BATTERY CHARGING BASICS & CHARGE ALGORITHM FUNDAMENTALS OCT 2015

Introduction:

The purpose of this document is to discuss methods of using Deltran Battery Tender® battery chargers to charge Lead Acid and Lithium Ion batteries. Many battery chargers work well with a particular type of battery, when that battery is used in a specific application. The parameters that define any battery application include not only electrical charge and discharge requirements, voltage and current amplitude limits and timing, but also environmental operating and storage conditions. Although not discussed in this document, a typical list of environmental conditions would include temperature, shock and vibration, particulate matter (dust, dirt, etc.) and moisture (humidity, spray, splash, and submersion).

Table of Contents

What happens to a battery when it is charged and discharged?

In the simplest sense, discharging a battery removes its stored electric charge and delivers it to an electrical appliance to do some type of work. When the charge moves it is called electrical current. Charging a battery reverses that process and attempts to restore the battery to its original condition, storing electric charge to be used during the next discharge event. The electric charge is supplied by an electronic power supply with special control circuitry to tailor the output characteristics of the power supply to the specific needs of a battery. We call that type of power supply a battery charger.

For Lead-Acid batteries:

The chemical reactions during discharge convert lead, lead oxides, and acid (the electrolyte) into free electrons (electrical charge to be delivered to the load), water, and lead sulfates. The chemical reactions during recharge attempt to completely reverse that process. The perfect recharge balance would completely break down the lead sulfates and convert them back to lead oxides, lead, and by recombining with water to re-form acid without losing the hydrogen and oxygen gasses that make up the water.

Also, the majority of lead would be returned to its initial pre-discharge state. The primary motivation for the Absorbed Glass Mat battery design is to minimize the loss of oxygen and hydrogen gas that will be released at recharge voltages that exceed levels between 13.8 V (2.30 volts per cell) and 14.2 V (2.37 vpc). These voltage ranges apply to 12 V lead acid batteries, which each contain six cells that have a nominal voltage of 2.15 V when fully charged. Most lead-acid battery chargers have output voltages during some portion of the charge algorithm that are higher than the gassing voltage.

For Lithium Ion batteries:

The chemical reactions during discharge and charge perform similar functions in terms of changing the characteristics of the anode material, usually some type of carbon and the cathode material, some type of lithium metal compound. For the Deltran Battery Tender® Lithium Batteries, the cathode material is Lithium Iron Phosphate ($LiFePO_4$). The specific chemical changes are obviously quite different but the principals of extracting and replenishing electric charge still apply in a general sense.

The specific voltages framing the charging parameters of lithium ion batteries' performance are quite different from those of lead-acid batteries. The lithium cell voltages are intrinsically higher: nominal fully-charged values are 3.3 to 3.6 volts per cell vs 2.15 volts per cell for lead acid. Therefore the voltage values affecting performance and representing state of charge will also be higher for lithium ion batteries. Also, it only takes four individual cells to make up a 12 V lithium ion battery.

What is a charge algorithm?

Generally, an algorithm defines a series of steps or a procedure or an equation for solving a problem. Now that we have survived deep into the age of digital technology, literally every electrical appliance and electronic device on this planet and beyond is saturated with software. Software is nothing more than a large collection of individual algorithms.

So what is a charge algorithm? The battery charger controls the voltage that is applied to the battery, the amount of charge current that is supplied to or more appropriately, made available to the battery, and the timing for these voltage and current amounts to co-exist. The battery charger attempts to recondition the battery to a useful state, with sufficient charge to do useful work on the next discharge. The ordered sequence of events that are observed during that reconditioning, the parameters that are monitored, the decisions that are made based upon the values of the data describing those parameters, and the display of indicator lights to help the user understand what progress is being made or what problems are occurring, all make up the 'charge algorithm'.

Note: The details of the chemical and physical changes inside a battery while it is being discharged or charged are not as important as the empirical observations of the effects of discharge current amplitudes and times and the application of charge voltages and currents over time. Just as the observations of the physical world around us have led scientists to apply mathematical structure to the phenomena responsible for those observations, the development of charge algorithms is far more dependent upon empirical observations than upon mathematical model predictions. Mathematical models are useful to a point. But the fine details of charge optimization often remain hidden until the correct charging sequence is discovered by evaluating experimental results in a controlled environment.

The following discussion is intended to be an overview of the different charging modes, or methods, or stages, or phases, or steps that may be included in a charging algorithm. Depending upon who you are talking to when discussing battery charging algorithms, any one of those 5 words may be used interchangeably. 'Steps' seems to be the preferred description throughout the battery charging industry.

Battery Charging Algorithm Fundamentals:

Distinct Steps and Infinite Sequential Monitoring (ISM™)

There are a number of distinct, definable charging modes, or methods, or stages, or phases, or steps within a battery charging algorithm. Not all of these steps are essential in every battery application for every type of battery. Also, given the increasing complexity of optimum charging requirements for many batteries in the 21st century marketplace, Deltran Battery Tender® battery chargers have come to depend more upon the Infinite Sequential Monitoring (ISM™) approach in the executive microcontroller code that governs the behavior of the battery chargers. In other words, although any number of specific charging steps may be available for execution, usually sequentially, in the definition of any given charging algorithm, the ISM™ executive control overlay performs the essential task of optimizing the battery charger performance over a wide range of operating conditions.

Let's consider what we can define as meaningful steps to be included in a charge algorithm. Let's also consider what often happens in the marketplace. The desire for a manufacturer to differentiate a product from its competitors can sometimes result in the creation of technical jargon that may not be the most beneficial in terms of helping end users really understand how the technology actually works.

So let's talk about the details of the steps and try to avoid unnecessary technical jargon. The numbering of the steps and the order of their presentation simply indicates a typical sequence in which they would appear in any given charge algorithm. Again, not all steps are available nor are they necessary in all charger algorithms.

First Step: Initialization or Qualification.

This step has been around and incorporated in battery chargers from day one. Although it may not have been clearly defined or even considered to be a step. But truthfully, it may be the most important step in terms of safety. Virtually all battery chargers measure the condition of the electrical connection between the battery and the battery charger output. The specific limits of the parameters may differ, but the behavior of the voltage and current measured at the battery charger output give a fairly clear indication as to whether things in the battery charging world are normal or not.

As an example, if the charger output voltage is positive and the output current is zero, then that is a good indication that there is either no connection or an extremely poor connection between the charger and the battery. In technical terms, that is an open circuit, or very high impedance at the output. This is a common circumstance caused when a fuse has opened between the charger and the battery. That is a condition where it is wise to shut down the charger output and give the charger operator an indication that something is wrong, like flashing a specific color light or flashing more than one color light in a specific timed sequence.

Another common example is when the output voltage is positive and the output current is negative. That would normally indicate that the battery terminals are connected backwards to the battery charger output. You would think that the voltage would also be negative, but because of the laws of physics and electrical circuits, it is still possible for the charger to read a positive voltage. One more thing, all Deltran Battery Tender® battery chargers are designed to prevent negative current, which if unchecked, would drain the battery.

Second Step: Recovery.

This step is necessary to deal with severe over discharge situations. Both lead acid and lithium batteries may be subject to this problem. If you forget to turn off your lights on a power sport vehicle, then you can completely drain your battery in a short time. The philosophy behind recovery is to use low amplitude current to gradually build up the charge stored in the battery and support a voltage sufficient for the battery to accept a normal recharge regime. Even with a small current, there should be a minimum amount of voltage available. For 12 volt lead acid and lithium batteries, that value is about 4 volts. Anything less than 4 volts, and the recovery mode will not be employed. In the family of lead acid battery chargers, the recovery step is more of a background, on-demand type of function. In the family of lithium ion battery chargers, the recovery function is more distinct and clearly defined because the lithium ion batteries are more susceptible damage if the recovery parameters are not tightly controlled.

Third Step: Bulk Charge.

This step has the honor of occupying the unique position as being the only truly essential step in a charge algorithm, at least for lead acid batteries. Here you allow the battery to draw as much current as the charger will allow (called the current limit) until the battery voltage rises to a predetermined maximum level. When the voltage reaches that maximum level, the charger may be turned off. Before the voltage reaches its predetermined maximum level, the current will stay at close to its maximum value, or the current limit. Most charger manufacturers refer to this step as a 'constant current charging mode'. In most cases, after bulk charge is complete, the battery will be about 80% charged. That is good enough to use it again without doing anything else.

Fourth Step: Absorption Charge.

During this step, the behavior of the voltage and the current is reversed from that observed during the bulk charge step. The voltage is held constant and the current is allowed to decrease naturally. If you look at the graphs, during bulk charge the voltage starts to increase in a straight, linear fashion. Then as the voltage approaches its predetermined maximum level, the curve follows more of an exponential curve. During absorption, the current decays following a straight, linear path, then curves and tapers into a very low level, where it stays until the value of the charger output voltage changes.

The importance of the absorption charge step directly relates to completing the full replenishment of the individual battery cells. There are very complex mathematical equations that could explain the chemistry of this phenomenon, but the truth is that most of the useful knowledge available for charge algorithm applications has come over decades of trial and error. You will be hard pressed to find an explanation that justifies the effectiveness of the absorption charge step that does not include a very strong dependence upon empirical data. That is particularly true when you consider that the absorption charge step is only completely effective if it is allowed to continue long enough so that there is a minimum of several hours, probably at least 4 hours, when the battery is drawing virtually no current, but the applied voltage is kept high, at the absorption level. At first glance, that seems to make no sense. But it is absolutely true.

Fifth Step: Equalization Charge.

For lead acid batteries, this step is important mostly for a number of batteries being charged by a single voltage output charger while the batteries are connected in a series string. It takes a number of batteries to clearly observe the effect. Four batteries are usually enough. The mechanics of the equalization step appear graphically similar to a combination of the bulk charge and absorption charge steps. The difference is that the current starts out a very low level, approximately at 2 to 5% of the current limit of the battery charger, or at simply a very low fixed level, like 0.5 or 1.0 amp.

Depending upon how the actual equalization charging current value compares to the numerical value of the battery capacity in amp hours, and depending upon the equalization charging voltage limit, the charging current will only remain constant for a very short time. Then, for the balance of the time remaining in the equalization step, the voltage and current will behave as they do in during the absorption step. However, both the voltage and the current amplitudes are different.

What is the observable effect on batteries connected in series? The fundamental definition of a series connection is that one current flows through all of the elements that are connected. If a single charge current is applied to 4 or more 12 volt batteries connected in series, then without the equalization step it is likely that the individual voltages on the 12 volt batteries may vary by as much as 0.2 volts. For example, after recharge, the voltages on the 4 batteries in a 48 volt string might be 12.85, 12.8, 13.05, and 12.9 volts. If you add these voltages together, the sum is 51.6 volts which is that same as 4 batteries with each voltage = 12.9 volts. That is the theoretical 100% SOC value for a lead acid battery.

We'll discuss why those individual differences might exist later. For now consider that 1.5 volts represents the full capacity range on a single 12 volt battery. Therefore 0.2 volts represents about 13% of that range on a single battery. What happens to those individual voltages when we employ the equalization step? The readings change to 12.89, 12.9, 12.91, and 12.9 volts. The range of variation is now only 0.02 volts, or 1.3% of a single battery's full capacity range. This shows that all 4 batteries are charged equally, based simply on the observation of the terminal voltage.

Why the initial difference? Remember that each 12 volt lead-acid battery is made up of 6 individual 2 volt cells. The fully charged voltage of each cell is 2.15 volts. What if the cells do not perform identically and their voltages vary to the point where their combined value varies between 12.85 and 13.05 volts. That is exactly what happened. The remedy, which is to apply equalization level charge current, does in fact "equalize" the voltages. But the explanation remains in the realm of empirical observation. Not as satisfying as solving some mathematical equation, but effective none the less.

Sixth Step: Float / Maintenance Charge.

This step is very important in terms of the fundamental Battery Tender® defining concept. The whole purpose of float / maintenance is to maintain a fully charged battery in that 100% State of Charge (SOC) condition. For nearly all batteries, that means applying a voltage to a fully charged battery that is 1 or 2 tenths of a volt above the voltage that the battery would support to indicate that its SOC = 100%. Also, the battery must be at rest, not being charged or discharged.

In most cases, a 12 volt lead-acid battery, at 100% SOC, will have a rest voltage between 12.8 and 13.1 volts. That means an effective float voltage need only be as high as 12.9 to 13.2 volts. However, most Battery Tender® battery chargers have float voltages between 13.3 and 13.5 volts. The important thing is that the float voltage should be higher than the fully charged rest state battery voltage and it should be lower than the gassing voltage which is about 13.8 volts. See the discussion about float charging on the Battery Tender® website. It is definitely worth your time to read that document.

The float voltage requirements for the 12 volt lithium ion battery, specifically the lithium iron phosphate battery are a little higher because the combined voltage of 4 lithium ion cells at 13.3 volts is higher than 6 lead acid cells at 2.15 volts.

5-Step Lead Acid Charging Algorithm

In the following figure, the text boxes above the voltage and current graphs contain the details for the charging steps. The time scale is not proportional to any real time. It set to match up with the text boxes. That is for display information only.

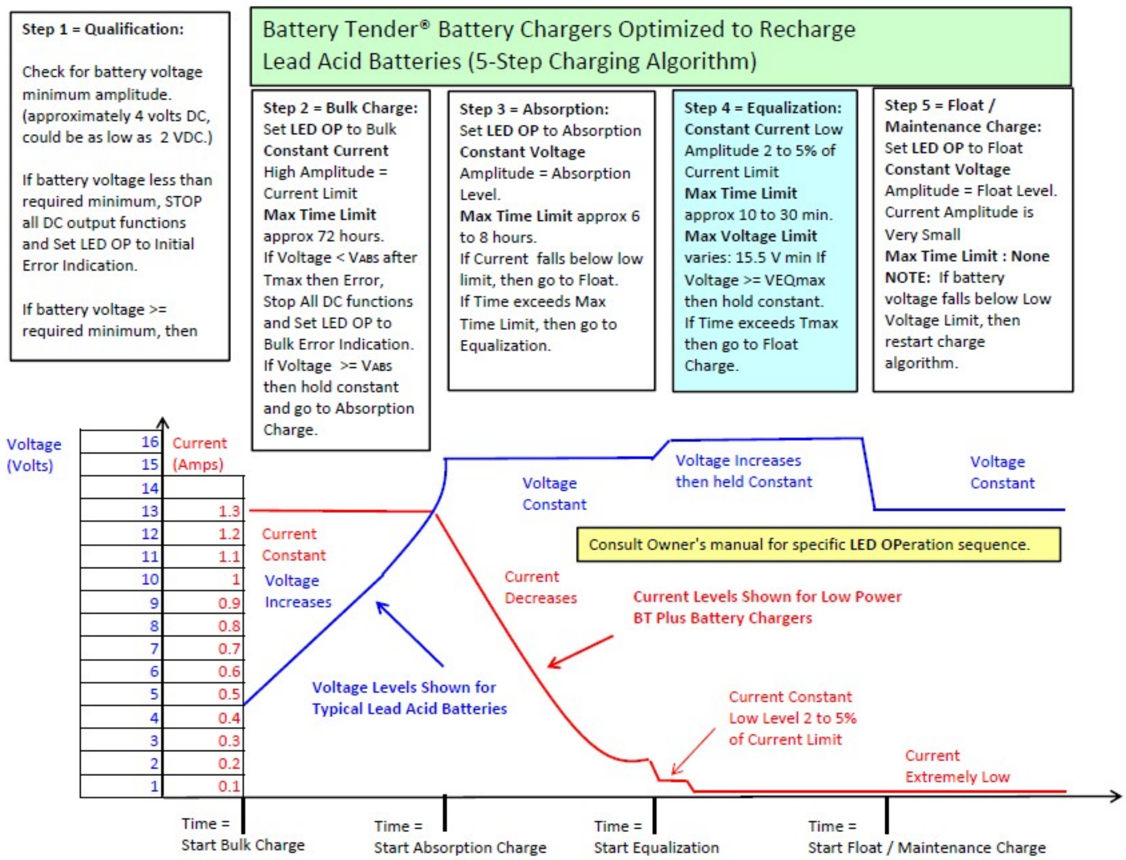

Figure 1 Lead-Acid 5-Step Charging Algorithm

Looking at the graph, the first real charging step is Step 2, Bulk Charge. After successful qualification, depending upon the charger being employed there are varying current limited, timed voltage generation tests that are not specifically shown. Given the complexity of those tests, they could certainly be considered to be a recovery mode, or at a minimum, an extended qualification mode. Suffice it to say that other factors are being considered to ensure safety and the validity of the decision to proceed into the basic charging steps.

5-Step Lithium Iron Phosphate Charging Algorithm

In the following figure, the text boxes above the voltage and current graphs contain the details for the charging steps. The time scale is not proportional to any real time. It set to match up with the text boxes. That is for display information only.

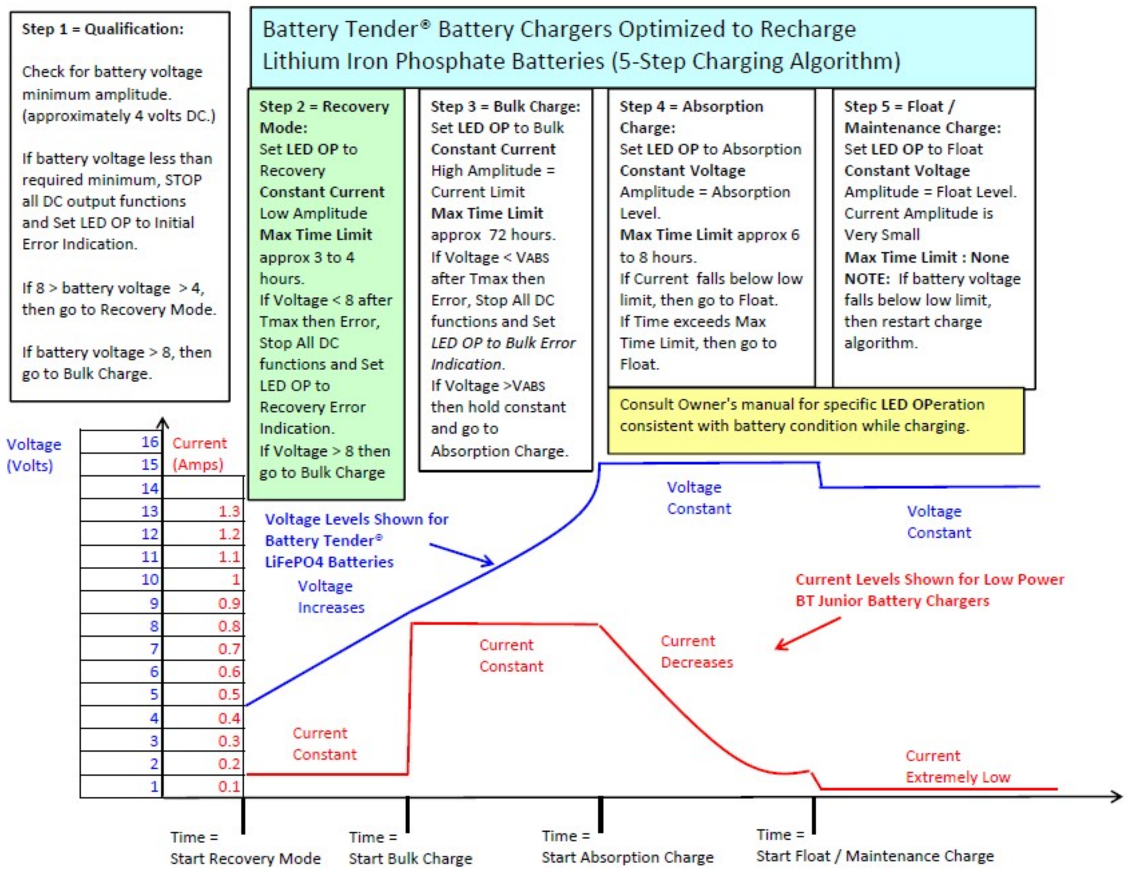

Figure 2 Lithium Iron Phosphate 5-Step Charging Algorithm

Looking at the graph, Step 2, Recovery Mode would seem to occupy the position as the first real charging step. It is specifically shown here and not for the lead-acid battery chargers because of the more sensitive nature lithium iron phosphate, certainly in terms of voltage dependence, but also with respect to charge current amplitude.

Don't forget that a 12 volt lithium iron phosphate battery consist of 4 individual 3.3 volt cells. That is a 13.2 volt 100% SOC voltage. Even though 8 volts is discussed as a low limit voltage, in fact, voltages just below 12 are more nearly an indicator of a fully discharged battery.

Summary

A charge algorithm defines a series of steps to control the characteristics of an electrical power supply configured to perform the functions of a battery charger. More specifically, the focus is on the output characteristics of voltage, current, and time. This is essentially a piece of software with many of the same basic characteristics as the software being used to control the computer screen that you are using to view this document.

For instructional purposes, only 5-Step algorithms were displayed in detail. With the display of the charging voltage and current graphs and the companion text blocks, the hope is that other charging configurations containing more or less than 5 steps could be sufficiently understood.

The optimum recharge of a discharged battery depends not only on the charge algorithm from the battery charger, but configuration and condition of both the battery and the battery charger, and the compatibility between the two. The application governing the use of the battery has a large impact on what parameters constitute an optimum recharge function for that battery.

It is interesting to track the progress of battery charging as a parallel effort with the advance of computer control technology. The search for the holy grail of battery chargers continues. One charger charges every battery perfectly, in a minimum amount of time, and in the process ensures that the battery will meet its design cycle life, with minimum degradation from application specific or environmental issues. Short of using a mini-Cray computer submerged in a tub of liquid nitrogen as the computer core for the HGC (Holy Grail Charger) it is unlikely that such an optimum charger will be found any time soon.

The good news is that the Deltran USA, LLC team has made great strides over the last 25 years, even more so in the last 5 years to optimize the Battery Tender® battery charger configurations. These newer versions of the classic Battery Tender® battery chargers leverage the advances in electronic components, application specific microcontroller technology, and computer aided design methodology to offer the most powerful, flexible, cost effective battery charging solutions in the industry today.