

# RECOMMENDATIONS ON THE PRACTICE OF INDIVIDUAL CELL VOLTAGE BALANCING (ALSO KNOWN AS INDIVIDUAL CELL EQUALIZATION)

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## Introduction

Because of the nature and method of their manufacturing, lead-acid cells have inherent variabilities in their components, resulting in a range of behavior that can be observed when recharged. Once multiple cells are connected in series and float charged at a constant voltage, this variability results in the cells floating with a measurable spread in cell voltages. It would be natural to conclude that it is better to continuously and individually adjust each cell voltage so as to maintain every cell at the exact midpoint of the recommended float voltage range. Although the intent to float at the manufacturer's exact recommended voltage is understandable, when put into practice, the methodology used has been shown to do more harm than good to the life and reliability of the lead-acid battery. This paper will identify the main reasons why the use of continuous adjustment of individual cell voltages is not recommended for lead-calcium batteries used in standby applications.

## Background

A standby battery is commonly kept on a continuous, float charge, which is used to recharge the battery following a discharge event. After the battery is fully recharged, the float charge continues and will provide the energy to negate the natural self-discharge reactions that are occurring within the battery. Note that the cell voltage is the resultant of the positive plate voltage (or polarization) plus the negative polarization. If the plates are not charged to a high enough level, then one or both plates will self-discharge, and lose capacity. If left in this state long enough, the capacity loss becomes permanent due to the creation of large lead sulfate crystals, known colloquially as 'hard' sulfate and technically as Ostwald ripening. The battery manufacturer provides a target float voltage, and also a range (such as 2.25 +/- .03 v times # cells). It is important to note that the range given is not the allowable cell-to-cell variation, but rather it is the allowable range of overall voltage for the string to be floated.

And so, the basic question is, 'What is a reasonable cell-to-cell range, and what is required?' Not long ago, requirements could be found requiring cell-to-cell variation in a series-connected string to be within a range of +/- 100 mV, or even +/- 50 mV. This was primarily due to the use of antimony as the additive used to harden the grids used in standby lead-acid batteries. Antimony slowly oxidizes inside the cell during its operation, and this antimony will diffuse to the negative plate and then be reduced (plated) onto the negative plate surface as a normal and expected side reaction as the battery ages. This slowly shifts the polarization (charge) on the negative plate to a more positive value, dropping the overall cell voltage. The overall result is that the negative is less charged, resulting in the positive becoming overcharged. Because they are floated at constant voltage, the float current will rise, which will directly result in greater water loss due to electrolysis, an increase in the gassing rate and an increase in maintenance as the antimony batteries age. This process will vary between cells, and so the cell-to-cell voltage variation will begin to grow. Once a pre-determined maximum range in cell-to-cell voltages is

reached, periodic boost charges were recommended. This cleared the accumulated antimony from the negative plate in the form of gases, and the negatives were then returned to their original condition. In practice then, antimony battery users were schooled in the belief that the widening range of cell-to-cell voltages was an indication of deteriorating battery health, and it has long been a recommended practice to actively watch and reduce this cell-to-cell voltage range. [6][7]

However, the lead-calcium batteries that are used in standby applications today should not be treated this same way. Lead-calcium batteries use calcium as the primary grid alloy hardener in place of antimony. Calcium is stable in the lead-acid battery environment and does not poison the negative plate in the same manner that antimony does. This means the cells' voltages on float charge are stable over life and do not expectedly change as the cells age on operation. Thus, **individual cell voltage is not an indication of the health of a battery**. In fact, in well accepted studies performed many years ago by AT&T and Bell Labs, it was noted that there was a total lack of correlation between cell float voltage and capacity. [8] Whereby periodic equalizing was a necessary process to return older antimony cells to their original capacity, it is an unnecessary and potentially harmful process for calcium cells.

The design life of a calcium lead-acid battery is primarily determined by the life of the positive plate, or more specifically, the positive grid. During float charging, the positive grid is slowly oxidized (corroded). It is thus most critical to the life and health of the calcium battery to maintain the health of the positive plate. The positive plate must be kept fully charged, but the charge voltage on the positive (i.e., positive polarization) must be carefully controlled within a limited range. The corrosion rate of the positive grid increases with increasing voltage. It also increases if the positive polarization is too low. This is the basis for the establishment of the float voltage by the manufacturer. It has been shown from several well accepted studies that the positive grid corrosion rate for calcium lead-acid batteries is minimized when the positive polarization is in the range of 40-80 millivolts.[9][10] When the float voltage results in a positive plate polarization less than or greater than this range, the positive plate will corrode faster and the battery will fail earlier.

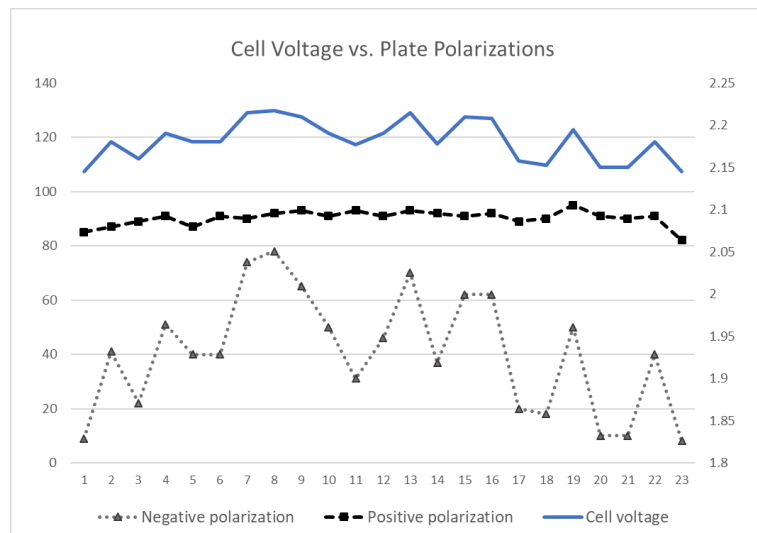
### **Individual Cell Balancing – A Misguided Solution**

It is this relationship that has initiated the use of individual cell voltage balancing or equalizing devices. Although there are different devices of this type, they all primarily monitor the cell voltage and either actively or passively shunt a portion of the float current to modify the cell voltage on float. Although the intention is to maintain a constant, proper cell voltage, there are several reasons why this process and these devices are not generally recommended in the industry.

The primary flaw in the use of these devices is that it has been shown that the majority of the voltage variation of cells on float is a result of the negative plate variation. The porosity and the surface area variability of the negative plate is reflected in the variability of the negative plate polarization. This variability is exacerbated in a VRLA battery, as the variability in the oxygen reduction rate on the negative plate adds to the overall cell voltage variability. The balancing devices cannot distinguish between negative and positive polarization, and can only react to overall cell voltages. As the voltage balancing device attempts to stabilize the cell voltage, it is actually changing the polarization of the positive plate based on the variation caused by the negative plate. What is seen in practice is that this can move the positive polarization out of the minimum corrosion rate band and can actually thus increase the corrosion of the positive grid. Ironically, several high-profile sites have reported dramatically shortened battery lives when such devices were used. [11]

As stated in a previous study by Feder, D.O and Garosella, G., “Voltage variations within a string of cells are due almost exclusively to variations in the negative plate potentials.” To visualize this, the figure below from their study shows both positive and negative polarization data from an actual installation of lead-calcium cells. The individual cell voltages can be seen with some variations from one cell to the next. Also shown are the positive polarization and the negative polarizations, that together, make up the cell voltages. As evident in this figure, the cell voltages can be seen to track the negative polarizations. If the cell voltages were individually adjusted to artificially make them float consistently, this would actually result in the positive polarizations diverging. If this caused the positive polarizations to deviate out of their ideal minimum corrosion range, then the service life of the battery would decrease from such a procedure –***that is, the cells would fail earlier, even though the cell voltages were made to be more consistent.*** [8][14]

The discussion above is based on the individual positive and negative plates, and the inability to control the positive plate voltage by minimizing the overall cell voltage range. The situation is actually much worse when some types of commercial battery models are considered. The 12-volt monobloc units that are in wide use today, are comprised of six cells internally connected in series. Each cell cannot be individually monitored and adjusted, and so one can only adjust the total block voltage, which adjusts all six cells at once. This reduces the resolution significantly, as a single cell would have to drift by over 30% to see a 5% variation in the block voltage. There is no way to know if a monobloc voltage drift is caused from a single cell or multiple cells in the unit. Because of this, trying to maintain individual cell voltages of a multi-cell monobloc is neither practical nor realistic.



It is also worth noting that even when individual cell models are used in an application, having an individual cell voltage does not mean the internal voltages within a cell’s element are exact and do not vary. Individual cells are assembled from multiple layers of positive and negative plates that are connected in parallel, sometimes as many as 20 plates or more. At the cell’s post, the voltage applied to all plates within a cell is equal, but because the welded connection to the strap and the internal resistance of each plate will vary, the localized voltages will vary throughout each plate. Some locations will always have higher voltages due to geometry, such as the corners of the plates, but other spots will be higher (or lower) in voltage due to materials, porosity or process variations within each plate. Even the electrolyte concentration will affect the local voltage. The effects of this variation can actually be seen visually in flooded (VLA) cells. The location of gassing bubbles will indicate local areas of high voltage, and this can be seen to be inconsistent and variable from one plate to another, even within the same cell. Even if the exact same voltage was applied to every unit in a battery bank, the internal voltages on the individual plates would vary. [6]

## **Grid Corrosion – Primary Failure Mode**

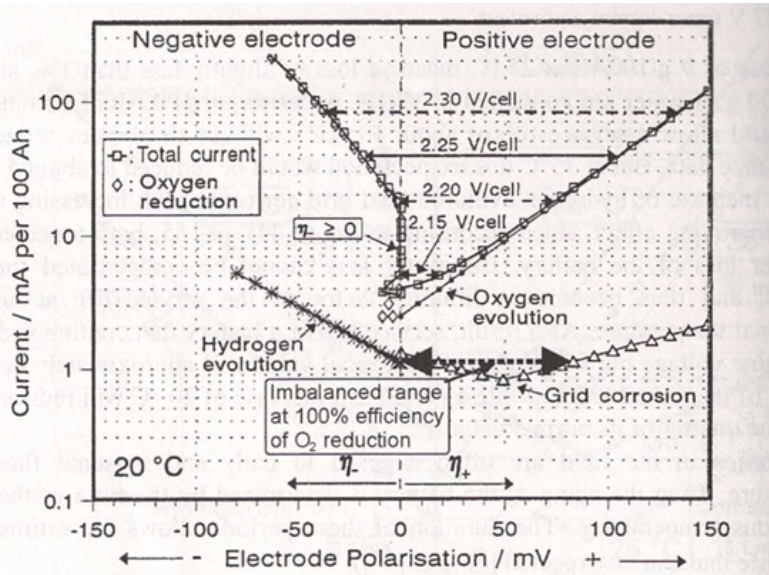
Corrosion of the lead grid is the primary failure mode in the lead-acid battery. Overall corrosion of the grid reduces its cross section, creating a higher resistance pathway for the current on discharge. This will result in a greater voltage drop during discharge and a shortened runtime. Additionally, corrosion will preferentially penetrate the grain boundaries of the grid, causing positive grid growth. Even if the grid cross section is minimally corroded, grid boundary corrosion can still cause significant plate growth resulting in failure as it will cause loss of contact between the active material and the grid. When this grid growth occurs, cell failure is typically expected after 8-10% growth in the grid dimensions. A third mechanism of note is that the grid metals have a protective layer of lead oxide that reduces ongoing corrosion of the lead grid metal. This protective layer is destroyed when the positive polarization drops to near the resting potential. This is the primary reason the grid corrosion rate increases when the float voltage is below the recommended minimum. [11]

Clearly, controlling positive grid corrosion is one of the keys to the life of a lead-acid battery. Anything that disturbs this should be avoided.

## **VRLA**

This discussion holds true for all lead-acid models, both vented lead-acid (VLA, or flooded) and valve-regulated lead-acid (VRLA). It is important to note that in VRLA models, the float voltage is not only keeping the plates charged, but is also balancing the energy for the recombination of the hydrogen and oxygen gases at the negative plate. The positive plate must have sufficient voltage to recharge the active material, while minimizing the corrosion of the grid and the evolution of oxygen gas. The negative plate must have sufficient voltage to recharge the active material, while also reducing the oxygen at the negative surface. These reactions must be balanced properly and their interrelationships are often shown on a Tafel Curve diagram (see example Tafel diagram shown below). Adjusting the float voltage will not only affect the float current, but often has a dramatic effect on these VRLA side reactions. This can significantly affect the grid corrosion and the recombination efficiency, and improper float voltages often result in undercharged and sulfated negative plates. [1][2]

In extreme examples of improper float voltages, a VRLA cell can generate excessive gases, resulting in premature loss of electrolyte. This was reported as dry out and resulted in failure from high internal resistance and cell shorting in the field. This was a common mode of failure in the first generation of VRLA cells. Although premature VRLA dry out can still occur from abuse, improper charging or improper material purity, it has been largely contained through careful control of the float voltage and the understanding of the importance of the proper plate polarizations and interrelationships of these side reactions. Similar to the VLA discussion on voltage variations, the positive polarization is relatively stable and the variations are primarily due to the negative. In the VRLA battery, the rate of oxygen recombination at the negative plate adds to this variation. Critical VRLA design factors such as the saturation level of the element, the compression and the electrolyte distribution all contribute to the dominating effect the negative plate has on cell voltage. [3][4][5]



Example Tafel Curve Diagram (from Maintenance-Free Batteries, A Handbook of Battery Technology, D. Berndt, Third Edition, 2003.[1])

To summarize, shifting the float voltage can result in several unintended consequences. [11][15][16]

- Moving the positive polarization outside of the recommended range
  - Can cause reduced capacity due to corrosion of grid members
  - Can cause early failures from grid growth and loss of active material contact
  - Can cause early failures by destroying the protective peroxide layer, thus increasing grid corrosion
- Moving the negative polarization outside of the recommended range
  - Can cause early failure due to sulfation of the negative plate
  - Can affect recombination efficiency resulting in water loss and dry out

### Diagnostic Loss

From a practical user's perspective, another key reason to discourage use of these devices is because it eliminates the ability to use trend analysis as a diagnostic tool in determining state-of-health of the battery string. As stated earlier, lead-acid batteries all have some process and material variability resulting in cell voltage variation when floated at constant voltage. The float voltage of a new VRLA battery is known to shift when initially installed (i.e., during the first six months to two years, depending on its design), as the recombination efficiency climbs. Once the recombination efficiency and hence the cell voltage stabilizes, as long as the cell voltages are within the manufacturer's expected range, there is no defect to correct and adjusting individual cells is unnecessary and unneeded. It is, however, important that the cell float voltages be recorded, whatever they might be, so that their movement over time can be observed. Since all items spontaneously degrade rather than spontaneously improve (2<sup>nd</sup> Law of Thermodynamics) a change in cell voltage over time, particularly during the latter 75% of the battery's life, can usually be confidently interpreted as a degradation in the state-of-health of the cell. This rate of change is an important diagnostic tool in identifying cells that may be failing. If a cell balancing device is continually adjusting the cell voltage, this trend is masked, and the degrading cell will not be identified until the cell actually fails during a discharge event. Ironically again, this will actually reduce the reliability of the battery string. It is much more important to be able to see when a cell begins to degrade, then to mask this degradation by artificially maintaining it at some fixed voltage.

## Where does individual cell balancing work?

There are some non-float applications where individual cell balancing or equalization are useful. In high rate recharging applications, the high currents generate a high level of power loss as well as a large variation in voltages between the high and low resistance cells. If the charge is terminated based on the average voltage, the low voltage cells could be undercharged. In this case, a balancing or equalization at the charge termination point could be useful. This may also occur in continuous cycling applications, which typically use higher charge voltages to ensure a full recharge in the limited time allowed. Again, these higher currents can cause a large range of cell voltages, with the possibility of undercharging the lowest voltage cells because of the limited charge times. This variation is magnified when very large series-parallel battery arrangements are utilized, such as electric vehicle packs and large photovoltaic systems, which can use hundreds of cells in series. Some past utility support battery systems have even been configured with thousands of cells in series. If only a few cells out of the entire string are weak, they can easily lag much lower in voltage, and thus they can benefit from cell balancing at charge termination to bring them to the same state-of-charge as the string in the allotted time. [12][13]

If these devices correct undercharged cells as described above, they will almost certainly improve battery discharge performance. However, this does not apply to a standby battery application, as these high-rate or cycling applications differ from standby battery applications in several key ways. The float currents are comparatively very low in a standby application, and as such, they do not create the same voltage spread, nor the variation in state-of-charge as seen in a cycling recharge. Also, the float charge period of a standby battery is not limited. The float charge runs continuously, so the lower cells will continue to receive the float current until they eventually reach a full state of charge. There is no need for the use of individual balancing to individually raise the state-of-charge of certain cells.

## Summary

In summary, Individual Cell Voltage Balancing, or ICE-type devices used on a standby lead-acid battery, that will continuously monitor and compensate individual cells to maintain them at a fixed voltage are reducing the reliability of the string. The float voltage is determined by the manufacturer to maintain the positive plate in its optimal, low corrosion voltage range. It has been shown that the majority of the cell voltage variation is not due to the positive plate, but to the negative plate instead. Therefore, adjusting the cell voltage because of this variability of the negative plate, can push the positive plate polarization out of its optimal range and actually cause it to corrode at a higher rate, thus reducing its service life.

Just as importantly, the diagnostics of cell voltages are lost when they are continuously adjusted. Once a string has been installed, trends in the individual cell voltages provide critical diagnostic data. How the voltage of a cell changes as it ages, allows weaker cells to be identified before they fail, and can identify a battery string that is degrading faster than expected due to unexpected site conditions. Masking these changes prevents early detection of failing cells.

For these primary reasons, the use of individual cell equalization devices is not recommended. Not only are they unnecessary, but they can actually reduce the life and reliability of a battery string, as well as prevent proper diagnostics of the battery string over its life.

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