What Causes Runaway Cell Voltage?

And what to do about it

Note: This paper is discussing LiFePO4 batteries used in typical DIY solar systems. These batteries almost always use BMSs with top-acting balance circuits. Furthermore, these systems typically have relatively low Discharge and Charge rates as compared to the size of the batteries. Systems with other characteristics or from other industries are beyond the scope of this paper.

Quite often, a cell will hit a High (or low) voltage unexpectedly and/or faster than the other cells. (On the DIY Solar Forum, this is usually called a ‘Runaway Cell’.) The runaway cell can eventually cause the BMS to unexpectedly shut down ether charge, discharge or both. This type of event can be broken down into two categories:

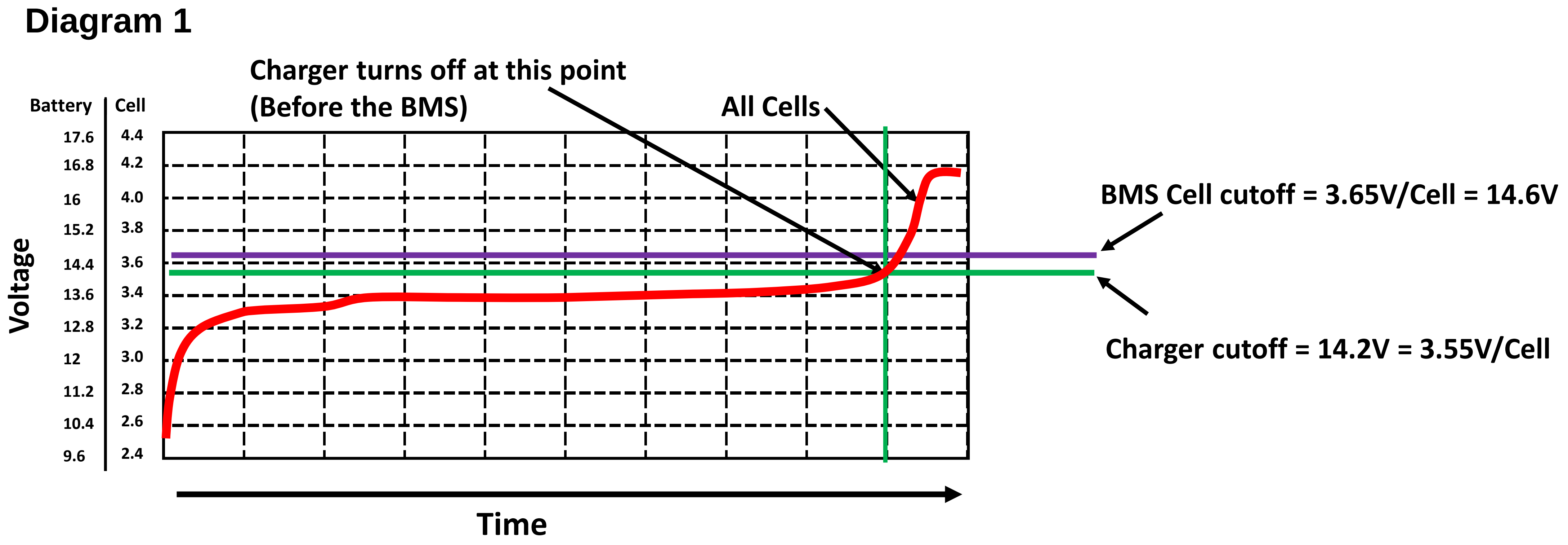
1) A cell races ahead in voltage during charging causing the BMS to turn off <u>charging</u> prematurely.
2) A cell rises (or drops) in voltage when under load causing the BMS to shut down unexpectedly.

This paper has a separate section for each of the two categories. Each section describes what is happening and briefly discusses what to do about it.

Part 1: Runaway Cell Voltage During Charging

1.1) The Ideal Case

If all the cells in a battery are identical in capacity and SOC, the charge curve for a 12V battery might look something like Diagram 1.

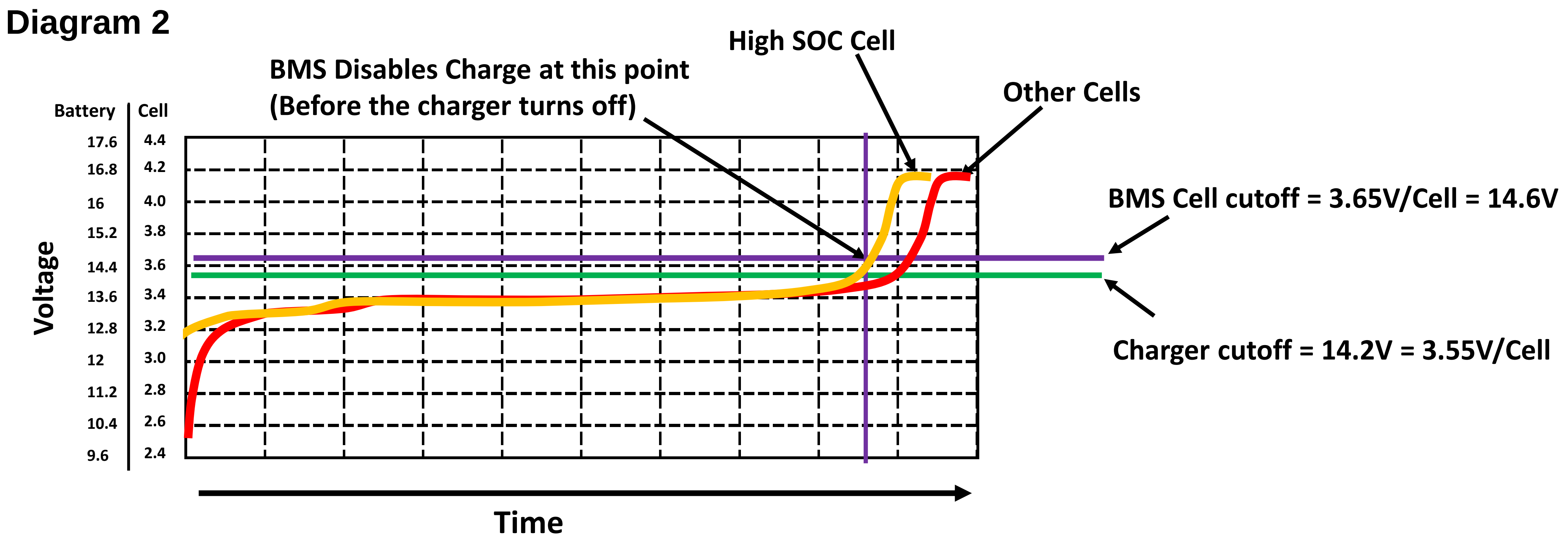


Notice that the charger shuts off at 3.55V/cell so the BMS never shuts off due to high voltage disconnect.

Note/Warning: The charts in this paper show cell voltages from 2.6V to 4.2V. **The system should never be operated to these extremes.** There is some debate as to what voltage levels are acceptable, but I like to keep the BMS between 2.8V and 3.65V, and the Loads/Chargers between 3.0V and 3.45V. Other people like more conservative settings.

1.2) Cell with higher State of charge

Now let's assume one of the cells has a slightly higher state of charge but all the other cells are the same SOC and Capacity. In this situation, the charge curve for a 12V battery might look like Diagram 2.



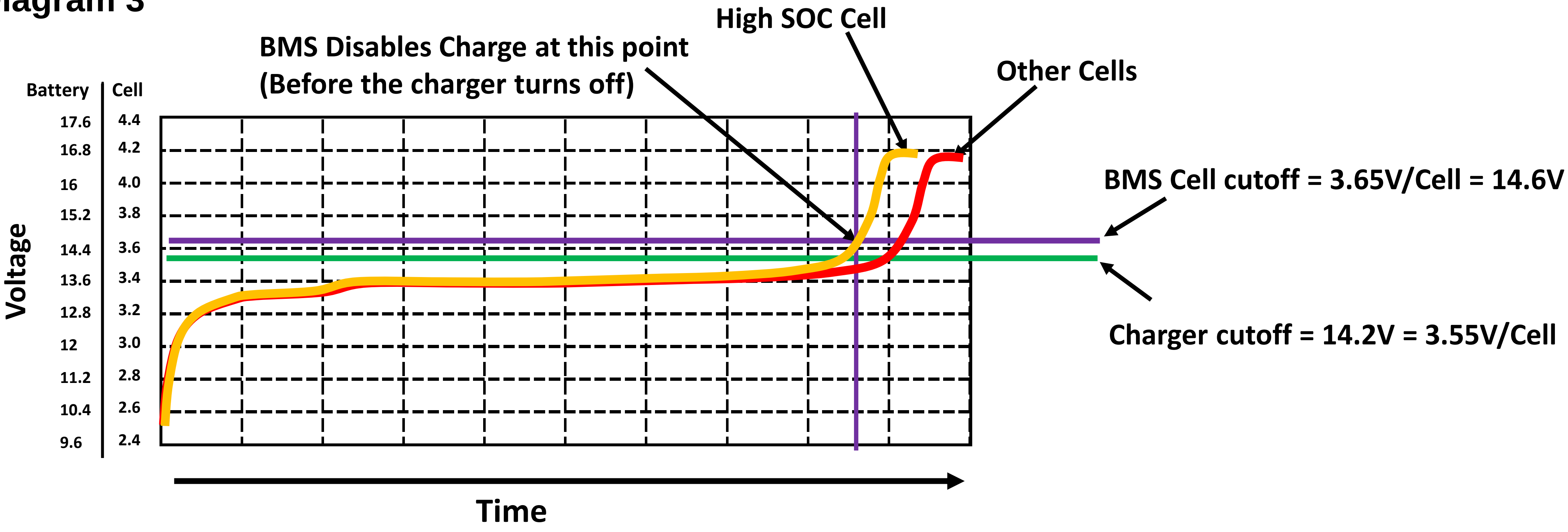
Notice that in this scenario the high-SOC cell reaches the knee of the curve sooner than the other cells and the voltage starts rising rapidly. This causes the BMS to hit a cell overvoltage and shuts off before the charger shuts off. Also notice that at the other end of the curve the other cells will hit the knee and the voltage will drop off before the high SOC cell.

1.3) Cell with a lower capacity (Weak cell)

Next, let's assume one of the cells has a slightly lower capacity than the other cells. The charge curve might look like Diagram 3.

BMS Disables Charge at this point

Diagram 3



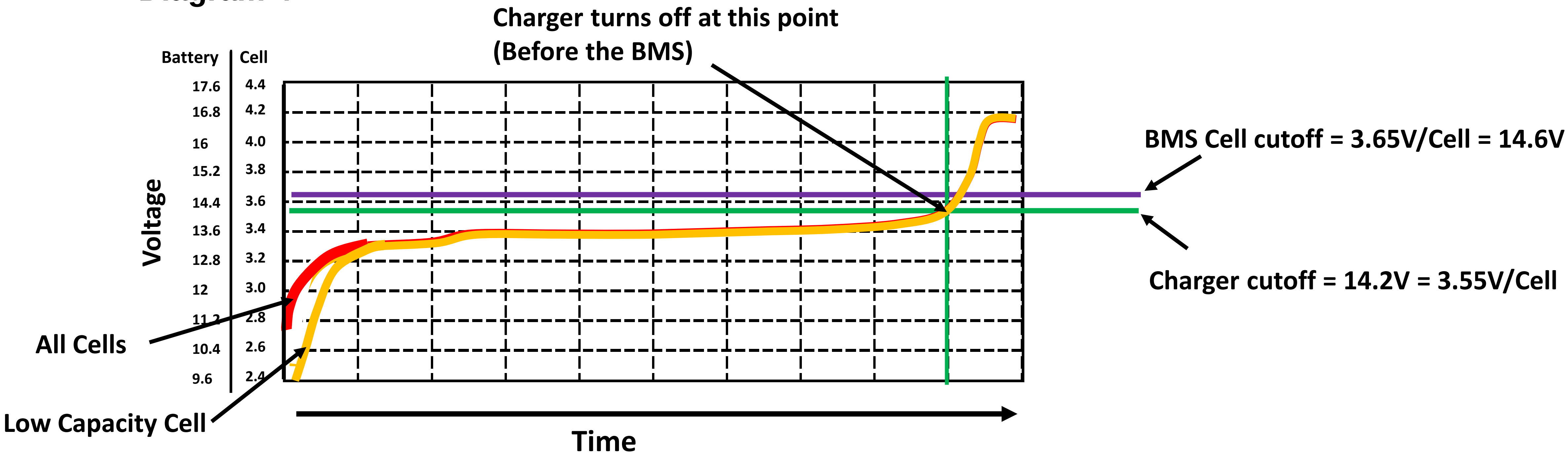
Notice that the low capacity cell tracks the other cells at the low end, but since it gets fully charged sooner, it hits the knee of the curve, rises in voltage and causes the BMS to shut off before the charger. Notice that the rest of the cells are never able to reach the full state of charge.

1.4) Top Balancing (The solution)

If all the cells are identical, top balancing gets them all to the same state of charge so the battery charge curve would look like Diagram 1 above.

For a battery with a weak (low capacity) cell, top balancing sets it up so all the cells get to full charge at the same time. The charge curve for a 12V battery with a weak cell might look like diagram 4 after a top balance.

Diagram 4

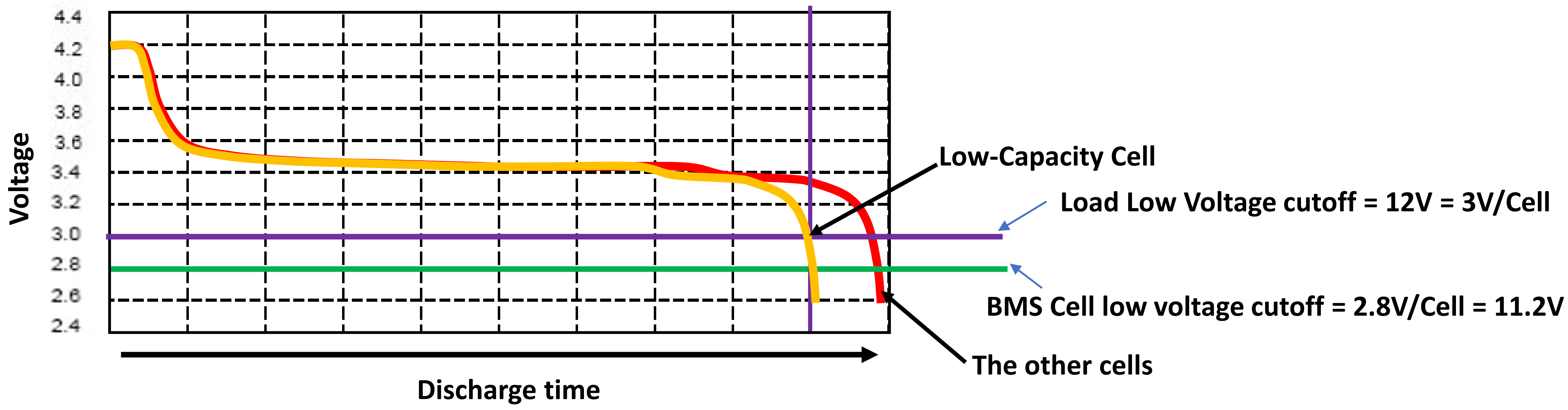


Notice that the weak cell will be at a much lower voltage when the battery is fully depleted, but as it charges, the cell will get to the flat part of the curve and track the rest of the cells rather closely.

1.4) Top Balancing (Continued)

After the cells are top balanced, the discharge path will look something like this. See Diagram 5

Diagram 5



The loads or BMS will cut off when the low-capacity cell hits the knee of the curve and the voltage rapidly drops off. Also note that even though the other cells still have stored energy, it is inaccessible once the BMS cuts off Discharge. Consequently, the capacity of the battery is defined by when the BMS shuts down due to the weakest cell.

1.5) Notes about Cell Balancers:

Nearly all BMSs used in the DIY battery space have a balancing function that is configured to support a top balanced battery. These functions have balance currents ranging from 50ma passive balancers to 2A active balancers. If properly configured, these balance functions can top balance a pack over time. However, depending on the balance current and how far out of top-balance the cells are, it may take a *very* long time for the balance function to bring the cells in line.

Balance circuits use cell voltage as a proxy for SOC, but in the flat part of the curve, the cell voltage is a very poor indicator of SOC. In fact, a cell measuring 3.25V might have an SOC that is <u>higher</u> than a cell measuring 3.28V! If a balancer tries to balance the voltage between these two cells it will be detrimental to the top balance and make things worse. (This is why the default turn-on point for balancing on a BMS is almost always around 3.4V.)

There are independent active and passive balancers on the market that can help speed up the balancing of the cells without doing a per-cell top-balance. Some of these drive as much as 4 amps balance. (Some of them are advertised as much higher balance current but rarely get much above 4 amps in actual practice)

Most of the independent balancers do not turn off when the charge voltage gets into the flat of the curve. Consequently, these balancers should *not* be left on the system permanently. They should only be put on the battery at the end of a charge cycle while the voltages are a reasonable proxy for SOC.

1.6) Top Balancing.

An alternative to waiting for the balance circuit to balance the cells is an independent top balance. A complete top balancing tutorial is beyond the scope of this paper but a paper describing several different top balance techniques can be found here:

https://diysolarforum.com/resources/top-balancing-lifepo4-cells-using-a-low-cost-benchtop-power-supply.65/

Unless the battery is way out of whack, I would lean toward individually top balancing the cells while they are still in place. (See appendix C of the above document) This can be done without disconnecting the busbars and BMS.

The following is a quick summary of insitu top balancing using a power supply:

1) Charge the battery till the BMS cuts off charge.
2) Ensure the battery is disconnected from the rest of the system.
3) Preset the voltage on the power supply to 3.65V
4) Place the preset power supply across one of the cells and leave it till the current goes to zero or near zero.
   Be patient. It might take a while. Once the power supply is preset, don't adjust it even if it shows a voltage drop when first connected to the cell. The voltage will come back up as the current drops to zero.
5) Repeat step 3 for each of the cells.
6) Reconnect the battery to the system.

Another technique is to drain the high SOC cell(s) through a resistor or incandescent bulb. This works but it is hard to be precise.

Part 2: Runaway Cell Voltage Under Load

2.1) Identifying the type of under-load runaway problem.
If a cell races to a high (or low) voltage when under heavy load, it could be due to one of two issues:

1) There is a bad connection between the cells
2) There is a bad cell (typically with a high internal resistance).

The vast majority of the time, the problem is a bad connection. Even when people say they fixed the problem by replacing the 'bad' cell, it is possible that in the process of replacing the cell they fixed a bad connection.

To differentiate between a bad connection and a bad cell, put the system under a moderately high load (As high as possible without the system shutting down) and start measuring the voltage at the cell terminal pads. <u>Do NOT measure on the busbar, the stud, or the nut. It must be measured on the terminal pad</u>. This may require contortions to get the probe to the pad, but it is important to do.

Notes:
1. Try to use a constant load. A load like a space heater with a thermostat might turn on and off, making it difficult to get a good measure. The best load is a large constant DC load, but many people will need to use the inverter and an AC load to get a high enough current.
2. The voltage differences we are looking for can be quite small. Perhaps as low as 50-100mV. Consequently, use the most accurate voltmeter available and take care with the measurements

If this measurement shows the cells are all in the same voltage range, or if the measurement is significantly different than what is being reported by the BMS, the problem is with a connection. If the measurement of one of the cells is way different than the others, it is probably a 'bad' cell with a high internal resistance relative to the others. (Sorry, I don't know a way to fix a 'bad' cell.)

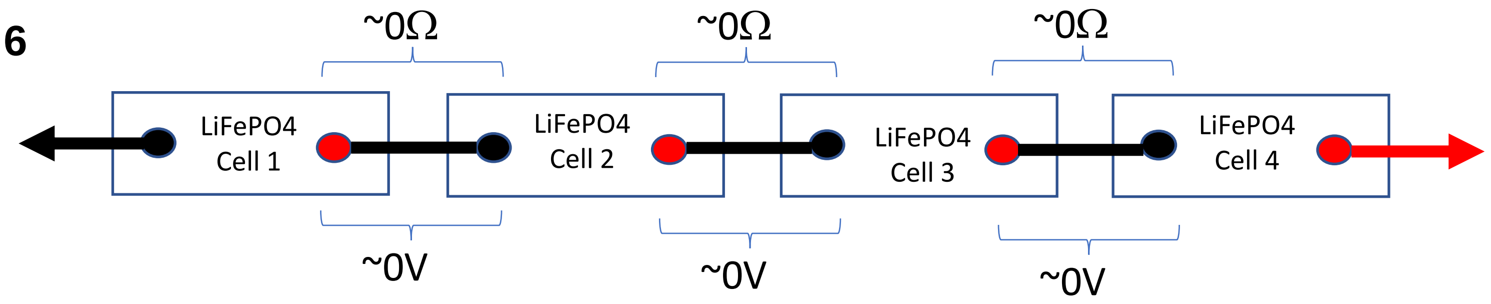
Note: <u>In situations where the cell races away during load. I just assume a bad connection and start trying to clean up the connections.</u> After checking and cleaning all the connections, if the problem persists on the same cell, I will start checking for a bad cell. (If the problem moves to a different cell, it is almost certainly a bad connection, not a bad cell)

2.2) Run away Cell due to bad connections

Sometimes a cell will appear to shoot up or down in voltage under heavy load.   This is almost always caused by a bad connection to one of the cell terminals.

If a system has good connection between all the cells, there will be very little resistance across the busbars.

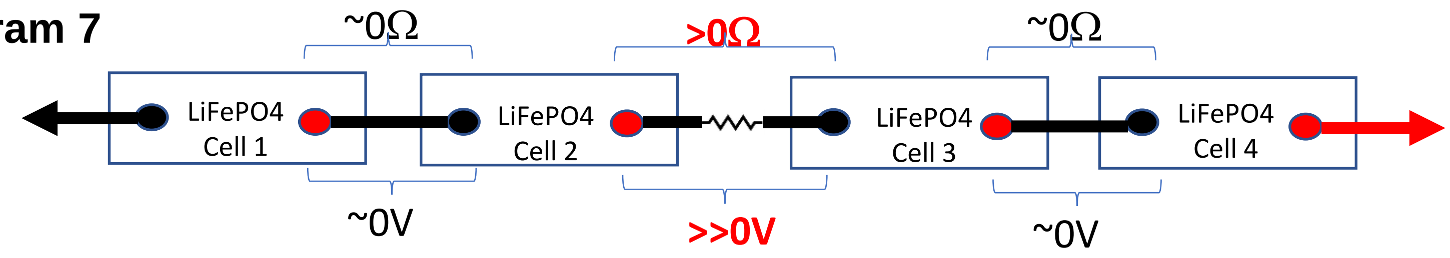
Diagram 6



Since Voltage drop is calculated as Current times Resistance (V=I*R), the voltage drop on these connections will remain very small.

Now let's assume a bad connection creates some resistance:

Diagram 7



As the current rises, a voltage drop will develop across the resistive connection.   Depending on how the BMS is reading and calculating the voltages, it will see this as either a high voltage on Cell 3 or a low voltage on cell 2 (Note: With the very high currents we deal with, a very low amount of resistance can cause these problems.)

The only way to fix this is to find and fix the resistive connection(s).

2.3) Finding/fixing bad connections.

Since each build is physically different, it is difficult to give advice on how to 'fix' the connection. However, here are some things to watch for:

- Screws/studs/bolts that are loose. (I advise using a torque wrench to tighten and/or check the screw)
- Stripped cell threads that can not be tightened. (Do a search on the forum to find resources and discussions about what to do for stripped threads.
- Stripped threads on cell terminals that can not be properly tightened. (Do a search on the forum to find resources and discussions about what to do for stripped threads. One recently popular solution is to force thread a ¼" stainless steel stud into the 6mm hole. It will self tap into the hole)
- Dirty or corroded bus-bars. This is particularly true of aluminum conductors. Aluminum Oxide is an insulator.
- Dissimilar metals. A raw copper busbar on an aluminum cell pad can cause corrosion. It is best to use tinned copper busbars.
- Bent, Cupped, Burred or otherwise not-flat busbars. Anything that prevents the face of the busbar from lying flat on the cell terminal pad can create a resistive connection. The connection will work fine for a low load but develops high voltage drop under heavy load.
- Washers or balance lead between the busbar and the terminal pad. The busbar should be flat on the pad.
- Bad Crimps. Typically, busbars are used so this is not an issue. However, if cables are used it can be a big issue. Furthermore, it can be very difficult to visually identify a bad crimp. Due to the sensitivity to even a small resistance on the battery connections, I recommend avoiding cables as the cell interconnect.

A couple other tricks:

- A bad connection is likely to get warm or even hot under heavy load. (I would <u>never</u> tell someone to touch a live electrical circuit, but I will mention in passing that a bad connection can be warm or hot to the touch ☺)