Charging LiFePO4 Batteries

How to best charge, discharge and get maximum life from LiFePO4 batteries

A consolidation from numerous opinion sites

This is about one specific category of lithium-ion batteries; Lithium-Iron-Phosphate or LiFePO4 in its chemical formula, also known as LFP batteries. These are a little different from mobile phones and laptops, those are (mostly) lithium-cobalt batteries. The advantage of LFP is that it is much more stable, and not prone to self-combustion. That does not mean the battery cannot combust in case of damage. There is a whole lot of energy stored in a charged battery and in case of an unplanned discharge the results can get very interesting very quickly! LFP also lasts longer in comparison to lithium-cobalt, and is more temperature-stable. Of all the various lithium battery technologies out there this makes LFP best suited for deep-cycle applications.

LFP batteries should have a BMS or Battery Management System, as almost all LFP batteries that are sold as a 12/24/48 Volt pack do. The BMS takes care of protecting the battery; it disconnects the battery when it is discharged, or threatens to be over-charged. The BMS also takes care of limiting the charge and discharge currents, monitors cell temperature (and curtails charge/discharge if needed), and most will balance the cells each time a full charge is done (balancing and bringing all the cells inside the battery pack to the same state-of-charge, similar to equalizing for a lead-acid battery).

Most recommendations are: DO NOT BUY a battery without BMS.

Lithium-Ion batteries

Lithium-ion batteries can sit at partial charge forever without damage. LFP batteries prefer to sit at partial charge rather than being completely full or empty, and for longevity it is better to cycle the battery or to let it sit at partial charge.

Lithium-ion batteries are the highest quality of batteries: With the right charge parameters there is no maintenance. The BMS will take care of it.

LFP batteries can also last a very long time. Most are rated at around 3000 cycles, at a full 100% charge/discharge cycle. If this was done every day it makes for over 8 years of cycling. They last even longer when used in less-than-100% cycling and use a linear relationship: 50% discharge cycles means twice the cycles, 33% discharge cycles and it can be reasonably expected to be three times the cycles.

A LiFePO4 battery also weighs less than 1/2 of a lead-acid battery of similar capacity. It can handle large charge currents (100% of Ah rating is no problem), allowing for rapid charging, it is sealed so there are no fumes, and it has a very low self-discharge rate (3% a month or less).

Battery Bank Sizing

Lithium-ion batteries have 100% usable capacity, while lead-acid really ends at 80%. That means an LFP battery bank can be sized smaller than a lead-acid bank, and still have it be functionally the same. The numbers suggest that LFP can be 80% the Amp-hour size of lead-acid.

For longevity lead-acid battery banks should not be sized where they regularly see discharging below 50% SOC. With LFP that is no problem. Cycling energy efficiency for LFP is quite a bit better than lead-acid as well, meaning that less energy is needed to charge the battery after a certain level of discharge. That results in faster recovery back to 100%, while having a smaller battery bank, reinforcing this effect even more.

The bottom line is that it would be comfortable to size a lithium-ion battery bank at 55% – 70% of the size of an equivalent lead-acid bank, and expect the same (or better) performance. Including on those days when sunlight is in short supply.

Series Connected Batteries

There is a potential issue when multiple lithium-ion batteries are connected in series. For example, two 12 Volt 100 Ah batteries, each with their own built-in BMS, connected in series to make 24 Volt 100 Ah. Assuming one of those two batteries is near-empty, the other pretty full, and putting a load on the batteries to discharge them. The near-empty battery will reach the point where the BMS decides there is enough charge in the bank and it will switch off that battery, in effect disconnecting the entire battery bank, even though the other battery is full.

The same potential for trouble exists when charging both batteries at the same time with a 24 Volt charging source. The fuller of the two batteries will fill up first, raising the charging Voltage over that battery, until reaching the point where the BMS once again intervenes to protect the battery and switches the full battery off. When the BMS switches off, the entire battery bank will switch off. If both started off uneven, then the other battery may well be nowhere near full yet, and this will not resolve over time or multiple charge cycles either.

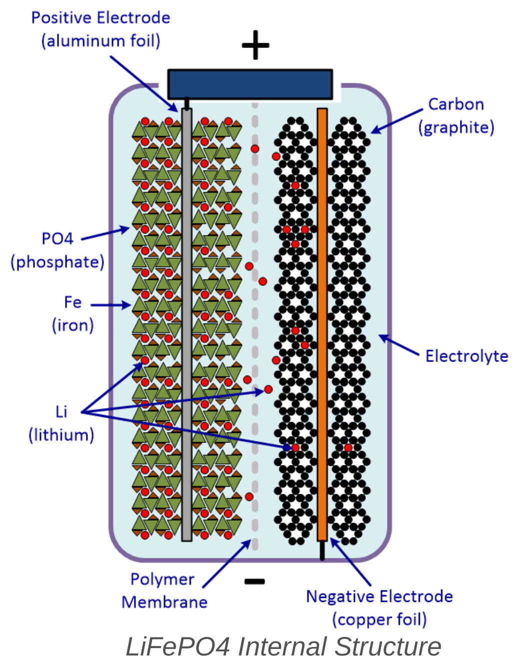
The dynamics of connecting multiple lithium-ion batteries in series should be understood. They do not quite behave like lead-acid batteries. Lead-acid batteries will self-balance when they are charged, all attaining a similar state-of-charge in the end. Lithium-ion batteries due to each having their own independent BMS do not. It is known, however, that by-and-large series connected batteries, each with their own BMS, can work fine. It would be a good idea though to make sure both are "in sync" every now and then, by charging them individually with a 12 Volt charger, until both are known to be fully charged, so they start off with the same state-of-charge.

LFP batteries too have their limitations. A big one is temperature: You cannot charge a lithium-ion battery below freezing, or zero Centigrade. Lead-acid could not care less about this. You can still discharge the battery (at a temporary capacity loss), but charging is not going to happen. The BMS should take care to block charging at freezing temperatures, avoiding accidental damage.

Temperature is also an issue at the high end. The biggest single cause of aging of the batteries is use or even just storage at high temperatures. Up to around 30 Centigrade there is no problem. Even 45 Centigrade does not incur too much of a penalty. Anything higher really accelerates aging and ultimately the end of the battery though. This includes storing the battery when it is not being cycled.

There is an issue that can crop up when using charging sources that potentially provide a high Voltage: When the battery is full the Voltage will rise, unless the charging source stops charging. If it increases enough the BMS will protect the battery and disconnect it, leaving that charging source to rise even more. This can be an issue with (bad) car alternator Voltage regulators, that need to always see a load or the Voltage will spike. This can also be an issue with small wind turbines that rely on the battery to keep them under control.

How Does a LiFePO4 Battery Work?



LiFePO4 Internal Structure

Lithium-ion batteries move ions, in this case lithium ions, from the negative to the positive electrode when discharging, and back again when charging. The diagram shows what goes on inside. The little red balls are the lithium ions that move back and forth between the negative and positive electrodes.

On the left side is the positive electrode, constructed from lithium-iron-phosphate ($LiFePO_4$). This should help explain the name of this type of battery. The iron and phosphate ions form a grid that loosely traps the lithium ions. When the cell is getting charged, those lithium ions get pulled through the membrane in the middle, to the negative electrode on the right. The membrane is made of a type of polymer (plastic), with lots of tiny little pores in it, making it easy for the lithium ions to pass through. On the negative side we find a lattice made of carbon atoms that can trap and hold those lithium ions that cross over.

Discharging the battery does the same thing in reverse: As electrons flow away through the negative electrode, the lithium ions once again go on the move, through the membrane, back to the iron-phosphate lattice. They are once again stored on the positive side until the battery gets charged again.

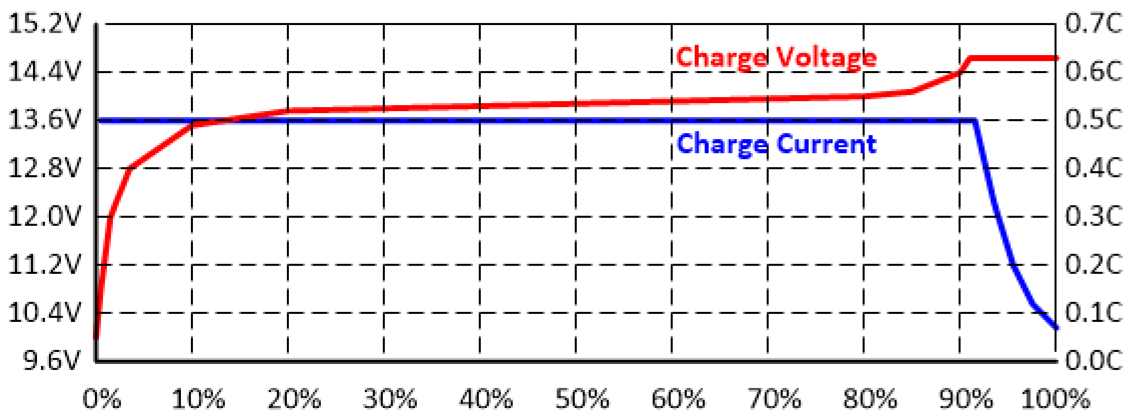
The battery drawing shows an LFP battery that is almost completely discharged. Nearly all the lithium ions are on the side of the positive electrode. A fully charged battery would have those lithium ions all stored inside the carbon of the negative electrode.

In reality lithium-ion cells are built of very thin layers of alternating aluminum – polymer – copper foils, with the chemicals pasted on them. Often they are rolled up like a jelly-roll, and put in a steel canister, much like an AA battery. The 12 Volt lithium-ion batteries sold are made of many of those cells, connected in series & parallel to increase the Voltage and Amp-hour capacity. Each cell is around 3.3 Volt, so 4 of them in series make 13.2 Volt. That is just the right Voltage for replacing a 12 Volt lead-acid battery.

Charging a Lithium-Ion Battery

Most regular solar charge controllers have no trouble charging lithium-ion batteries. The Voltages needed are very similar to those used for AGM batteries (a type of sealed lead-acid battery). The BMS helps too, in making sure the battery cells see the right Voltage, do not get overcharged, or overly-discharged, it balances the cells, and ensures the cell temperature is within reason while they are being charged.

This graph shows a typical profile of a $LiFePO_4$ battery getting charged. To make it easier to read the Voltages have been converted to what a 12 Volt LFP battery pack would see (4x the single-cell Voltage).



LiFePO4 Charge Voltage vs. SOC

Shown in the graph is a charge rate of 0.5C, or half of the Ah capacity, in other words for a 100Ah battery this would be a charge rate of 50 Amp. The charge Voltage (in red) will not really change much for higher or lower charge rates (in blue), LFP batteries have a very flat Voltage curve.

Lithium-ion batteries are charged in two stages: First the current is kept constant, or with solar PV that generally means that we try and send as much current into the batteries as available from the sun. The Voltage will slowly rise during this time, until it reaches the ‘absorb’ Voltage, 14.6V in the graph above. Once absorb is reached the battery is about 90% full, and to fill it the rest of the way the Voltage is kept constant while the current slowly tapers off. Once the current drops to around 5% – 10% of the Ah rating of the battery it is at 100% State-Of-Charge (SOC).

In many ways a lithium-ion battery is easier to charge than a lead-acid battery: As long as the charge Voltage is high enough to move ions it charges. Lithium-ion batteries do not care if they are not fully 100% charged, in fact they last longer if they are not. There is no sulphation, there is no equalizing, the absorb time does not really matter, you cannot really overcharge the battery, and the BMS takes care of keeping things within reasonable boundaries.

Charge Voltage Needed

So what Voltage is enough to get those ions moving? A little experimenting shows that 13.6 Volt (3.4V per cell) is the cut-off point; below that very little happens, while above that the battery will get at least 95% full given enough time. At 14.0 Volt (3.5V per cell) the battery easily charges up to 95+ percent with a few hours absorb time and for all intents and purposes there is little difference in charging between 14.0 or higher Voltages, things just happen a little faster at 14.2 Volt and above.

Bulk/Absorb Voltage

To summarize, an absorb setting between 14.2 and 14.6 Volt will work great for LiFePO4. Lower is possible too, down to about 14.0 Volt, with the help of some absorb time. Slightly higher Voltages are possible, the BMS for most batteries will allow around 14.8 – 15.0 Volt before disconnecting the battery. There is no benefit to a higher Voltage though, and more risk of getting cut off by the BMS, and possibly damage.

Float Voltage

LFP batteries do not need to be floated. Charge controllers have this because lead-acid batteries have such a high rate of self-discharge requiring them to keep trickling in more charge. For lithium-ion batteries it is not great if the battery constantly sits at a high State-Of-Charge, so if the charge controller cannot disable float, just set it to a low enough Voltage that no actual charging will happen. Any Voltage of 13.6 Volt or less will do.

Equalize Voltage

With charge Voltages over 14.6 Volt actively discouraged, it should be clear that no equalize should be done to a lithium-ion battery. If equalize cannot be disabled, set it to 14.6V or less, so it becomes just a regular absorb charge cycle.

Absorb Time

There is a lot to be said for simply setting the absorb Voltage to 14.4V or 14.6V, and then just stop charging once the battery reaches that Voltage. In short, zero, or a short Absorb time. At that point the battery will be around 90% full. LiFePO4 batteries are suited best in the long run when they do not sit at 100% SOC for too long, so this practice will extend battery life. If you absolutely have to have 100% SOC in your battery then absorb will do that. Officially this is reached when the charge current drops to 5% – 10% of the Ah rating of the battery, so 5 – 10 Amps for a 100Ah battery. If you cannot stop absorb based on current, then set absorb time to about 2 hours.

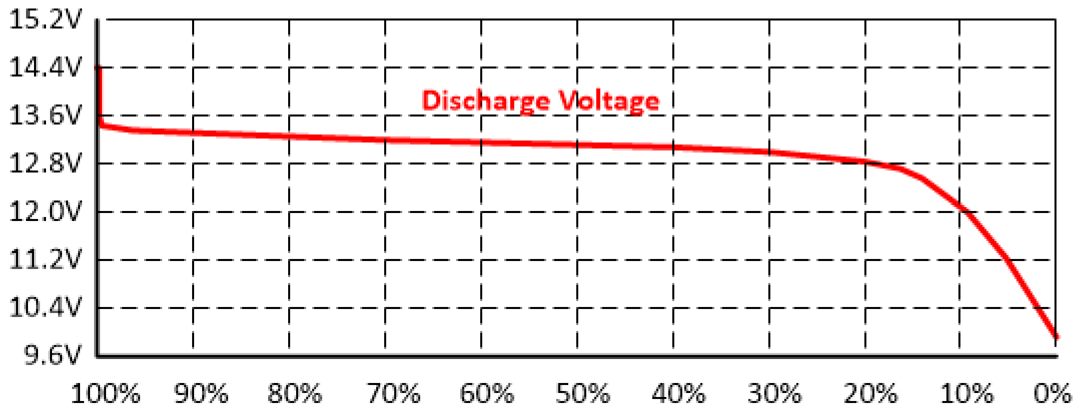
Temperature Compensation

LiFePO4 batteries do not need temperature compensation. Switch this off in your charge controller, or your charge Voltage will be wildly off when it is very warm or cold.

Check your charge controller Voltage settings against those actually measured with a good quality digital multi-meter. Small changes in Voltage can have a big impact when charging a lithium-ion battery. Change the charge settings accordingly.

Discharging Lithium-Ion Batteries

Unlike lead-acid batteries, the Voltage of a lithium-ion battery stays very constant during discharge. For a battery with a moderate load the discharge curve looks as follows.



LiFePO4 Discharge Voltage vs. SOC

Most of the time during discharge, the battery Voltage will be right around 13.2 Volt. It varies by just 0.2 Volt all the way from 99% to 30% SOC. The current types of LFP batteries will quite merrily discharge all the way down to 0% for many cycles. However, there is benefit in cycling less deep. It is not just that cycling to 30% SOC will get you 1/3 more cycles vs. cycling down to 0%, the battery will likely last for more cycles than that. Cycling down to 50% SOC seems to show around 3x the cycle life vs. cycling 100%.

Below is a table that shows battery Voltage for a 12 Volt battery pack vs. Depth-Of-Discharge. Assume these Voltage values lightly as the discharge curve is so flat that it really is hard to determine SOC from Voltage alone. Small variations in load, and accuracy of the Volt meter, will throw off the measurement.

100%	14.0 Volt	13.6 Volt
99%	13.8 Volt	13.4 Volt
90%	13.4 Volt	13.3 Volt
70%	13.2 Volt	13.2 Volt
40%	13.2 Volt	13.1 Volt
30%	13.0 Volt	13.0 Volt
20%	12.9 Volt	12.9 Volt
17%	12.8 Volt	12.8 Volt
14%	12.6 Volt	12.5 Volt
9%	12.4 Volt	12.0 Volt
0%	10.4 Volt	10.0 Volt

Storing Lithium-Ion Batteries

The very low self-discharge rate makes it easy to store LFP batteries, even for longer periods. It is no problem to put a lithium-ion battery away for a year, just make sure there is some charge in it before placing it in storage. Something between 50% – 60% is ideal. That will give the battery a very long time before self-discharge brings the Voltage close to the danger point.

Storing batteries below freezing is fine, even at very low temperatures such as -40 Centigrade or even less. The electrolyte in LiFePO4 cells does not contain any water, so even when it freezes (which happens around -40 Centigrade, depending on the particular formulation) it does not expand, and does not damage the cells. Let the battery warm up a little before starting discharging it again, which is OK at -20 Centigrade and above. There will be an apparent loss of capacity when discharging at below-freezing temperatures that reverses when the battery gets above freezing, and there is a slightly accelerated effect on aging. Storing them at low temperatures is certainly much better than storage at high temperatures: Calendar aging slows down dramatically at low temperatures. Avoid storing them at 45 Centigrade and above, and avoid storing them completely full or nearly empty.

If it is necessary to store batteries for longer periods, simply disconnect <u>all</u> cables from them. That way there cannot be any stray loads that slowly discharge the batteries.

Life End of Lithium-Ion Batteries

Battery manufacturers consider a battery “dead” when its capacity falls to 80% of what it should be. So, for a 100Ah battery, its end comes when its capacity is down to 80Ah. There are two mechanisms at work towards the demise of the battery: Cycling and aging. Each time the battery discharges and recharges it does a bit of damage and it loses a bit of capacity. Also, the battery can end by calendar life.

Some scientific studies were done on the effect of extremes (in temperature, and SOC) on calendar life, and those help set limits. What has been determined is that not abusing the battery bank, avoiding extremes, and generally just using the batteries within reasonable bounds, there is an upper limit of around 20 years on calendar life.

Besides the cells inside the battery, there is also the BMS, which is made out of electronic parts. When the BMS fails, so will the battery. Lithium-ion batteries with a built-in BMS are still new, and will need to be monitored, but ultimately the Battery Management System has to survive for as long as the lithium-ion cells do as well.

Processes inside the battery conspire over time to coat the boundary layer between electrodes and electrolyte with chemical compounds that prevent the lithium ions from entering and leaving the electrodes. Processes also bind lithium ions into new chemical compounds, so they are no longer available to move from electrode to electrode. Those processes will happen no matter what is done, but they are very much dependent on temperature. Keep the batteries under 30-40 Centigrade. Over 45 Centigrade they diminish considerably. The greatest cause of failure for lithium-ion batteries is heat.

There is more to calendar life and how quickly a LiFePO4 battery will age: State-Of-Charge has something to do with it as well. While high temperatures are bad, these batteries do not like to sit at 0% SOC and very high temperatures. Also bad, though not quite as bad as 0% SOC, is for them to sit at 100% SOC and high temperatures. Very low temperatures have less of an effect. You cannot (and the BMS will not let you) charge LFP batteries below freezing. As it turns out, discharging them below freezing, while possible, does have an accelerated effect on aging as well. Nowhere near as bad as letting the battery sit at a high temperature, but if the battery is going to be subjected to freezing temperatures it is better to do so while it is neither charging nor discharging, and with some charge in the battery. In a more general sense, it is better to put away the battery at around 50% – 60% SOC if it needs longer-term storage.

Cycle life. It has become common to get thousands of cycles, even at a full 100% charge-discharge cycle, out of lithium-ion batteries. There are some things that can be done though to maximize cycle life.

Each time the battery gets charged the electrode swells a bit, and each discharge it slims down again. Over time that causes microscopic cracks. It is because of this that charging to a little below 100% will give you more cycles, as will discharging to a little above 0%. Also, the ions as exerting “pressure”, and extreme State-Of-Charge numbers exert more pressure, causing chemical reactions that are not to the benefit of the battery. That is why LFP batteries do not like to be put away at 100% SOC, or put into float-charging at (or near) 100%.

While LFP batteries will routinely do charging and discharging at 1C (i.e. 100 Amp for a 100Ah battery), there will be more cycles out of a battery if it is limited to more reasonable values. Lead-acid batteries have a limit of around 20% of Ah rating, and staying within this for lithium-ion will have benefits for a longer battery life as well.

The last factor is Voltage, though this is really what the BMS is designed to keep in check. Lithium-ion batteries have a narrow Voltage window. Going outside that window very quickly results in permanent damage. For LiFePO4 that window is about 8.0V (2.0V per cell) to 16.8 Volt (4.2V per cell). The built-in BMS should take care to keep the battery well within those limits.

Summary

There are some aspects to note which is covered by the list below. Primarily, the first two should be given the highest consideration as they have by far the most effect on the overall life of the lithium-ion battery. The other aspects will help also to have the battery last even longer.

For long LFP battery life, you should be mindful of the following:

1. Keep the battery temperature under 45 Centigrade (under 30C if possible) – This is by far the most important.
2. Keep charge and discharge currents under 0.5C (0.2C preferred).
3. Keep battery temperature above 0 Centigrade when discharging if possible – This, and everything below, is nowhere near as important as the first two.
4. Do not cycle below 10% – 15% SOC unless it is absolutely necessary.
5. Do not float the battery at 100% SOC if possible.
6. Do not charge to 100% SOC if not needed.

Definitions and Settings of Solar Charge Controllers

PARAMETER MEANINGS:

Over Voltage Disconnect Voltage: if the battery volts exceed this, the load outputs disconnect from the load from the battery.

Charging Limit Voltage: if the battery volts exceed this, charging the battery from solar is stopped.

Over Voltage Reconnect Voltage: if the load outputs have been disconnected due to the battery exceeding over voltage a reconnect will occur at this value.

Equalize Charging Voltage: is a higher voltage intended to gasify and stir battery electrolyte. So is not applicable to Lithium battery charging.

Boost Charging Voltage: this term is used to indicate the maximum voltage level that will be applied for a period (default 2 hours) once the boost target voltage has been reached. Most everybody else uses the term absorption for this stage.

Float Charging Voltage: once the boost stage has been completed the controller will modify the maximum power search and load the panels to produce constant float volts at the battery.

Boost Reconnect Charging Voltage: once the unit is in Float mode the voltage may vary due to solar conditions and any load on the battery. If the battery voltage falls to this value the controller re-enters the Boost stage.

Low Voltage Reconnect Voltage: if the load outputs have been disconnected due to a low battery, this voltage is the turn on value.

Under Voltage Warning Reconnect Voltage: warning turned off at this voltage.

Under Voltage Warning Voltage: warning set at this voltage.

Low Voltage Disconnect Voltage: load outputs are disconnected from the battery at this voltage.

Discharging Limit Voltage: issues a warning at the set voltage, however, the charging unit cannot do anything about this.

Equalize Duration: the time duration where the voltage is held constant once the equalize voltage has been reached. This should be disabled (set to zero) for LiFePO4 battery charging.

Boost Duration: the time period that power will be applied to the battery until the boost target voltage is reached.

Temperature Compensation Coefficient: a conductivity measurement. The default is usually -3mv/C/2v. LiFePO4 setting is 0mv/C/2v.

<u>OVERVIEW:</u>

Bulk Charging Cycle is the cycle the controller automatically starts the day in -- maximum MPPT charging with constant current until the Constant Charging voltage settings are achieved. The maximum power control process will try to 'pull' maximum power from the panels. Under poor solar conditions with a discharged battery it should remain in this mode for some time. Chargers may limit these modes to 2 hours as a default. There are no settings for the Bulk cycle.

Constant Charging is the second cycle, made up of two sub-cycles, Boost and Equalize, and both are constant voltage.

Most charge guides describe the Equalize cycle as intended to gasify and stir battery electrolyte. This setting needs to be disabled for Lithium Battery charging.

Most charge guides describe the Boost cycle as used to prevent heating and excessive gassing. This is what is commonly known as "absorption."

The third cycle is the Float cycle.

So a Constant Current cycle is followed by an Absorption cycle. Translated to general terminology, this would be Bulk followed by Boost and then followed by Float.

The Boost at 14.6 and float at 13.6 may be considered by some as too high and may wish to adopt more conservative values. (See note below).

Many charging systems start with the current at the maximum that the solar can provide.
Once the 'boost' target voltage is reached, the voltage is held constant for the 'boost period', which can be set normally up to two hours. 'Boost Duration' is equivalent to absorption period, and 'boost charging voltage' is equivalent to absorption voltage.

Once in the float stage the controller will attempt to hold the voltage at that level. If loads and solar conditions allow the voltage to fall below the 'boost reconnect,' the whole charge sequence starts over again.

The equalization voltage should be set to the same as boost or lower (to be on the safe side) and the equalization duration period should always be set to zero.

Setting the boost duration, where the voltage is held constant will depend how the battery is charged and if you need an additional time for balancing. If the charge current is low compared to the battery capacity, the boost duration could be much lower than the usual default of 2 hours. With a high charge current compared to capacity the full period may be needed.

Note:

It seems to be accepted that, by using charge target volts lower than 14.6 volts, and also keeping the time that the batteries are at such a high level to a minimum, the battery life will be extended. Thus a boost target of 14.0-14.4 volts, and a float voltage of 13.4-13.5 volts, with a short absorption period, may be an advantage.

My current charger settings shown in the Edited column. I am reviewing and experimenting with these settings.

◆ **Lithium battery parameters**

The parameters are in 12V system at 25 °C, please double the values in 24V system and quadruple the values in 48V system.

Battery type / Voltage	LiFePO4 Default	LiFePO4 Blank	LiFePO4 Edited
Over Voltage Disconnect Voltage	15.6V		14.8V
Charging Limit Voltage	14.6V		14.2V
Over Voltage Reconnect Voltage	14.7V		14.3V
Equalize Charging Voltage	14.5V		14.2V
Boost Charging Voltage	14.5V		14.2V
Float Charging Voltage	13.8V		13.5V
Boost Reconnect Charging Voltage	13.2V		13.2V
Low Voltage Reconnect Voltage	12.8V		12.8V
Under Voltage Warning Reconnect Voltage	12.8V		12.8V
Under Voltage Warning Voltage	12.0V		12.0V
Low Voltage Disconnect Voltage	11.1V		11.1V
Discharging Limit Voltage	10.6V		11.1V

The following rules must be observed when modifying the parameter values in User for lithium battery.

Ⅰ. Over Voltage Disconnect Voltage>Over charging protection voltage(Protection Circuit Modules(BMS))+0.2V※;

Ⅱ. Over Voltage Disconnect Voltage>Over Voltage Reconnect Voltage=Charging Limit Voltage ≥ Equalize Charging Voltage=Boost Charging Voltage ≥ Float Charging Voltage>Boost Reconnect Charging Voltage;

Ⅲ. Low Voltage Reconnect Voltage>Low Voltage Disconnect Voltage ≥ Discharging Limit Voltage;

Ⅳ. Under Voltage Warning Reconnect Voltage>Under Voltage Warning Voltage≥ Discharging Limit Voltage;

Ⅴ. Boost Reconnect Charging voltage> Low Voltage Reconnect Voltage;

Ⅵ. Low Voltage Disconnect Voltage ≥ Over discharging protection voltage (BMS)+0.2V※.

⚠ **WARNING:** The voltage parameters of lithium battery can be set, but you must refer to the voltage parameters of lithium battery BMS.

⚠ **WARNING:** The required accuracy of BMS shall be at least 0.2V. If the deviation is higher than 0.2V, the manufacturer will assume no liability for any system malfunction caused by this.

Temp Comp Coeff -	**-3mv/C/2v**	**0mv/C/2v**
Rated Voltage -	**Auto**	**Auto**
Equalize Time -	**120mins**	**0mins**
Boost Time -	**120mins**	**60mins**