AVOIDING THE PITFALLS OF VRLA BATTERY CHARGING

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ABSTRACT

The market for large VRLA batteries is now some 15 years old, but the charging needs of this battery type continue to be poorly understood. Horror stories of battery explosions and thermal runaway have caused some users, and even manufacturers, to adopt damagingly low float voltages. System integrators routinely install unnecessarily large chargers with VRLA batteries, sometimes pushing an unstable battery into thermal runaway. Manufacturers of electronic equipment may apply sophisticated techniques to minimize overcharging or to equalize charging voltages, without fully appreciating the damage that this can cause.

This paper explains the charging characteristics of VRLA batteries as they relate to such problems. Of particular importance is the way in which these characteristics vary over time—both the rapid changes that occur early in life and the progressive changes associated with battery aging. By adopting the principles outlined in this paper, the user can ensure that VRLA battery life is not shortened by poor charging practices.

AGING CHARACTERISTICS

The best place to start out is with the VRLA battery aging process. As with most electrochemical systems, there is an extremely complex interaction between the various reactions that are occurring, but a few important points can be clearly made.

Water Loss

There is a fine balance in the amount of water in a VRLA cell, particularly in absorbed electrolyte types. Too much water, and the cell behaves like a vented unit, with little recombination of charge gases and liberation of those gases to the atmosphere. Too little water, and the electrolyte is unable to sustain the cell reaction, causing discharge capacity to be lost. The initial filling of absorbed electrolyte cells aims to leave the glass mat separator just short of being saturated, so there is no free electrolyte.

Recombination Efficiency

During float charging, water is broken down at the positive plate and oxygen gas is produced. If that oxygen reaches the negative plate, the recombination reaction occurs, returning water to the system. In its almost-saturated state, the separator is not able to transport much oxygen to the negative plates, so only a small amount of charge gas recombination can occur. If there is no recombination, then hydrogen and oxygen are liberated from the cell and water is lost. For a new cell, however, this is not as bad as it sounds, since the loss of liquid leaves void spaces in the separator, thus allowing more oxygen transport and therefore more recombination. Thus, there is a rapid change in the recombination efficiency of a new cell in the first weeks and months of its life on float. The improvement in recombination efficiency continues, albeit at a much slower rate, as the cell ages.

Float Current

The float current in a VRLA cell is largely determined by the cell's temperature and its polarization. Polarization is the difference between the open circuit voltage and the charge voltage. For example, a VRLA cell with 1.300 Sp.Gr. electrolyte will have an open circuit voltage of 2.15 V (applying the Nernst equation to the lead-acid system yields a simple equation, V_{oc} = Sp.Gr. + 0.85). If that cell is floated at 2.27 V, the polarization is $2.27 - 2.15 = 0.12$ V. This overall polarization of 120 mV is shared between the positive and negative plates.

In VRLA cells, there is generally more variability in the behavior of the negative, while the positive behaves more

predictably. In a hypothetical single-cell system, one way of looking at the relationship between positive and negative polarization and float current is that the behavior of the negative determines how much polarization is left over for the positive, which in turn determines the float current. When the recombination reaction occurs, there is no net chemical change at the negative plate, and the negative is depolarized. This reduction in negative polarization allows a corresponding increase in positive polarization, since the overall voltage is imposed on the cell by the charger and must remain constant.

This means that cells with higher recombination efficiency, allowing more oxygen to reach the negative plate, will show a higher positive polarization and higher float current than cells with low recombination efficiency.

Changes in recombination efficiency and ongoing water losses from the VRLA cell give rise to a characteristic pattern of float current over life for a battery on continuous float. The early increases in recombination efficiency cause a rapid increase in float current. The float current continues to rise for the next year or two, as the recombination efficiency continues to improve.

During this time, however, the cell has been losing water. Water loss results from the small but measurable inefficiency in the recombination reaction, and from grid corrosion. When the positive grid corrodes from lead to lead oxide, oxygen from water is tied up in the grid material and is not available for recombination. The only possible reaction at the negative is the production of hydrogen gas, so that water is lost from the system.

This progressive water loss results in an increase in the specific gravity of the electrolyte. As this occurs, the overall polarization decreases. In the example above, if the acid Sp.Gr. changes to 1.320, the polarization at a 2.27 V float voltage is reduced from 120 mV to 100 mV. Eventually, this process becomes dominant and the float current begins to decrease. The drop in float current becomes more pronounced as the cell approaches the end of life. Figure 1 shows the typical behavior of float current in a 10-year VRLA cell.

Recombinant Limit

The number and size of voids in the separator limit the amount of oxygen that can pass through to the negative plate for recombination. This recombinant limit can be expressed in terms of the current that the cell can absorb without causing full gassing and water loss. From the discussion above, it can be readily understood that the recombinant limit for a new cell is low, then rises rapidly in the first weeks or months of float operation. The recombinant limit continues to rise steadily as the cell ages and water is lost.

It is extremely important to understand that there is a downside to the recombination reaction. Chemically speaking, the reaction is a closed loop, with no net chemical change occurring. However, charging energy is being absorbed by the cell and the laws of physics demand that this energy be accounted for. The electrical energy is converted to chemical energy to drive the recombination reaction, which in turn releases that energy in the form of heat. This heat must then be dissipated
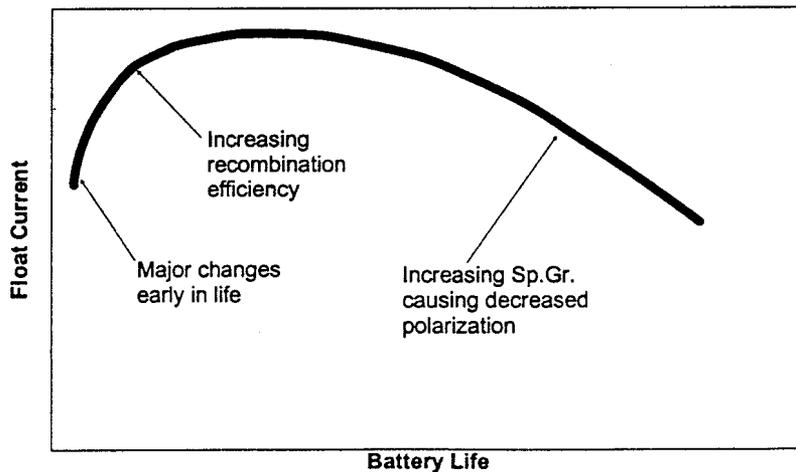
Figure 1 - VRLA Float Current

If thermal equilibrium cannot be reached, the cell's temperature will rise. In a straightforward constant potential charging scenario, a warmer cell will accept more charging current, which leads to more recombination and heat generation. This sets up a spiral of increased current and increased heating known as thermal runaway.

CHARGER CURRENT LIMIT

About the only time that charger current limit is discussed is in relation to the ac ripple content in the dc output. In addition to causing potential noise problems, ripple can damage VRLA batteries by causing unwanted heating. Traditionally, ripple has been rated when the charger is connected to a battery with an ampere hour capacity that is four times the rated current output of the charger.

There is, however, another aspect to the charger's current limit. Although a typical battery will spend more than 99% of its life on float, the way in which it is recharged following a discharge can be crucial.

There are two stages in a constant potential recharge. The first stage is characterized by high current and relatively low voltage, and is in effect a constant current charge at the charger current limit. When the battery approaches a fully charged state, the second stage takes over, characterized by low current and a constant potential at the charger's voltage setting. It is at the transition point between the two stages that problems can begin. At this point, the positive has started to produce oxygen gas, but the charge current is still very high—up to two orders of magnitude higher than the stabilized float current. Gassing studies[1] have shown that there can be a significant emission of gas during this transition, with larger volumes of gas emitted for higher charger current limits.

When a VRLA battery is new, only a small amount of this gas can be recombined, so the excess gas is vented through the valve. As the battery ages, however, the recombinant limit is much higher, so large amounts of heat can be generated at this point. The potential for problems is further increased when there is considerable variability amongst the cells within a battery. The first cells to approach a fully charged condition will continue to be charged at a high current, generating excessive amounts of heat, until the remaining cells reach a similar state of charge.

The heating effects encountered during recharge can be a primary cause of thermal runaway in VRLA batteries. The risk can be minimized by limiting the charge current to 10-20% of the battery's ampere-hour capacity. In the case of a large, lightly loaded UPS system, it may be necessary to install separate current limiting circuitry to accomplish this.

VARIATION IN CELL FLOAT VOLTAGES

It is a time-honored tradition in the battery industry to monitor cell or module float voltages, and to equalize any battery in which the voltage spread exceeds a certain level. With VRLA batteries, however, voltage levels can be highly misleading, especially when dealing with a new battery.

Self Discharge During Storage

VRLA cells show a higher rate of self-discharge than their vented counterparts. In addition to the normal self-discharge reaction, there is another type of self-discharge that can arise from excess oxygen in the cell's internal atmosphere. To make matters worse, the rate of self-discharge typically varies somewhat from cell to cell. This means that when a battery is first placed on charge, there can be a large variability in cell condition. Since the charger output current tapers off when the majority of the cells have reached a high state of charge, any cells that are lagging behind will take that much longer to catch up. This effect can give rise to a disparity in float voltages.

Just Starting Out – An Equalizing Paradox

The exact opposite of the self-discharge effect can be seen in batteries over the first six months or so of battery life. The initial changes in float current shown in figure 1 are subject to the same cell-to-cell variability. Since there can only be one current passing through the battery, this variability will be seen in the spread of float voltages. Assuming all cells are fully charged, cells with higher recombination efficiency will exhibit lower float voltage and vice versa. Thus, we have an initial

picture in which only a few cells are showing a high level of recombination, and therefore low float voltage. As other cells start to recombine more fully and their negatives become depolarized, their relative voltage will be reduced and the string float current will increase. This rising current will bring the remaining cells into line more quickly.

This effect gives rise to an equalizing paradox. An accepted method for bringing cell float voltages into line is to perform single-cell equalize charging on the low voltage cells. In this case, however, the voltages would be brought into line more effectively by equalizing only the *high* voltage cells! The high voltage cells will lose water when equalized, thus improving their recombination efficiency and bringing them into line with the lower voltage cells.

In practice, the best course to follow is virtually to ignore float voltages for the first few months of operation. Of course, all cells should be above the open circuit level, but beyond that it is best to let nature, in the form of electrochemistry, take its course.

AVOIDING THERMAL RUNAWAY

Thermal runaway is probably the most feared battery phenomenon for battery users. In contrast to dryout, it is an attention-grabber that can be dangerous for both equipment and personnel. Consequently, many users and even some manufacturers will go to great lengths to try to avoid thermal runaway.

Float Voltage – How Low Is Low Enough?

One of the 'quick fix' solutions is simply to reduce the float voltage. This will lower the float current, meaning that the battery will produce less heat, and therefore be less likely to go into thermal runaway. There is also the perception of an added bonus in that a lower float current should cause less grid corrosion.

Unfortunately, this is not the case. Grid corrosion studies[2,3] from 20-30 years ago demonstrated that the rate of grid corrosion was minimized at a positive plate polarization of 80-100 mV, and that the corrosion rate was much more rapid both above and below this level. A later study[4] found the minimum to be in the 40-50 mV range, and found the corrosion rate at lower polarizations to be less extreme. It should be borne in mind, however, that these studies were carried out on vented lead-acid cells for telecommunications, using 1.215 Sp.Gr. acid. The situation for VRLA cells, which typically use 1.300 Sp.Gr. acid, appears to be that the corrosion rate is very high at low positive polarization values. This can be seen in Figure 2 below, which shows a VRLA module that was floated at about 2.19 V/cell for less than two years in a high temperature
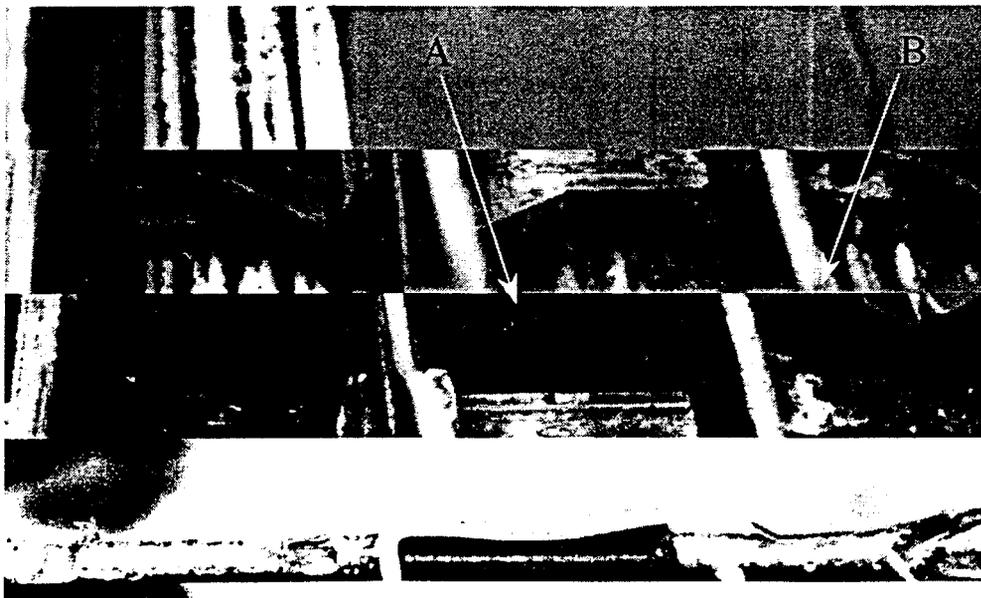
Figure 2 - Effects of Undercharging

environment. The negative bus bar (A) of most cells was heavily sulfated, indicating that the negatives had been self-discharging. The positive bus bar (B) in the photograph has lifted at its free end (the other end is anchored by the through-the-wall connection), indicating massive plate growth. The white marks also indicate that sulfation has occurred. Based on an open circuit voltage of 2.15 V/cell and assuming no polarization of the negative (because it had self-discharged), this left about 40 mV for the positive plate polarization. Since the charging in this case was clearly inadequate, it would be reasonable to assume that the 80-100 mV positive plate polarization range (from the earlier studies) is safer for VRLA cells.

This demonstrates the potential problem that can be caused by lowering float voltage too much. Taking a 1.300 Sp.Gr. VRLA cell with an open circuit voltage of 2.15 V, adding 80 mV for the positive polarization and assuming approximately 10 mV for the negative, we arrive at a float voltage of 2.24 V/cell. This could be used as a reasonable float voltage for a new cell. As the cell ages, however, it loses water, so the Sp.Gr. will increase. For a typical older cell that has lost 10% of its water, the electrolyte Sp.Gr. will be around 1.320 Sp.Gr., so the open circuit and float voltages will be correspondingly higher. The float voltage in this case should be around 2.26 V/cell, which is very close to the 2.27 V/cell recommended by many manufacturers.

This is not to say that lower float voltages cannot be used. The point is that at some point below 80 mV of positive polarization, the rate of grid corrosion will show a rapid increase. It is not appropriate simply to reduce the float voltage to a point where thermal runaway is unlikely to occur, as has been done by some users and even manufacturers in the past. Any reduction should be carefully justified by grid corrosion studies.

Temperature Compensation – Too Much of a Good Thing?
Similar thinking should be used when considering temperature compensation of the charger's output voltage. Battery manufacturers sometimes quote the slope of the compensation curve—typically –3 mV/cell/°C—without giving any limits to its applicability. Since temperature compensation is often a part of the overall strategy for combating thermal runaway, there may be a sense of, 'can't have too much of it' when applying this slope.

This outlook runs into problems at both ends of the temperature spectrum. Recombination efficiency is reduced at low temperatures, so continuing to increase the float voltage as the temperature drops only promotes water consumption. Since the rate of all reactions, including grid corrosion and self-discharge, will be lower, it is probably better to allow some undercharging at low temperature.

At high temperatures there can be major problems. If we take an aged cell with 1.320 Sp.Gr. and an open circuit voltage of 2.17 V, and assume zero negative polarization and a minimum positive polarization of 50 mV (the minimum may have to be higher, as mentioned previously), the absolute lowest float voltage that should ever be applied to that cell is 2.22 V. For a recommended float voltage of 2.27 V/cell at 25°C, the maximum allowable compensation value is therefore –50 mV. With a slope of –3 mV/cell/°C, this represents a temperature swing of only 17°C. This means that the maximum compensation for temperature is limited to 42°C (108°F). With temperatures in outside plant cabinets often reaching 50-60°C, this is a real issue. The price to be paid for overcompensation is accelerated grid growth and a rapid end to battery life.

THE FOUNTAIN OF BATTERY YOUTH?

With the advent of microprocessor-controlled chargers and improvements in monitoring techniques and communications, the question is often asked, "How can we better manage the charging of our battery systems?" To be sure, there are some very worthwhile equipment options that can modify the charging regime to eliminate the possibility of thermal runaway and generally make charging as 'comfortable' as possible for VRLA batteries. However, there is a limit to what can be done, and these systems certainly cannot change basic electrochemical principles.

Attempts to Reduce Grid Corrosion
Since grid corrosion is caused by charging, and grid corrosion is a primary aging mechanism, wouldn't it be possible to extend battery life by just charging less? We have already seen the perils of undercharging, but what about leaving the battery on open circuit for part of the time? Just such a charging regime has been reported on previously.[5] The conclusion from this 1984 paper was that it was possible to extend VRLA battery life by virtually 100% using a 50% float regime. In this case, 50% float means that the battery is on float for 50% of the time and on open circuit for the remaining 50%.

Accelerated aging test data at 71°C were presented to show this effect.

What is not mentioned in the 1984 paper is the exact method for artificially aging the batteries at the test temperature. It is this author's belief that water additions were allowed, assuming that the only significant aging process was grid corrosion. We now know that water losses can be of vital importance and can often determine battery life. If water was added during the testing, this important aging process would have been completely masked.

The Water Loss Problem

The limiting factor in this case is the rate of self-discharge of the negative plate. This reaction is represented by the equation:

$$Pb + H_2SO_4 \rightarrow PbSO_4 + H_2$$
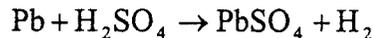
Thus, hydrogen gas is being continually emitted by a VRLA cell on open circuit. Although the above equation does not involve water loss, it is necessary to look at what happens during charging. For the negative plate to be recharged, the reaction is as follows:

$$PbSO_4 + 2H^+ + 2e^- \rightarrow Pb + H_2SO_4$$
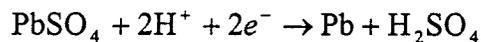
Since the positive has not undergone self-discharge, the predominant reaction at the positive would be as follows:

$$H_2O \rightarrow \tfrac{1}{2}O_2 + 2H^+ + 2e^-$$
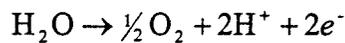
The end result is that self-discharge causes water loss in lead-acid cells. (The alternative to the recharge reaction is that the oxygen from the positive plate, instead of being vented from the cell, travels through to the negative where it recombines to liberate water. Although this would avoid water loss, it would also mean that the negative would never be recharged.)

It is an electrochemical fact that hydrogen emissions, and hence water losses, from a VRLA cell can never be less than those that result from self-discharge on open circuit. This principle is covered in some depth in a paper by Jones and Feder.[6] It is also possible to see this from some typical battery measurements.

Looking at a typical 100 Ah cell, the rate of self-discharge is around 4% of rated capacity per month, or 4 Ah per month. As seen above, this lost charge will result in water losses from the cell. During normal charging, the cell will stabilize at a float current of around 1 mA/Ah, or 0.1 A. If the recombination reaction is around 99% efficient and the grid corrosion reaction accounts for 2-3% of the current, we can say that 3-4% of the float current will result in water loss. A continuous current of 0.003-0.004 A amounts to 2.2-2.9 Ah in a month. Although this level is not quite the same as the 4 Ah in self-discharge losses, it can readily be seen without an extensive electrochemical analysis that the two processes result in a similar level of water loss.

This brings us to a fuller understanding of the significance of water loss in VRLA cells. Not only does water loss reduce available capacity by increasing the cell's impedance, but it also affects charging in fundamental ways. Water loss increases acid Sp.Gr., which increases the open circuit voltage, which decreases the available plate polarization. Decreased polarization can result in a large increase in the rate of positive grid corrosion and rapid aging. Also, if the charge current falls below a certain level, the negative may start to self-discharge, leading to premature failure. It is the author's opinion that many of the premature failures reported for VRLA cells are directly or indirectly caused by water loss.

We can also see that VRLA cells continue to age, even when sitting on open circuit. This means that any attempt to increase battery life by limiting charging is doomed to failure. Even worse, if the battery remains connected to the dc bus with the charger set at the 'open circuit' level, as has been suggested, this operating mode will actually accelerate aging. Since the open circuit voltage changes slowly but continuously, the charger set point will almost always be either just above or below the true battery open circuit level. If it is just above, rapid grid corrosion will result; if below, the battery will be partially discharged and will most likely sulfate. There is no free lunch!

CONCLUSION – STICK TO THE BASICS

As our knowledge of VRLA characteristics improves, we are constantly struck by just how complex this system is. All too frequently, a change that is made to avoid a potential problem such as thermal runaway leads to other, and sometimes worse, problems. It is almost as if Newton could be paraphrased: 'every desirable action has an equal and opposite undesirable reaction.' In this light, battery users should carefully consider any proposed change in their VRLA battery operations, and should beware of simplistic fixes or extravagant claims.

Microprocessor-controlled charging can indeed make life better for VRLA batteries. It can soften the transition from high current charging to low current during recharge, and can impose a low battery current limit during stabilized float charging. Both of these steps can reduce or virtually eliminate the possibility of thermal runaway. The danger lies with using electronics to try to alter fundamental aspects of battery operation.

The basics of good VRLA charging are as follows:

- Adopt the manufacturer's recommended float voltage at 25°C, and don't use low float voltage as a means to avoid thermal runaway.

- Implement temperature compensation of the charger's output voltage, using the manufacturer's recommended slope. Limit the compensation to an acceptable temperature range, such as 0-40°C.

- Limit the battery charge current to 10-20% of the rated battery capacity

- Don't overreact to float voltage variability within a string, particularly during the early stages of battery life.

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