EAGLE EYE WHITE PAPER

Title	**The Proper Charging of Stationary Lead-Acid Batteries**
Document No.	**WP-050110-1**

Revision History

Date	Revision	Change Description	Author(s)
5/1/10	0	Initial Release*	JAB
6/13/17	1	Grammatical and format changes	JAB
6/18/17	2	Code updates	JAB
10/15/18	3	Font and Format Changes	JAB

The Proper Charging of Stationary Lead-Acid Batteries

Your battery is only as good as how you charge it

Overview

All too often, stationary batteries are not correctly or adequately charged. This leads to a shortened battery life and may also cause a premature and sometimes catastrophic battery failure. It is the author's experience that almost 50 percent of all stationary batteries are not being properly charged. This observation is based upon hundreds of site visits, multiple battery system tests, and the examination of numerous maintenance records and warranty claims.

Battery charging is a complex process. Consideration has to be given to several fixed and varying parameters such as battery type and chemistry, battery application, and the environment in which the battery is being used. In many cases, batteries are installed and put into service connected to chargers that have been factory preset and not readjusted to suit the batteries that they are charging.

The intent of this technical note is to educate battery users on battery charging and detail the proper methods of float (maintenance) charging, recharging, equalize (boost) charging, adjusting the charge for temperature and limiting the charge current when necessary. Since there are many types of stationary batteries in use today and each chemistry has its own unique and often complex charging requirement, for the purpose of this paper, the discussion is restricted to the lead-acid type which is by far the most commonly used stationary battery. The focus is on maintaining battery health and extending battery life and reliability. The suitability of certain types of battery chargers is also discussed.

The basic building block of a lead-acid battery is the cell. Cells that are connected internally in series is a battery unit and cells or units connected in series to achieve a required voltage are called a battery string. Cells that are connected in a series-parallel configuration to achieved required capacity can be referred to as a battery, battery system or battery plant.

The Lead-Acid Battery Cell

There are two basic types of lead-acid battery cells. One is the Vented Lead-Acid (VLA), which is commonly referred to as a "flooded" or "wet" cell because the dilute sulfuric acid electrolyte is in a liquid form. The other is the Valve-Regulated Lead-Acid (VRLA) cell which is erroneously referred to as "sealed" or "maintenance free" or even a "sealed maintenance free cell." This is because it is neither sealed or maintenance free. There is a pressure relief valve installed in the cell which opens in reaction to internal pressure build-up and VRLA cells certainly require maintenance.

Within these two types there are different plate chemistries and construction methods. The most common types of lead-acid battery designs used in North America are the pasted (flat) plate followed by the tubular plate design. The plates are mainly lead with an additive aimed at strengthening the plates or extending plate life. These additives include calcium, antimony, selenium and tin. In all cases, the electrolyte is dilute sulfuric acid. With VLA cells the electrolyte is a free-flowing liquid; whereas, with VRLA cells, the electrolyte is in an immobilized form. This is achieved either by absorbing the liquid electrolyte in micro-porous, sponge-like plate separators or by adding a gelling agent to the electrolyte. Hence the terms “absorbed” electrolyte and “gelled” electrolyte.

The Battery Cell Discharge and Charge Cycle

A battery cell is an electrochemical device. The process of discharging a cell is the conversion of the stored chemical energy to electrical energy that is used to power an electrical load. The charging process is the opposite reaction, which is the conversion of electrical energy in the form of electric current from an external source which is stored as chemical energy in the battery cell.

In all of the cell types mentioned above, the electrochemical reaction for the discharge and recharge of lead-acid batteries is basically the same. The basic battery cell design has three or more positive and negative plates which are immersed in an electrolyte that provides a medium for the transfer of electrons between the plates. There is always one more negative plate than the number of positive plates. The negative plates are made of sponge lead and the positive plates are made of lead dioxide. If the battery is connected to a load, a circuit is formed where electrons flow from the positive to the negative through the dilute sulfuric acid electrolyte. This discharges the battery and both positive and negative plates progressively change into lead sulfate and the electrolyte, losing the sulfuric component, progressively changes to water. The nice thing about a secondary (rechargeable) lead-acid battery cell is that the discharge cycle is completely reversible. In order to recharge the battery, this electrochemical reaction has to be reversed. When the charging current flows through the battery cell it causes the conversion of the discharged lead sulfate plates to reverse and forces the sulfate back into the electrolyte. Simplified formulae for a battery cell discharge and recharge are:

Discharge cycle.

$$Pb + 2H_2SO_4 + PbO_2 \rightarrow PbSO_4 + 2H_2O + PbSO_4$$

Charge cycle.

$$PbSO_4 + 2H_2o + PbSO_4 \rightarrow Pb + 2H_2SO_4 + PbO_2$$

We learn in basic chemistry and physics that you can't get something for nothing and in order to recharge a battery more energy (current) has to be returned to the battery than has been removed in order to restore the battery to a fully charged state. Once it is restored to full charge the battery has to be continuously supplied with energy in order to maintain it in that fully charged condition. How the recharge and maintenance charging (float) current is delivered to the battery is the focus of this paper.

Charging Methods

There are basically two methods of charging lead-acid batteries and these are constant current charging and constant voltage charging. Constant current charging means that the battery charger output voltage is varied so that it supplies a relatively uniform current regardless of the battery state of charge. This is appropriate for a battery used in a cycling application such as a traction battery and requires that the charger be removed from the battery when the battery is fully charged. This is not appropriate for batteries used in standby applications such as Uninterruptible Power Supplies (UPS's) or DC battery backed power systems.

The preferred method for charging batteries in standby use is constant voltage charging where the same voltage is applied to the battery throughout the charging process irrespective of the battery state of charge (SOC). With a discharged battery, because of the potential difference between the charger and the battery, the recharge current is initially high and tapers off as the battery voltage and SOC increases. This results in the battery being partially recharged quickly but it requires prolonged charging in order to obtain a fully charged state.

With constant voltage charging there are two common charging voltage levels. Float charging is the normal charging method where the battery is recharged and maintained in a fully charged condition by "floating" the battery at a voltage level that will keep the battery charged. Equalize or boost charging is when the charger voltage level is raised to a level somewhat higher than the float charge voltage in order to "equalize" the voltage levels of the individual cells or affect a quicker recharge. In this method the battery is usually connected in parallel with the charger and the load. This allows for the battery to be available to power the load without any switching or interruption.

Overcharging and Undercharging.

The VLA cell is somewhat more forgiving to overcharging than the VRLA cell. This is because the two main reactions caused by overcharging are increased gas generation and heat. Since the VLA cell is open to the atmosphere, the oxygen and hydrogen which is given off from the plates can exit the cell. The resulting water loss (H_2O) can be periodically replaced by adding water into the cell. Also, since the VLA cell has liquid electrolyte, which is always in contact with the cell container, excessive heat generated by overcharging can be dissipated to the outside of the cell. However, the resulting higher charge current caused by the higher battery temperature will accelerate the positive plate corrosion and shorten the life of the cell.

The VRLA cell works on a “recombination” principle. Since under normal circumstances, the pressure relief valve is closed, the oxygen and hydrogen generated during charging is recombined within the cell and no water is lost. Charging above the recombinant limit will result in the evolution of oxygen and hydrogen gas which escape from the cell through the pressure relief valve and contribute to a condition called dry out. When a VRLA cell loses water, it will eventually result in a loss of capacity. Since the VRLA cell is not designed for the replenishment of water, the water loss is irreversible. Also, because the electrolyte is either absorbed or gelled, the physical contact of the electrolyte with the cell container is not always very good and consequently this does not allow for efficient heat dissipation.

Undercharging is also a problem. When recharging a cell, the electric current flowing is driving the sulfate from the cell plates back into the electrolyte solution. Undercharging or the failure to fully recharge the cell results in some of the sulfate being retained on the plates. This causes “plate sulfation” and results in the reduction of cell capacity. If undercharging occurs over a period of time or the cell is left discharged or not fully charged, the sulfation is irreversible and the cell will fail. Even before sulfation occurs, undercharging will mean that the cell is never at full capacity.

The Correct Charging Voltage Levels.

Float Charging

In order to correctly charge a battery, a somewhat exacting recharge voltage level has to be applied. It is analogous to fine tuning a car engine so that it keeps ticking over properly but uses the minimum amount of fuel to do so. This is dependent upon the type and size of engine, the type of fuel, the temperature and so on. With a battery cell, pretty much the same applies. The specific gravity (SG) of the electrolyte, the grid alloy and the ambient and internal battery temperature are the variables that have the greatest effect on the correct charge voltage

The SG of the electrolyte determines the open circuit voltage (OCV) of a battery cell. If a constant of 0.845 is added to the SG that will determine the OCV. To maintain a charge on the cell, the charging voltage must be slightly higher than the OCV in order to overcome the inherent losses within the battery caused by chemical reaction and resistance. For a lead-acid battery the value above the OCV is approximately 0.12 volts. This “adder” voltage will vary very slightly (+/- 0.02V) for different plate additives and construction but it is a very good rule of thumb. Although the following shows some example calculations, the manufacturer’s recommended float voltage should always be used. Also, some manufacturers do not reveal the electrolyte SG, it may not be possible to perform the above calculation.

For a typical VLA cell with a SG of 1.215 the OCV would be: 1.215 + 0.845 = 2.060V.

The correct charging voltage would therefore be approximately 2.060V + 0.12V = 2.18V

For a typical VRLA cell with a SG of 1.300 the OCV would be: 1.300 + 0.845 = 2.145V

The correct charging voltage would therefore be approximately 2.145V + 0.12V = 2.265V

The above examples are for a single battery cell. To determine the float voltage for a 6 cell (12V) battery unit the cell charge voltage would be multiplies by 6. For a complete battery string, the cell voltage would be multiplied by the number of cells in the battery.

Note. With VLA cells, the distribution of charge voltage between the positive and negative plates sometimes leads to a higher recommended float voltage.

Freshening Charge

Lead-acid batteries will self-discharge from the day they are manufactured until they are put into service. As it is often several months before the battery is installed, it is important that a "freshening" charge be given before the battery exceeds it storage shelf life. For lead-selenium this is usually 3 months and 6 months for lead-calcium. Some other additives may extend shelf life, but it is important that all be given a "freshening" charge before they are placed in service. This freshening charge is manufacturer defined but is normally about 100 mV per-cell above the recommended float voltage for a period from 24 to 72 hours. If batteries that have been in storage did not receive a freshening charge and they are placed on float charge immediately after installation and are used in standby service where they are not regularly cycled, they may never reach full charge

Equalize Charging.

An equalize charge is essentially a boost charge for an extended period at an elevated level above the normal float voltage of the entire battery string and is normally manufacturer specified. It is so called because it is used primarily to "equalize" the voltage and SG inequalities between individual cells. It is also used to try to remove sulfation from the plates and to prevent electrolyte stratification in VLA cells. It can also be used to recharge the battery more rapidly after a discharge. An equalize charge should be avoided with VRLA cells unless recommended by the manufacturer.

There is a “caution” when applying an equalize charge. As with float charging, the level is largely determined by the SG and plate chemistry. Because of the elevated charging current, all cells in the battery are basically being overcharged, and this should only be allowed for a short period of time which shouldn’t exceed about 72 hours. As equalize charging increases the rate of gassing, with VLA batteries it is important that the electrolyte level is correct before applying an equalize charge. For VRLA batteries, it is important not to exceed the gassing rate of the cells which can be as low as about 2.4 volts-per-cell. Typically, manufacturers of VRLA cells do not recommend the use of periodic equalize charging except for cycling service applications.

When equalize charging is used, always follow the manufacturer’s instructions with respect to voltage levels and time, Also, always check the upper voltage tolerance of the load as the higher voltage being applied to the dc bus may not be acceptable to the load.

Gassing.

Battery cells start to produce gas when they are charged faster than they can absorb the energy. In VLA cells the excess energy drives electrolysis which results in the loss of water. This in itself is not too problematic as it is a relatively simple matter to replenish the water in the cells. Only use deionized or distilled water and never add sulfuric acid. In a VRLA cell, the excess energy is converted to heat which can lead to thermal runaway (see below). This is where it is important to use a charger that has two basic control features. One is the ability to limit the charging current applied to the battery and the other is the means to automatically adjust the charge voltage based upon battery temperature.

Charge Current Control

Most manufacturers recommend a maximum recharge current that can be applied to their VRLA product. This is usually indicated on the data sheet in terms of battery cell capacity at a given discharge time divided by a constant. For example, C/5 amps at the 8-hour rate. What this simply means is that, for example, for a cell rated at 100 ampere hours (Ah) at the 8-hour rate, the recharge current should not exceed 100/5 or 20 amps.

Temperature Compensation.

In North America, it is usual that battery performance and charging voltage is referenced to a nominal 77ºF (25ºC). Significant excursions above or below this norm will affect the way the battery should be charged, and this is significant for VRLA cells. Besides shortening battery life by causing electrolyte depletion (dry out) and positive grid/plate corrosion, improper charging at high ambient temperatures can also lead to a dangerous condition called "thermal runaway." This can also be caused if the battery is charged too fast. In simple terms, when a battery is operating at an elevated temperature it causes the float current to increase which in turn causes the battery to heat up internally which in turn causes it to draw more current. If left unchecked, this destructive cycle can eventually lead to the battery cell melting, rupturing or even exploding. If it is not possible to regulate the ambient operating temperature then the charge current must be adjusted for any temperature excursions. This is called temperature compensation and is a feature of most modern chargers. Manufacturers state this compensation factor in terms of voltage adjustment per degree of temperature; for example, 1.7mV per ºF. This means that the charger should be programmed to adjust its voltage output up or down by this amount based upon the reading of a temperature probe placed on a battery. This is important in order to prevent overcharging or undercharging a battery.

An important fact that is often overlooked in battery operation is that the life of the battery is reduced by half for every 18ºF (10ºC) above the 77ºF (25ºC) optimum operating temperature.

The Charger

It is important that the battery charger is suitable for charging the battery to which it is connected. Just as all batteries are not alike, all chargers are not the same. In order to adequately charge a battery without damaging the battery, a charger must have tight voltage regulation, low ripple voltage and low Electromagnetic Interference (EMI) and Radio Frequency Interference (RFI) noise characteristics.

The output voltage should be regulated over the full range of the charger output and typically this should be +/- 0.5%. In other words, the voltage output should be stable irrespective on the load that is being placed on it.

Good output filtering is important in order to minimize the charger output ripple and noise being imposed on the battery. It is also necessary because should the battery be taken off-line for any reason, then the charger will be connected directly to the load and the charger output will lose the filtering effects of the battery. Consequently, any ripple and noise from the charger will be applied directly on the load and this may be problematic. This is really important in telecom applications where electrical ripple and noise can be induced into voice circuits. Maximum charger output ripple in these cases is typically required to be less than 30 mV rms. Chargers in UPS's are often a high source of ripple voltage because of inadequate output filtering and regulation of the charger and this reduces battery life. Many battery manufacturers offer lower warranty periods for batteries used in UPS applications.

A high ripple component in the battery float voltage will result in excessive charging of the battery and may cause excessive heating, gassing and the deterioration of the plate active material. High ripple can also interfere with battery monitoring and test equipment. A low ripple voltage is more important when charging VRLA batteries and manufacturers typically require a maximum ripple voltage of +/- 0.5% rms of the float voltage and a maximum ripple current of 5 amps rms per 100 Ah of rated capacity. A good way of determining if the battery charger is acceptable is to measure the temperature of a fully charged battery at the negative terminal and it should be less than 5ºF (3ºC) above room ambient.

Different Charging Methods.

While this paper is focused on constant voltage charging there are other methods of charging that have emerged recently. One of these is intermittent charging where the charger is switched on and off at predetermined intervals. While purportedly designed to prolong battery life, any benefits obtained may be outweighed by the difficulty in measuring or monitoring the actual battery state of charge at any given time or even determining battery capacity when placed on load. This author is neutral on this method.

Conclusion.

Proper battery charging involves many considerations but it pretty much boils down to one thing and that is ensuring that the battery receives the correct current to adequately charge/recharge the battery and keep it charged. For a typically lead-acid battery, the float charging current on a fully charged battery should be approximately 1 milliamp (mA) per Ah at 77ºF (25ºC). Any current that is greater than 3 mA per Ah should be investigated. At the 2009 International Battery Conference (BATTCON®), a panel of experts when asked what they considered were the three most important things to monitor on a battery, the unanimously agreed on two, which were battery temperature and current.

Bibliography.

The following IEEE codes and standards contain some very useful information on the subject of battery charging. All are available from IEEE, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA. www.ieee.org

1. IEEE Std. 484 - 2008. *IEEE Recommended Practice for Installation Design and Installation of Vented Lead-Acid Batteries for Stationary Applications.*
2. IEEE Std. 450 – 2010. *IEEE Recommend Practice for Maintenance, Testing, and Replacement of Vented Lead-Acid Batteries for Stationary Applications.*
3. IEEE Std. 1106 – 2015. *IEEE Recommended Practice for Installation, Maintenance, Testing, and Replacement of Vented Nickel-Cadmium Batteries for Stationary Applications.*
4. IEEE Std. 1184 – 2006. *IEEE Guide for Batteries for Uninterruptible Power Supply Systems.*
5. IEEE Std. 1187 – 2013. *IEEE Recommended Practice for Installation Design and Installation of Valve-Regulated Lead-Acid Storage Batteries for Stationary Applications.*
6. IEEE Std. 1188 – 2005. *IEEE Recommended Practice for Maintenance, Testing, and Replacement of Valve-Regulated Lead- Acid (VRLA) Batteries for Stationary Applications.*
7. IEEE Std. 1188a – 2014. *IEEE Recommended Practice for Maintenance, Testing, and Replacement of Valve-Regulated Lead- Acid (VRLA) Batteries for Stationary Applications Amendment 1. Updated VRLA Maintenance Consideration.*
8. IEEE Std. 1491 – 2005. *IEEE Guide for Selection and Use of Battery Monitoring Equipment in Stationary Applications.*