Tutorial: Top Balancing LiFePo4 Cells using a low cost 10A benchtop power supply.

Disclaimer: There are a lot of opinions about how to properly top balance LiFePO4 cells. Some of the debates get almost religious in the fervor. I do not profess to be the final word on this, but I am willing to share what works for me. If you can use this tutorial or even parts of this tutorial, great. If you totally disagree, that is fine as well.

NOTE1: Appendix B, C and D briefly describe alternate methods of top balancing a battery.

NOTE2: In the following, I show how to top balance to 3.65 volts. This is an aggressive top balance. Many people top balance to 3.6 volts or lower. If you decide to use a different voltage, adjust the voltages accordingly. (See more on this in Section 2 of this paper.

Warning: This procedure involves assembling and disassembling the cells into different configurations: Be careful of the threads in the cell terminals. Taking stainless steel studs in and out <u>will</u> damage the aluminum threads. I advise putting the studs into the cell terminals once with red Loctite and never taking them out again.

1 <u>Power Supply:</u>

For top balancing, I use this 10 Amp power supply:
https://www.amazon.com/gp/product/B07ML2MP9Q

There are several similar supplies available in this price range. The key is to have both Constant Voltage and Constant Current controls for your supply. @Will Prowse recommends a similar one on his tools page:

https://www.mobile-solarpower.com/tools.html

Note 1: The above power supplies will work for top balancing any LiFePO4 Cell but will only work for 24V and 12V Pre-charging (See below about pre-charging). If you need to pre-charge 48V banks, a 60V supply is recommended.

Note 2: 10A supplies tend to be the sweet spot for pricing. Higher amp supplies will allow you to top balance faster, but they tend to be a lot more expensive.

Note 3: The leads that come with these supplies are not particularly good. They tend to be high enough resistance that you can get a large enough voltage drop when driving 10 Amps that it will slow down the process. The factory leads will work fine and achieve the same result, but it is advisable to build your own heavy duty leads to speed up the process. Using a larger wire size is good, but the most important 'upgrade' for the leads are the end connectors. The best leads for this purpose will have properly sized ring connectors on both ends. (Not banana plugs and allegator clips) (See Appendix D)

2 <u>When to top balance.</u>

Top balancing is typically done when your cells are going to be assembled into a battery with a BMS for solar systems. In this case, the BMS will typically be top balancing the cells so any other type of cell balancing will quickly be defeated. Furthermore, the batteries will spend little of their life at the bottom levels of charge so balancing them at the top will be most effective.

Quite often, new and matched cells will be delivered 'balanced.' Unfortunately, I do not know of a way to determine that they are balanced other than to build the battery and do a capacity test or watch the cell voltage at the endo of a charge. If you assemble the pack and find it meets the Ah rating expected, or if the cell voltages stay close at the end of a charge, there is little need to do an additional top balance.

Once you top balance the first time, you will not typically need to top balance again, particularly if you are starting with matched cells. The cells will tend to age similarly to each other and the BMS balancing will tend to keep them top balanced. The exception to this is if you are charging and discharging at very high C rates. In these conditions, the differences between the cells can be amplified and the BMS may not be able to keep up. (This is not typical for solar installations).

3 Pre-charging the cells to get them 'mostly' charged.

If your cells are mostly charged, you can skip this section and go to next section: "**4 Top Balancing your cells**".

If your cells are not mostly charged, trying to top balance them in parallel with a 10A supply means you are only charging at ~3.4V X 10A = 34 watts. This could take an exceptionally long time, possibly days. To speed up the process, I charge them in series with a BMS first:

1. Assemble the cells in series and add your BMS to create a full battery.
2. Set the BMS to shut off charge when any cell reaches 3.65V. (3.6V for 3.6v top balance)
3. Set the power supply constant current to .2 C or less.
   A. While the power supply is disconnected from the batteries and turned off, short the leads together.
   B. While the power supply is off, Set the voltage arbitrarily high and the current as low as it will go.
   C. Turn on the power supply and slowly turn up the current till you hit the target current.
   D. Disconnect the leads

   Note: For most cells used in solar systems, .2 C is a lot more than 10 Amps. (.2C of 100Ah cells is 20A). Consequently, in most cases you can just max out the current setting on the supply.
4. With the power supply disconnected, set the voltage to your target pack voltage.

For a 12 V system:	3.65 X 4=14.6 Volts.	(Or 14.4 V for 3.6v top balance)
For a 24 V system:	3.65 X 8 = 29.2 Volts.	(Or 28.8 V for 3.6v top balance)
For a 48 V system:	3.65 X 16 = 58.4V.	(Or 57.6V for 3.6V top balance)

   Hook the power supply to the + and – of the battery. (Be sure to get the polarity correct or you will get a very large spark and possibly damage the power supply… do not ask how I know this.)
5. Let the battery charge till the BMS does an over-voltage disconnect. Depending on the Cell size and SOC, this could take several hours.

   Note: If the voltages stay close together toward the end of the charge cycle, then the cells are already balanced, and top balancing is not necessary.

   - If the cells stay within 50mV of each other, Call it good and skip the top balance step
   - If the cells are more than 150mV apart, do a top balance
   - In between 50 and 150mv, it is the user's choice.
     Note: if the normal charging voltage is going to be set close to 3.65V/cell, then you are more likely to get BMS High Voltage cut-offs with a 150mV delta. However, if the charge voltage is going to run at a conservative ~3.5V/cell, then having a larger cell voltage delta will be less likely to cause BMS High Voltage cut-offs.

   Note: Once the charge completes and the BMS cuts off, the cell voltages will settle and will no longer be a good indicator of how well they are balanced.

6. Once the BMS shuts off charge, turn off the power supply and disassemble the battery. At this point your cells are mostly charged but they may not be balanced.

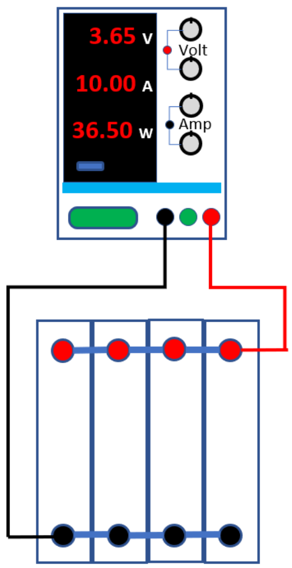
Note 1: This pre-charging step assumes your cells all start out at a similar state of charge. However, if one of the cells starts out at a significantly higher SOC, it will hit 3.65V and stop the process before the other cells get mostly charged. This does not hurt anything, but the top balancing process in the next section will take a lot longer. If you suspect your cells are starting with significant differences in SOC, you can put them in parallel overnight to let them equalize before you start the pre-charge. (I do not find this necessary with new cells.)

Note 2: The low-cost Power Supply referenced above will not reach the required voltage for pre-charging a 48V bank. However, the power supply for this step can be any supply that will achieve the required voltage. I will often use an Inverter/Charger or an AC charger for this step.

4 Top Balancing your cells

Note 1: The following procedure is essentially the same as what Will Prowse shows in his video: https://diysolarforum.com/threads/top-balancing.8193/page-4#post-89059

Note 2: The procedure below uses 3.65V as the target voltage for top balancing. Some people feel this is higher than necessary. One common target voltage that others use is 3.6V and I have heard a few even use as low as 3.5V. (I would not recommend anything lower than 3.5V). For best results, be sure to charge to a voltage that is above the max cell voltage your BMS will be set to during normal usage. This will help prevent one cell from suddenly going over-voltage when the cells are nearly charged.



1. Wire all your cells in parallel.
   Note: If your cells are more than about .15V different, it is best to charge the lower cells to about the same as the higher cell(s) before paralleling them. To do this, parallel the lower voltage cells and use this top balance procedure to get them close to the voltage of the higher cells and then top balance them all)
2. Before hooking the power supply to the cells, set the power supply to .2C or less of the combined AH of the cells. This will usually turn out to be the max current setting of the power supply.
3. Set the voltage on the power supply to 3.65V.
4. Hook the negative lead to the negative pole of one end of the series of cells and the positive lead to the positive pole at the other end of the series of cells as shown in the image on the right (Be sure to get the polarity correct). The diagonal hook-up helps balance the resistance between the power supply and the individual cells.
5. At this point the cells are all being charged to 3.65 volts. Depending on the SOC of the cells, your power supply might be current limited and the voltage on the display will be less than 3.65 volts. <u>Do not adjust the voltage!</u>

   NOTE: You might notice that the voltage at the cells is lower than the voltage shown on the power supply. You might also notice that the voltages between individual cells are different. This is normal and is due to the resistance of the leads and interconnects. As the cells charge and the current starts to drop, you will see the voltage differences between the Cells and the power supply go to zero.

   NOTE: **<u>Be patient</u>**. Depending on the state of charge when the top-balancing started, this can take a long time. Perhaps multiple days. It may sit at the same voltage and not change for a long time. This is normal. Do not give up and do not try to increase the voltage to speed things up.

Because the voltage clamp on the low-cost power supplies often has a small drift (Typically ~0.02V) I do not leave cells unattended if the Power Supply is set at 3.65V. If I need to leave the cells unattended, I will set the PS to 3.6V or even 3.55V and let them top charge unattended. When I have time to 'babysit' the cells I will then re-do the balance at 3.65V. Since the cells are already top balanced to above 3.5V, the final top balance is very quick (Even at 3.55V I do not leave them unattended for extended periods. I do not want them to sit at even 3.55 volts and no current for more than over-night).

6. Once you see the voltage at the cells reach ~3.5 volts, the voltage will start going up much faster. At this point start watching the voltage at the power supply closely. I do not trust the constant voltage circuit on the power supply to hold the voltage exactly at 3.65V, so at the end of the charging I use my multimeter and adjust the power supply to make sure the voltage **at the power supply** does not go above 3.65V. Do not worry if the voltage at the cell is lower than the Power Supply…they will catch up. (I find that the cells take 1-4 hours to get to 3.65 V with 200AH 24V banks. Higher capacity banks of cells will take longer)

7. Once the cell voltage starts rising, the current will start dropping. Keep the power supply voltage at 3.65 volts till the current is zero or near zero. This usually takes less than an hour after you see the cell voltage rising quickly.
8. Once the current is zero, the cells are top balanced. Disconnect the power supply, disassemble the bank of cells, and reassemble them into your final battery.

Note: It is best not to let the cells be driven to the 3.65 volts for an extended period. Consequently, disconnect the cells as soon as the current goes to zero. A few extra hours at zero current will not hurt anything.... but do not let them sit at 3.65V for multiple days.

Note: After you complete the top balance and disconnect the power supply, you will see the voltage on the cells drift down to a lower resting voltage. Furthermore, the resting voltage might be a few millivolts different between the cells. This is normal.

Appendix A: Other opinions

This section is to acknowledge a few things that others might do differently. I would not say the other opinions are wrong, it is just that my experience drives me to different conclusions.

1. **Target voltage.**
   When I top balance, I push the cells to 3.65V. However, when I am setting the voltages in my charge controller, the cell voltage target is closer to 3.5V. Some folks believe that it would be better for me to top balance at 3.5V to match my run-time target voltage. I find it works better to balance to the higher voltage.

2. **Do not top balance at all.**
   Since most BMSs will work to top balance the cells, some folks feel the whole top-balance process is unnecessary. There is some truth to this, particularly if your BMS has an aggressive balancing algorithm and high balancing current. However, it is likely to take the BMS an extremely long time to balance the cells… **if ever.** If you choose not to balance your cells, you must set your charge voltage low enough to prevent the BMS disconnecting due to a cell voltage getting too high. Otherwise, the BMS will cut out before the charger does. Likewise, your loads must disconnect at a high enough voltage to prevent the BMS from disconnecting due to a Cell undervoltage.

Also, if you are going to do a capacity test on the battery you just built with your new cells, balancing first will give you a more accurate result.

3. One reviewer felt that letting the current go to zero while balancing the cells to 3.65 would damage the cells. The reviewer said:

   "Paragraphs 4.6 and 4.7 can result in cell damage. Cell charge termination is typically at around 0.05C depending on manufacturer. This method of charging is typical at a tiny fraction of C, thus the INSTANT the CELLS hit 3.65V, the cells are OVER charged due to the very low current. There is no reason to wait for the current to taper to zero."

   I agree that the current does not have to go all the way to zero and that you can stop the top balance at near-zero current. However, LiFePO4 can tolerate charges higher than 3.65 without damage, so letting them go to zero current will not damage the cells. Furthermore, the cells are not fully balanced till the current goes to zero. If someone is concerned about this, they can either stop the top balance before the cells get to zero current or Top Balance to 3.64V.

Appendix B: Step-and-Pause top balance.

There is a slightly more involved 'stepwise' top-balancing process where the cells are balance charged to a lower voltage, let rest, and then driven to a slightly higher voltage. This continues till the target top voltage is reached.

(This is essentially the same process discussed in section 4 but done in multiple steps.)

There is nothing wrong with the step-and-Pause approach and there is general agreement that both approaches achieve an acceptable result. The debate between the two approaches comes down slight differences in the outcome.

Regardless of whether the 'step-and-pause' or 'single step' method is used, the top balance concept and goal is the same: Get the cells all to the same state of charge and the same voltage.

I personally use the single step approach but have no issues with the multi-step approach either.

The following is a brief outline of the step-and-pause process as described on the MarineHowTo site. (https://marinehowto.com/lifepo4-batteries-on-boats/)

Note that they use a different target top voltage. If you want to target 3.65V you can adjust the voltages below accordingly.

1- *Wire the cells in parallel*
2- *Set the power supply to 3.400V and 80% or less of the rated amperage (80% to not burn it out)*
3- *Turn on power supply and charge cells to 3.400V*
4- *When current has dropped to 0.0A at 3.400V turn off the power supply & set it to 3.500V*
5- *Turn on power supply and charge cells to 3.500V*
6- *When current has dropped to 0.0A at 3.500V turn off the power supply & set to 3.600V*
7- *Allow current to drop to 0.0A (or very close) at 3.60V*
8- *Done, pack is balanced.*

WARNING: *Top each cell up to a similar SoC level, prior to wiring them in parallel*

WARNING: *Top balancing, even at 3.600VPC needs to be closely monitored. Like equalizing flooded batteries, you simply do not want to leave them unattended at these voltages for extended periods of time. Once the cells hit 3.600VPC you may need to adjust your power supply, very carefully, so it does not overshoot target top-balance voltage. Watch your DVM not the power supply display*

Appendix C: Top Balance by charging individual cells.

Some people like to top balance by charging each cell individually to the target balance voltage. The arguments for doing this is that it can be done without disassembling the battery (Less chance of striping terminal threads). They also feel that doing it this way is safer (less likely to mess up and over charge, but I do not understand that argument.

Note: This can also be done by only charging the cells that are 'behind' the other cells during normal charging. As an example, if you find one cell is consistently a few mV behind the others when normal charging stops, charging just that cell can bring it back in line.

Instructions for using the power supply to top balance cells while they remain wired in series.

Before you begin,

A) fully charge the battery using the inverter.
B) Turn off or disconnect from all loads on the battery (Including the inverter)
C) Disconnect the ribbon cable from the BMS
D) One cell at a time, do the following steps:
    1) With the leads not connected to anything, set the voltage to 3.65V
       Note that there is a course setting knob to get it close and a fine setting knob to tune it in.
    2) Turn the current all the way down.
    3) Connect the Positive lead to the positive of the cell.
    4) Connect the Negative lead to the negative of the cell.
    5) Turn the current all the way up.
    6) When the current goes below .5A as shown on the power supply, the cell is done.
    7) Repeat step D for each cell.

NOTES:

- When you turn the current all the way up in step 5, it may not go to the full 10A of the power supply. This is OK,
- When you turn the current all the way up in step 5, if the current goes to the full 10A, the voltage at the supply might drop. This is OK. DO NOT ADJUST THE VOLTAGE!!!
- As the current gets lower and lower, the voltage at the power supply might drift above 3.65. If to adjust it <u>down.</u>
- At the very end when the current is below one amp, if the voltage is below 3.65, adjust it up to 3.65V and then let the current go back down. <u>*This is the ONLY* time you should ever adjust the voltage up*</u>
- You can do all this with factory leads, but heavy duty leads with ring terminals will make it go faster.

Appendix D: Top Balance by discharging individual cells.

Similar to charging individual cells, the battery can be brought into balance by discharging cells that hit the charge limit and start to rise in voltage before the others. By placing a power resistor or an incandescent bulb across this cell some of the energy can be drained off in order to bring the cell in line with the others

Appendix D: Top Balance using an active balancer.

There are many active balancers available that can be used to balance the cells in a pack without putting the cells in parallel.

Once a cell reaches 3.45 volts during a charge cycle, turn the active balancer on and let it actively balance till all the cells are fully charged. This works best if the charge current is low. Otherwise the charge current overwhelms the balance current and one of the cells can still 'run away'. One good way to prevent this is to start with a reasonably low charge voltage like 3.5V/cell (14V pack voltage for a 12 V system) and low charge current (1 or 2 amps) and let it go till the cells are all balanced. Then step the voltage up a bit and let it repeat. Keep doing this till the voltage reaches 3.6V/cell and the current drops off to near zero.

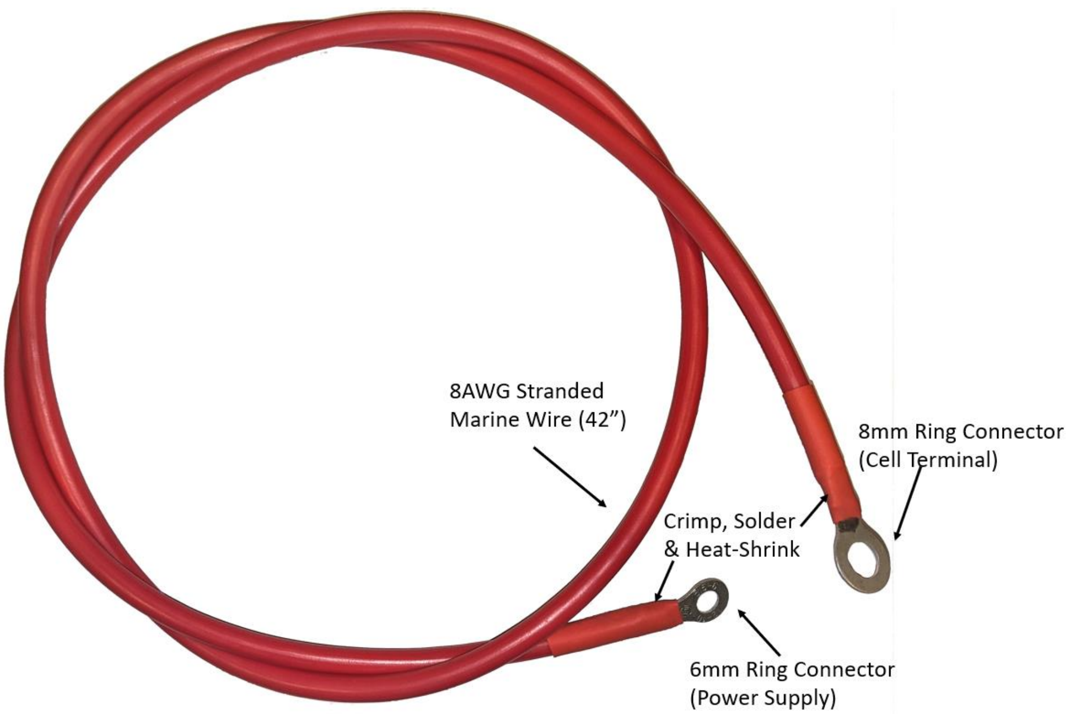
Note/Warning: On $LiFePO_4$ cells, the balancer should only turn on when the cells are above 3.45V. Many (Most?) active balancers will run continuously. This does not work well on $LiFePO_4$ cells. When the SOC is in the flat part of the curve, the cell voltage is no longer a good indicator of the SOC of the cell. If the balancer tries to balance the voltage between cells in the middle of the charge curve, it can actually be making the balance worse.

Appendix E: Power Supply Lead for minimizing Voltage Drop.

The leads that come with the low-cost supplies are adequate but not great. The factory leads will work, but they will slow down the process due to voltage drops across the leads and connections. Consequently, I built heavy duty leads to use for this procedure. Using a larger wire size is good, but the most important 'upgrade' for the leads are the end connectors. The best leads for this purpose will have properly sized ring connectors on both ends. (Not banana plugs and allegator clips)

This is one of the leads I built for top balance work with the low-cost Power Supply. I used 8AWG stranded wire because that is what I had on hand. If I had 10AWG stranded or even 12AWG stranded on hand I would have used that instead.

Also note that for power supply leads, flexibility makes them much easier to use. Stranded wire from the hardware store is OK, but I like using high-strand Marine cable or welding cable because of its flexibility.



Note: I have cells with both 8mm and 6mm studs, so I built it with an 8mm connector for connecting to the cells. This will work for 6mm studs, but if you are only doing cells with 6mm studs, a 6mm connector for the cell terminal would be better.

Appendix F: Edits from original version.

(Most recent change listed first)

- Throughout: Minor formatting and typo updates.
- Section 4: Added Link to @Will Prowse's top balance Video
- Section 3: Added and then updated note about starting with cells that have significantly different SOC.
- Section 5: Added the "Other Opinions" section.
- Section 4: Added note about voltage drift after top balancing.
- Section 1: Added link to @Will Prowse's tools page for his power supply recommendation.
- Section 5: Added reviewers concern about letting the current go to zero at the end of top balancing.
- Added appendix that notes some people top balance by charging individual cells.
- Section 2: Added comment that if you assemble new cells and a capacity test indicates full capacity, the cells came balanced and further balancing may not be necessary.
- Section 3: Added note about getting cells close in voltage before putting them in parallel.
- Appendix D: Added appendix about DIY power supply leads.
- Section 4: Added image and text about hooking up the power supply to diagonal posts on the cells.
- Introduction: Added warning to be careful of cell terminal threads.
- 5/29/21 - Appendix D: Added comments about wire size and type.
- 5/29/21 - Section 4: Added note about target top-balance voltages.
- 5/29/21 - Section 1: Added note about Power Supply Amps
- 5/29/21 - Section 1: Added note that a higher voltage supply would be needed for pre-charging cells for 48V systems.
- 5/30/21 - Section 4: Added note about being patient with the process and about leaving the cells unattended.
- 5/30/21 – Section 3: Added note about power supplies for pre-charging.
- 12/29/21 - Section 3: Added note about checking cell voltages at the end of the pre-charge to determine if top balancing is necessary.
- 12/29/21 - Section 4: Added note about not letting the cells sit at the balance voltage longer than necessary.
- 12/29/21 – Corrected grammar and spelling throughout.
- 9/3/23 – Added appendix on using an active balancer. Added detail on how to top balance by charging individual cells.