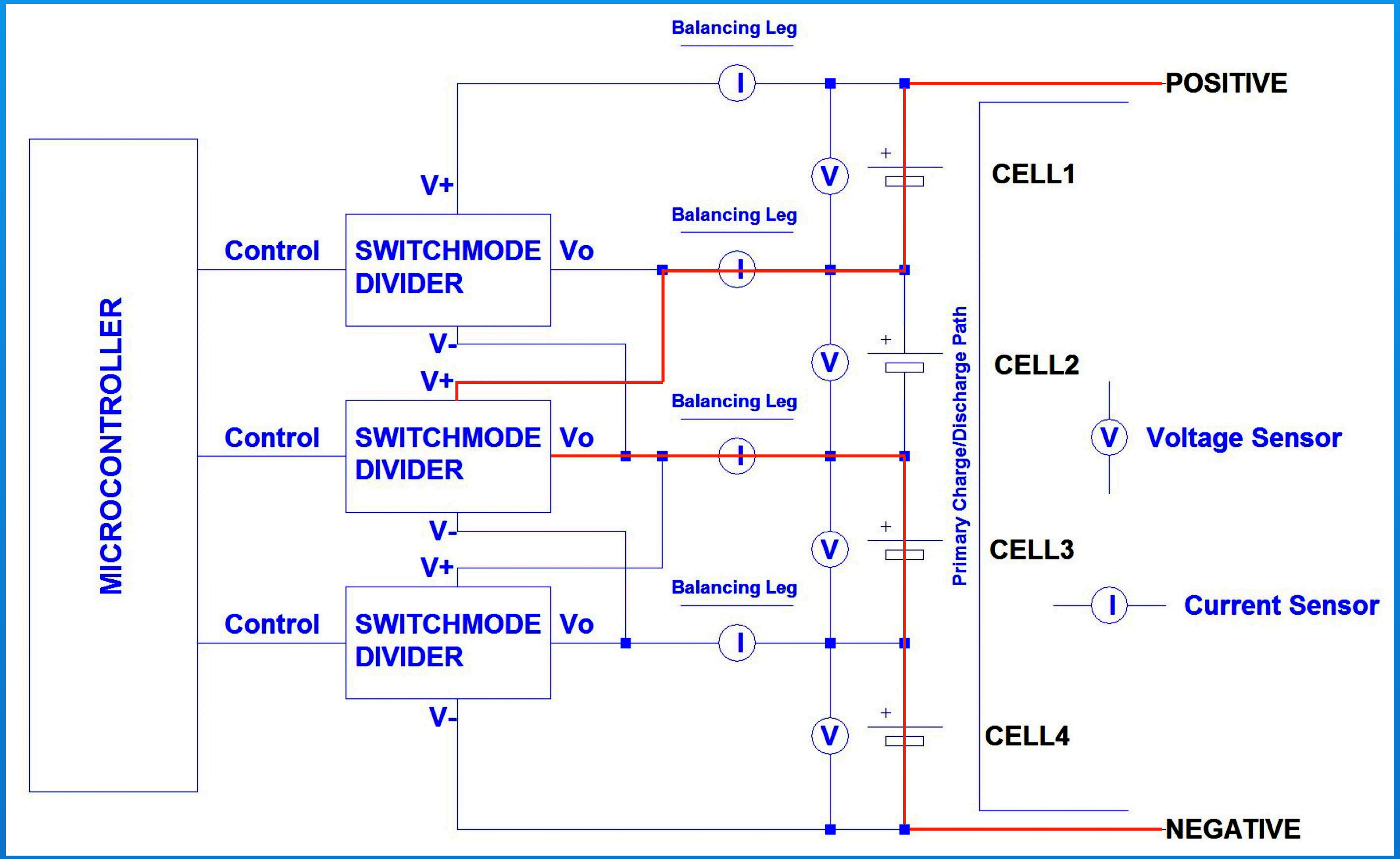
Second Task: Bring Every Cell to FCV

The Cells Start Reaching Full Charge Voltage

When the first cell in the battery reaches FCV, True Balancing starts operating. The charging profile starts a transition from constant current to constant voltage.

Charging energy is diverted around cells that are at FCV (red line) and is applied to all cells that are still below FCV. In this example, charging energy is being diverted around cell 2.

As each cell reaches FCV, True Balancing modulates the switch mode dividers to float these cells at FCV. This allows the other cells to continue charging until all cells reach FCV.



Third Task: Know When to Stop Charging Each Cell

When to Stop Charging? Monitor Dynamic Impedance of the Cells

The ability bring every cell to FCV on every charge cycle (previous page) is enough to make True Balancing an improvement over existing balancing systems. The ability to continue charging each cell until it reaches true 100% SOC and knowing when to stop is what really sets True Balancing apart.

The goal is to bring every cell to 100% SOC (which is different from FCV) without overcharging the cells (which risks damaging the cells and shortening the life of the battery).

It takes a few slides to explain how True Balancing knows when to stop charging and how it differs from other balancing technologies. It starts with the shape of the impedance curve of a typical lithium-ion cell.

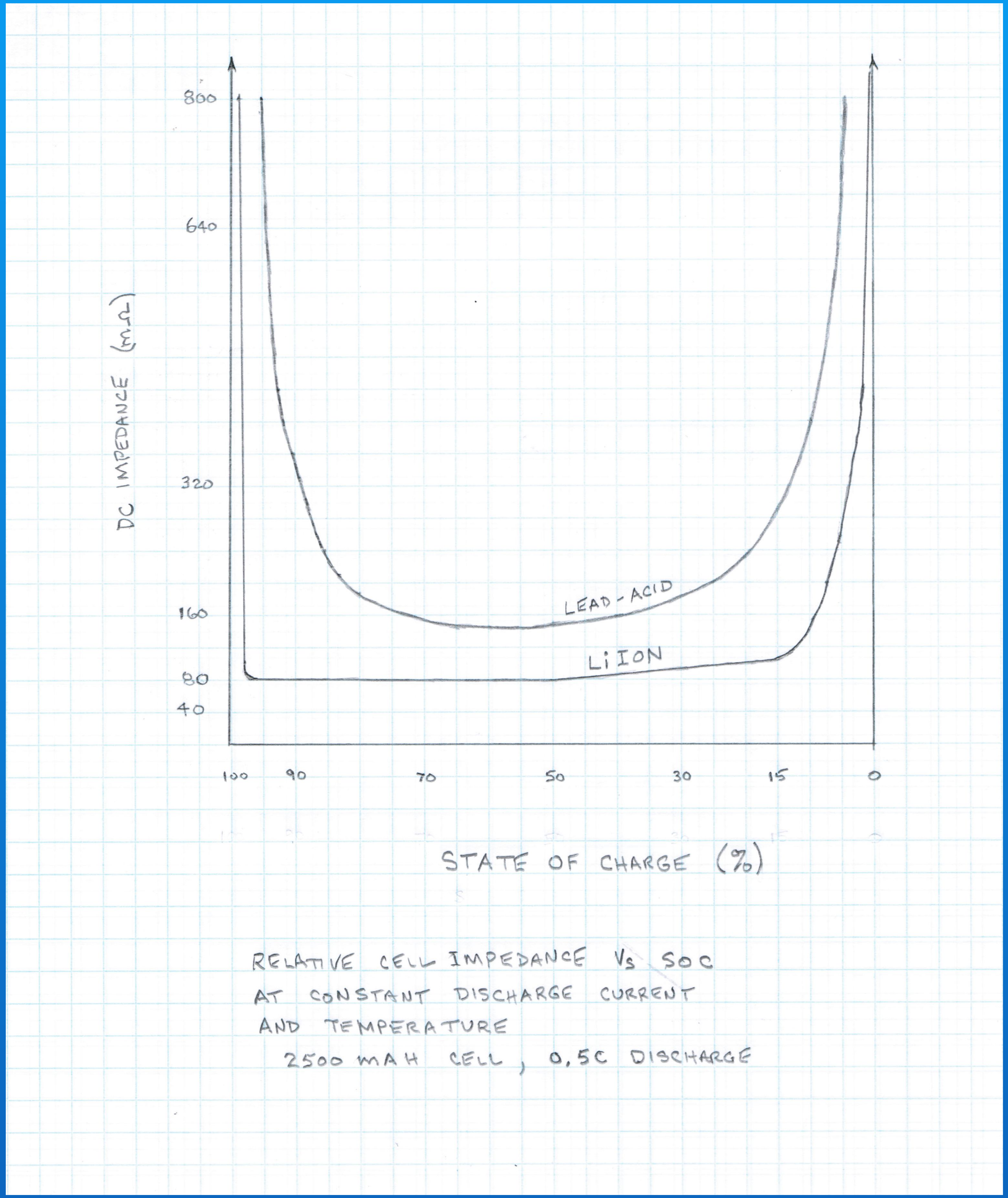
This graph compares the impedance curves of a lithium-ion cell[1] and a lead-acid battery. This is empirical data that we measured and recorded while developing True Balancing.

A key point to observe in this graph is that the impedance curve of the lithium cell is much lower than the lead-acid battery, and the impedance of the lithium cell remains low for a very wide range of SOC. This characteristic is what makes lithium-ion batteries (LIBs) such excellent energy storage systems.

It is also what makes them so hard to keep in balance.

The key to knowing when to stop charging is True Balancing's ability to monitor the dynamic impedance of the cells. Read on!

(1) The lithium-ion cell is a 2500mAh NMC 18650 cylindrical cell.



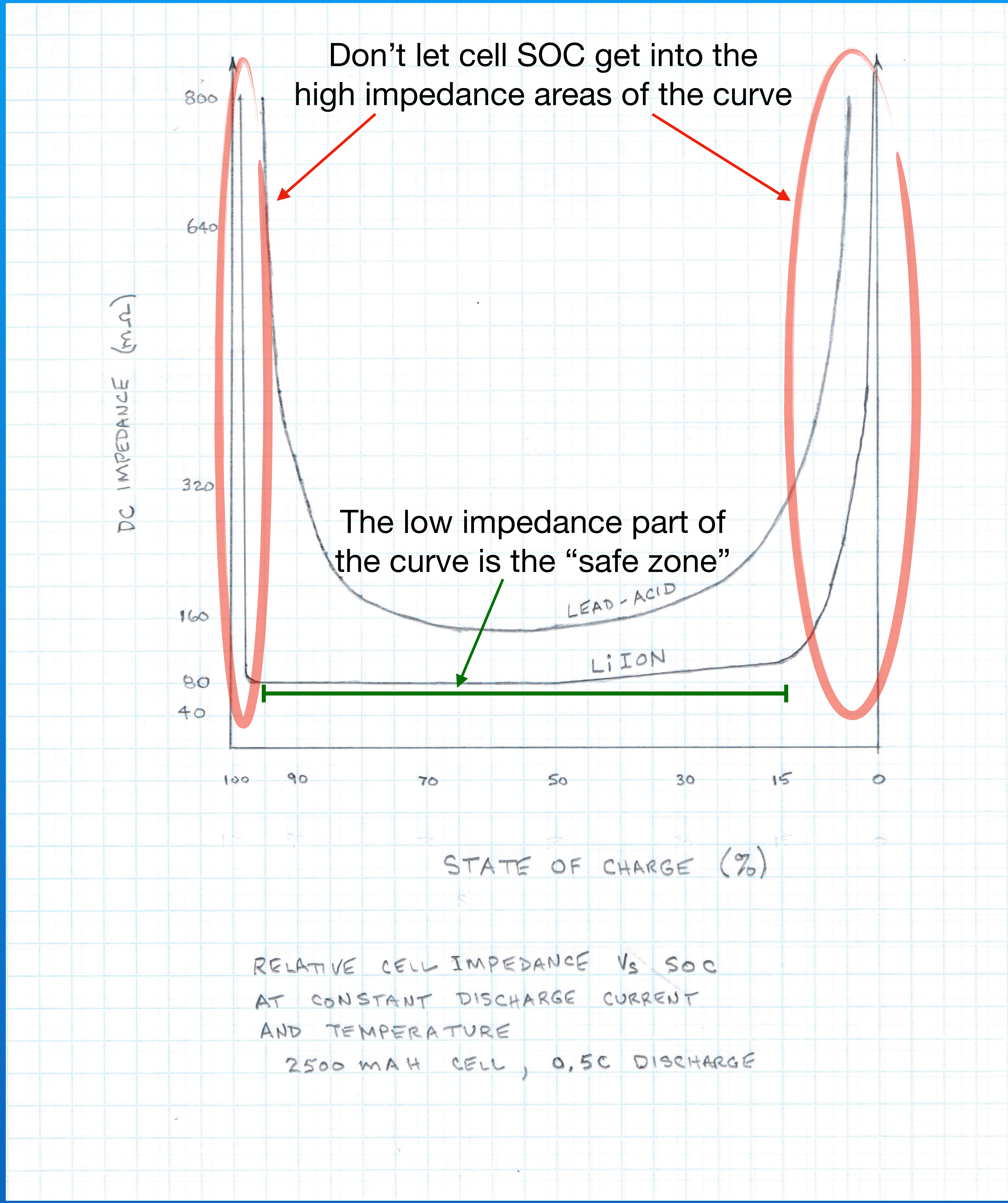
Stay Out of the High Impedance Zones!

Avoid the High Impedance Areas of the Curve

If you always keep every cell in the low impedance area of the curve you will keep cell degradation to a minimum, which maximizes battery life.

It is critical to stay out of the high impedance areas of the curve. Repeated charge or discharge cycles that extend into the high impedance zones will stress the cells, shorten the life of the battery and could cause severe failures such as battery fires.

Before explaining how True Balancing avoids the high impedance areas of the curve, we will look at how existing balancing systems address this situation.



How Existing Balancing Systems Work

How Do Existing Balancing Systems Avoid the High Impedance Areas?

Existing balancing systems have no way of knowing impedances of individual cells. Honestly speaking, they don't even know the SOCs of the cells. The only hard data they have is cell voltage, which they use as a proxy for SOC.

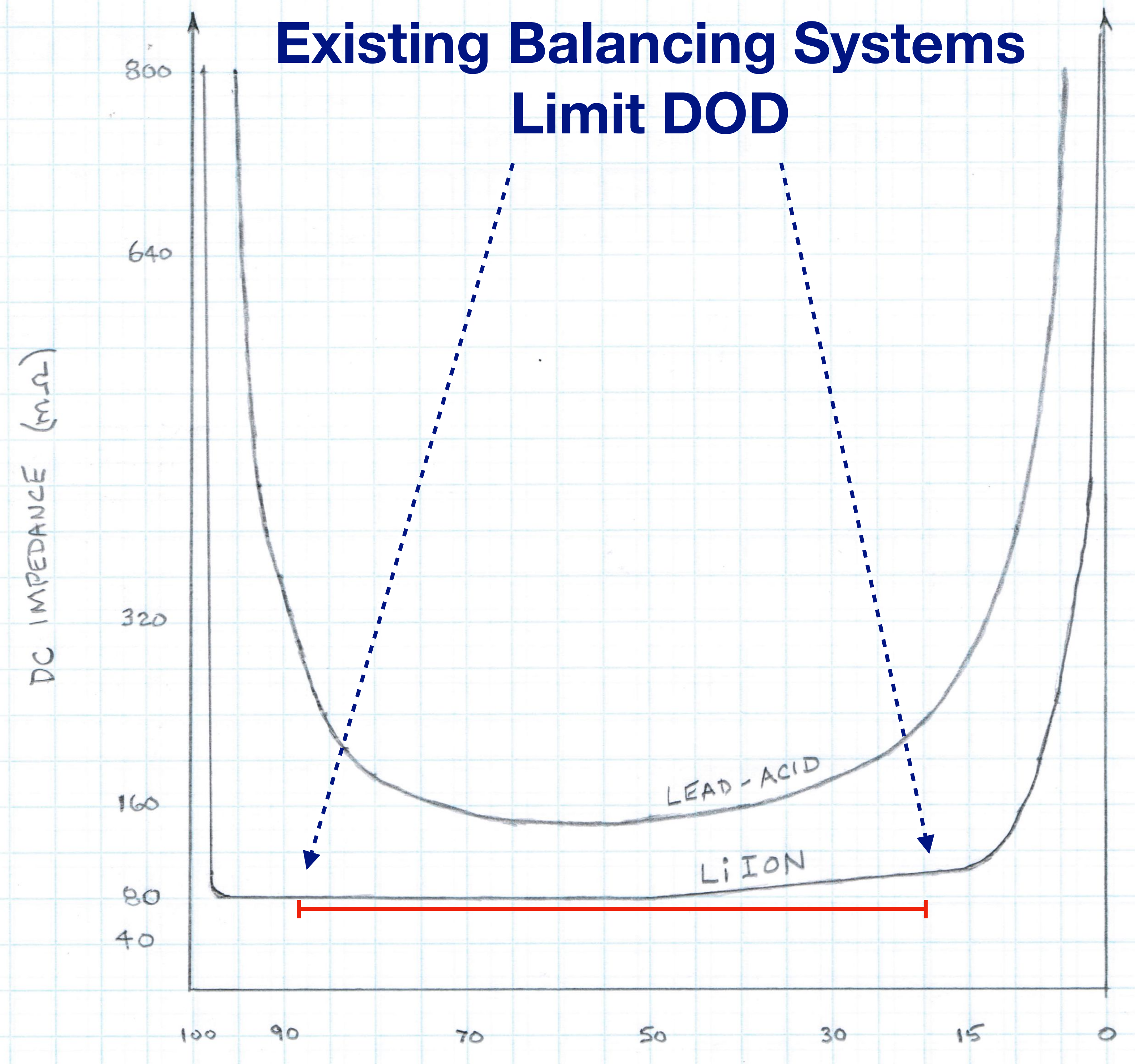
If the battery has good quality cells and if the cells are tightly matched, there will be a close correlation between cell voltage and SOC when the battery is new. However as the battery ages, the error term associated with this correlation grows, and it grows in an unpredictable manner. The unpredictability of this error term forces existing balancing systems to limit the DOD profile to be sure they never push the cells into the high impedance areas of the curve.[1]

A typical DOD profile is 90%–10%. Ostensibly, this means that the BMS limits the range of SOC to 90% at the top and 10% at the bottom.

In reality this means that the battery engineers specified parameters for a high voltage cutoff and a low voltage cutoff. A safety margin is used when setting the cutoff voltages to be sure there is a buffer zone between the cutoff voltage and the high impedance areas of the curve. The safety margin needs to consider the potential magnitude of the error term associated with the correlation of cell voltage to SOC. So what is called "90% SOC" in the DOD profile could be (and usually is) less than true 90% SOC.

Bottom line: Because of inherent technological limitations, existing balancing systems must cut off charging well before the battery reaches true 100% SOC.

[1] Actually, there are a few reasons why existing balancing systems limit the DOD profile. Avoiding the high impedance areas of the curve is one of them.



Existing balancing systems set cutoff voltages at the high and low ends of battery operation. The cutoff voltages are specified to have a margin of safety to assure that SOC of any cell never goes into the high impedance zones.

This underutilizes the battery at the high end (the battery never reaches full state of charge) and at the low end (there is energy stored in the battery that can never be used to power the load).

A typical DOD profile is 90%-10%, but those numbers are approximations. DOD is limited by voltage (not SOC), and the upper and lower voltages are specified with conservative safety margins.

How True Balancing Charges the Battery

How Does True Balancing Avoid the High Impedance Areas?

True Balancing monitors voltage and current sensors that are connected to each cell in the series stack.[1] This allows calculation of impedance of each cell in the stack. Knowing impedance on a cell-by-cell basis allows True Balancing to unlock the full capacity of the battery.

As the battery is charging, True Balancing monitors the voltage of each cell. When a cell reaches FCV, True Balancing locks in the cell voltage, preventing it from rising any higher (to prevent damage to the cell). Then True Balancing continues charging the cell using a constant voltage profile while monitoring voltage and current and calculating impedance. The True Balancing algorithm monitors dynamic impedance (the first derivative of impedance – dV/dI).[2]

When the algorithm detects a rise in dV/dI, that cell has reached true 100% SOC and True Balancing stops charging that cell. The cell is fully charged, but has not risen above FCV, so it does not experience high voltage conditions that accelerate cell degradation. With True Balancing termination of charging is not triggered by cell voltage, but by change in dynamic impedance of each cell. This is a significant breakthrough in battery management.

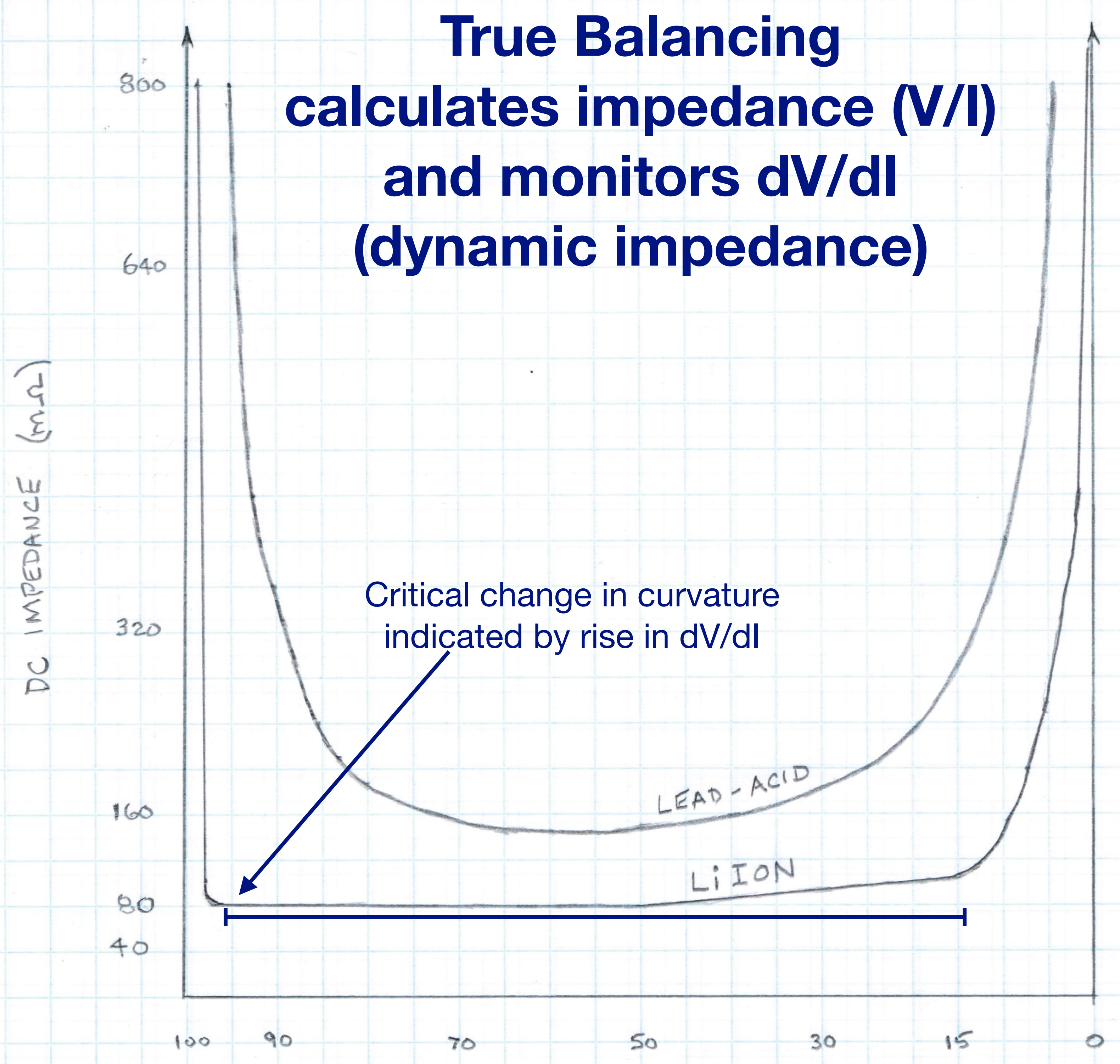
True Balancing performs this algorithm on each cell in the battery until every cell has reached true 100% SOC.

<u>It's impossible for existing balancing systems to do this.</u>

Because of their inherent limitations, existing balancing systems must cut off charging early – typically at 90% SOC or less. They cannot utilize the full capacity of the battery.

[1] Some battery architectures have strings of cells connected in parallel, and then connect the parallel strings in series. True Balancing treats a parallel string of cells as one big cell.

[2] The first derivative is a sensitive indicator of change in curvature of any nonlinear function.



Every True Balancing charge cycle is functionally equivalent to bringing each cell up to 100% SOC using a CCCV charge profile.

Prior to any cell reaching FCV, True Balancing uses constant current charging on the primary charge path.

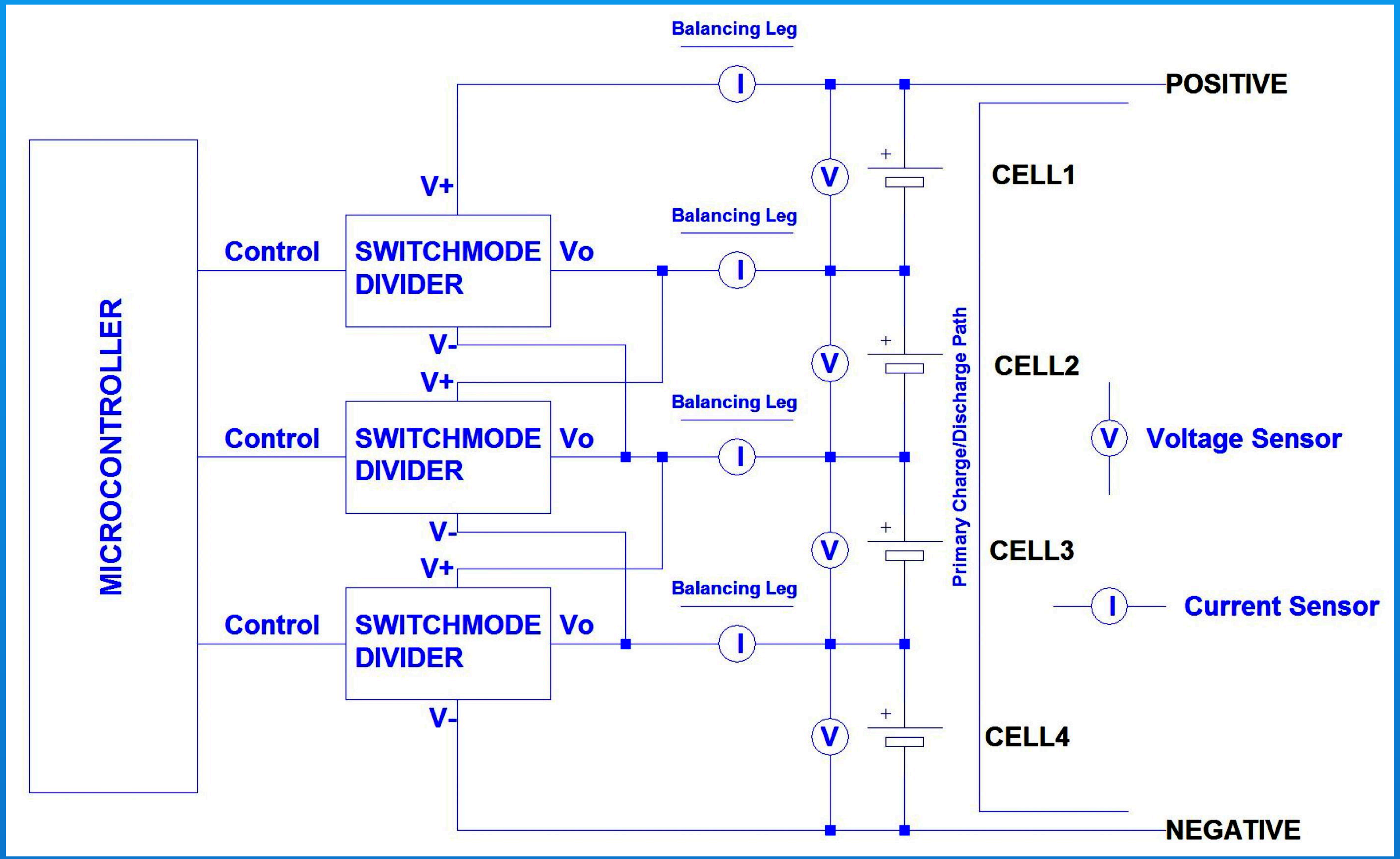
As soon as one cell reaches FCV, the balancing circuit becomes active and starts to transition to a constant voltage profile.

After reaching FCV, each cell is charged using a constant voltage profile until there is a rise in dV/dI, indicating the cell has reached true 100% SOC.

True Balancing repeats this pattern until every cell in the battery is at true 100% SOC.

Summary

- The unique design of True Balancing enables you to bring every cell of your battery up to true 100% SOC on every charge cycle…
  - Regardless of cell chemistry
  - Regardless of age and condition of individual cells
- There is no need to limit the DOD profile
- Cell voltage doesn't rise above FCV, so there is no damage due to over-voltage
- Balancing currents can be as high as you want, so charging and balancing can be completed very quickly



The gold standard for charging any battery is to individually connect each cell to an isolated power supply and then charge each cell using a CCCV profile that is optimized for that particular cell.

True Balancing is the only charge management system we know of that achieves the equivalent of a CCCV charge cycle on every cell in a battery. And True Balancing does this at high speed and low cost.